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Deforestation on the Indonesian island of Sulawesi and the loss of primate habitat

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ABSTRACT

Sulawesi is an important island for primates. All 17 species that are found there are endemics. The island also includes contact zones between species of macaques (genus *Macaca*) where hybrids may arise. Sulawesi continues to be deforested, especially in the lowlands most suitable for estate crops and other agricultural products. We carried out an island-wide review of the current extent and rates of deforestation, and the impact this is having on the habitat available to all primates and within macaque hybrid zones. The provinces of West Sulawesi and Southeast Sulawesi suffered the highest rate of deforestation. *Macaca ochreata* in Southeast Sulawesi and *Tarsius pelengensis* on Peleng island in Central Sulawesi have lost the most habitat at 14%, followed by *M. hecki* and *M. tonkeana*. Forest loss also occurred in all macaque contact zones. The greatest losses occurred at contact zones between the western population of *M. tonkeana* and *M. ochreata*. Corn, coffee, cocoa, and oil palm are commodities that are spreading throughout the island. The extent of deforestation in the hybrid zones is alarming, particularly as none of them are represented in protected areas. To help address these problems, a careful integration of conservation and development is suggested, including making trade-offs explicit, and conducting transdisciplinary research on social-ecological systems at the interface of policy and management at local scales.

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1. Introduction

Sulawesi is part of the Wallacea hotspot, so named for Alfred Russel Wallace, the co-discoverer with Charles Darwin, of the theory of evolution. Hotspots are defined as regions of the world with at least 1500 endemic vascular plants and less than 30% of their original primary vegetation cover remaining (Myers et al., 2000; Mittermeier et al., 1998). The Wallacea hotspot overall still has about 45% forest cover, however, the percentage drops to only 15%, or about 50,774 km^2 when only intact forest in a pristine condition is considered (Supriatna et al., 2015).

The evolutionary history of the fauna of Sulawesi is a function of geological history and dispersal. Sulawesi has not been connected to other large islands for about 50 million years (Hall, 1996, 1998). More recently, ocean inundation, large rivers, and even unproductive low habitat quality forests, posed barriers to species dispersal (Evans et al., 2001; Whitten et al., 2002). This geological and physical history is reflected, for example, in the patterns of endemism among macaques on a fine geographic scale (Fooden, 1969; Hall, 1998; Whitten et al., 2002; Evans et al., 2003b). Other fauna showing similar patterns of endemism include fanged frogs (Evans et al., 2003a), Celebes toads (Evans et al., 2003c), flying lizards (McGuire et al., 2007), and tarsiers (Shekelle and Leksono, 2004). The narrow areas of Sulawesi (see Fig. 2 below) represent several contact zones where macaque species may intergrade and sometimes produce hybrids. However, gene flow is low and although unlikely to be followed by speciation, may show molecular variations in mitochondrial DNA and nuclear DNA (Evans et al., 2003a).

1.1. Deforestation in Sulawesi

As elsewhere, things have changed dramatically in Sulawesi during the course of the past century. The human population has nearly quadrupled, and development has grown tremendously in Indonesia in general. In Sulawesi, the first commercial logging operation began in the early 1970s, and forests have been cleared for agriculture and for land settlement schemes like the infamous transmigration program that resettled hundreds of thousands of people from densely populated Java to other less inhabited (but much less productive) corners of Indonesia (Whitten et al., 2002). Gold and Nickel mines were opened in the early 1980s, while oil palm plantations were established in the early 1990s mostly in West Sulawesi and later in large areas in Gorontalo province. This has greatly reduced the amount of forest habitat, particularly in the lowlands, and has caused dramatic and severe declines in the populations of many forest species (World Bank, 2011). The forest cover that remains is also partly a function of rainfall and altitude. Drier areas have generally been more impacted than the wetter areas and lowland areas more so than the upper reaches of mountains. Dry forest types in general have only about 10–20% of their original area remaining, while moist and wet forest types have substantially more (FWI/GFW, 2002).

Because most of Sulawesi's pristine lowland forests had been lost nearly two decades ago, its current rate of deforestation doesn't seem too high compared to Sumatra and Kalimantan. In reality however, should the present rate of forest loss continue, it could be catastrophic for the island's remaining wildlife and natural ecosystem services (Laurance, 1999; Butler, 2013). When deforestation occurs, forest habitat is fragmented, isolating sub-populations from one another. Fragmentation also leads to greater access for hunting and wildlife trade (Clayton et al., 1997). The effects of forest fragmentation are exacerbated by the shape of Sulawesi, which includes long narrow areas, limiting options for dispersal and re-colonisation.

1.2. Sulawesi primates

Indonesia contains one of the most diverse primate faunas on earth. The country boasts at least 64 of the world's approximately 516 species (Mittermeier et al., 2013; Supriatna, 2019), the most recent addition being *Tarsius niemitzi* from Togean Island in central Sulawesi (Shekelle et al., 2019). Indonesia's primates represent 5 families from 9 genera, and 37 of them are endemic (Groves, 2004; Mittermeier et al., 2013; Roos et al., 2014; Supriatna and Ramadhan, 2016; Supriatna, 2019). The species are distributed across the archipelago from north Kalimantan to the south coast of Java, and from westernmost Sumatra east to Sulawesi and Timor. Indonesia contains primates of every type, from primitive 'living fossils' such as tarsiers through to the advanced apes, both the small apes (gibbons), and great apes (orangutan) (Supriatna, 2019). The greatest number of endemic primates are on Sulawesi and adjacent islands (17 species) followed by the Mentawai island group (5 species) (Brandon-Jones et al., 2004; Supriatna, 2019; Shekelle and Leksono. 2019).

Sulawesi has only two primate genera, *Tarsius* and *Macaca* but they have diversified into more species than those same genera on other islands of Indonesia and astonishingly, all 17 species are endemic to Sulawesi. Tarsiers are one of the smallest primates in the world. Adult male body weight is only 50–150 g (Shekelle et al., 2013; Supriatna et al., 2015). At least 11 species of tarsiers occur on Sulawesi and adjacent small islands (Shekelle et al., 2013; Shekelle et al., 2019). Macaques are the most widespread genus of monkeys in the world, with a total of 20 species found from African deserts to the snowy mountains of Japan. In Indonesia, 11 species occur throughout Sumatra, Kalimantan, Java, Sulawesi, and islands in the east as far as Timor, where they have been introduced. If we include *Macaca brunescens* from Buton island and *Macaca togeanus* in the West-central Sulawesi (Froehlich et al., 1996; Evans et al., 2003; Supriatna, 2019) there would be 8 species in Sulawesi. However, as *M brunescens* is still recognized by most authorities as *M. ochreata brunescens* and *M. togeanus* as *M. tonkeana togeanus*, we have accepted only 6 for the purposes of this analysis.

The island of Sulawesi has an importance in primate endemicity that is similar in kind, though not in scale, to that of Madagascar. Sulawesi's 17 species comprise more than 27% of all primates in Indonesia. Four of the macaques are classified as vulnerable, while one, *Macaca maura,* is endangered and one other, *Macaca nigra,* is critical (IUCN, 2019). Field research

suggests that there may still be undescribed tarsier species. The vertical distribution of tarsiers over a short distance in Lore Lindu National Park, where populations of *Tarsius dentatus* and *T. pumilus* possibly border or overlap vertically, suggest the strong possibility of undescribed species in the forest canopy on other parts of the island (Gursky-Doyen, 2010).

The many documented declines in forest cover and therefore primate habitat in Indonesia (for example, Supriatna et al., 2001, 2002; Mittermeier et al., 2007; Mariati et al., 2014; Supriatna and Mariati, 2014, Supriatna et al., 2017, Sloan et al., 2018), have largely been ignored by government policy makers and the private sector. Forest loss has continued to proceed at a high rate (Rijal et al., 2019). Studies on the impact of deforestation and conservation of Sulawesi primates have been carried out by Sugardjito et al. (1989) on macaques in northern Sulawesi and Supriatna et al. (1991) on macaques in southern Sulawesi. Supriatna et al. (2015) reviewed the literature on population status, habitat loss and conservation measures for selected Sulawesi primates. Hybrids and backcrosses of Sulawesi macaques are also renowned making Sulawesi an important field laboratory for the study of genetics and of primate evolution (Supriatna et al., 2015). Here we present recent data from Sulawesi on the extent of deforestation and primate distributions, including zones of hybridization between species and propose actions that we believe will be necessary if extinctions in the near future are to be averted and primate evolution on the island is to proceed unimpeded. We take an island-wide view of current extent and rates of deforestation and the impact this is having on the habitat available to all primates and in primate hybrid zones.

2. Methods

We followed the procedure adopted by Supriatna et al. (2017) in their study on the impact of deforestation on primate habitat on the island of Sumatra.

2.1. Mapping forest loss

Forest loss data were derived from Global Forest Change (GFC) Maps from 2000 to 2017. This dataset defines forest as "all vegetation taller than 5 m in height", while forest loss is defined as the removal of tree canopy at the Landsat pixel scale (Hansen et al., 2013). The annual rate of change in forest cover was measured by comparing the area under forest cover at different times. We estimated the deforestation rate using the method of Puyravaud (2003), which is based on Compound Interest Law. The formula is as follows:

$$r = \frac{1}{t_2 - t_1} ln \frac{A_2}{A_1}$$

Where r is the rate of forest change, while A_2 is estimated forest cover at time t_2 and A_1 is estimated forest cover at time t_1.

The GFC maps cover all primary and secondary forest but are less effective at identifying tree crops or production forests. Thus, we also obtained the forest and non-forest land use maps from the Ministry of Environment and Forestry, Government of Indonesia. Province boundaries were added to the maps, as was the protected area dataset of the World Database on Protected Areas (WDPA).

The resulting maps of forest loss were ground-truthed with three visits in 2019, February in Northern Sulawesi, May in East Central Sulawesi and Southeast Sulawesi and June in the Southern and Western part of Sulawesi.

2.2. Mapping the distribution patterns of primates

Many researchers have carried out primate surveys in different parts of Sulawesi including Sugardjito et al. (1989), Supriatna et al. (1992), Supriatna and Ramadhan (2016) and Supriatna et al. (2017) for macaques. Tarsier surveys have been conducted by Shekelle (2008), Shekelle et al. (2017), and Rosyid (2019). Additional data on taxonomic status and distributions were gathered from Groves (2001), Brandon-Jones et al. (2004), Mittermeier et al. (2013), Roos et al. (2014) and Supriatna (2019). We examined all records of primates on Sulawesi in the Bogor Museum, and updated the distribution data of Groves (2001). These were published in Supriatna and Ramadhan (2016) and Supriatna (2019).

Ground-truthing of these geo-referenced distribution maps was conducted by car throughout Sulawesi in 2018 and 2019. We ground-truthed from North Sulawesi to Gorontalo, from Makassar in South Sulawesi to Palu in Central Sulawesi and then from Central to Southeast Sulawesi at 30 locations (Fig. 1). Using GPS we checked the accuracy of forest cover and cover change maps. Dialogues were conducted with the Head of National Parks, Head of Forest Protected Areas, with farmers, scientists at the University Hasanudin, Makasar, State University of Gorontalo, University Sam Ratulangi and University Tadulako, Palu. Survey locations were chosen using the following criteria: areas likely to have species that had not been studied intensively, for example, species recently described such as *Tarsius supriatnai* (Shekelle et al., 2017); areas with species whose systematics had recently been revised; areas that had been recently logged and/or converted to plantations; and areas that had been recently burnt by forest fires. Further aspects of primate ecology and conservation status were gathered from primatologists who have studied these issues in the field and the considerable experience of most of the present authors, especially the first two. New surveys were also made of primates in several national parks and other protected areas, and in deforested areas. During the ground truthing, the extent and current condition of the forest and local land uses were recorded. This included recording dominant agricultural plants and the ethnicity of people inhabiting the deforested land to help

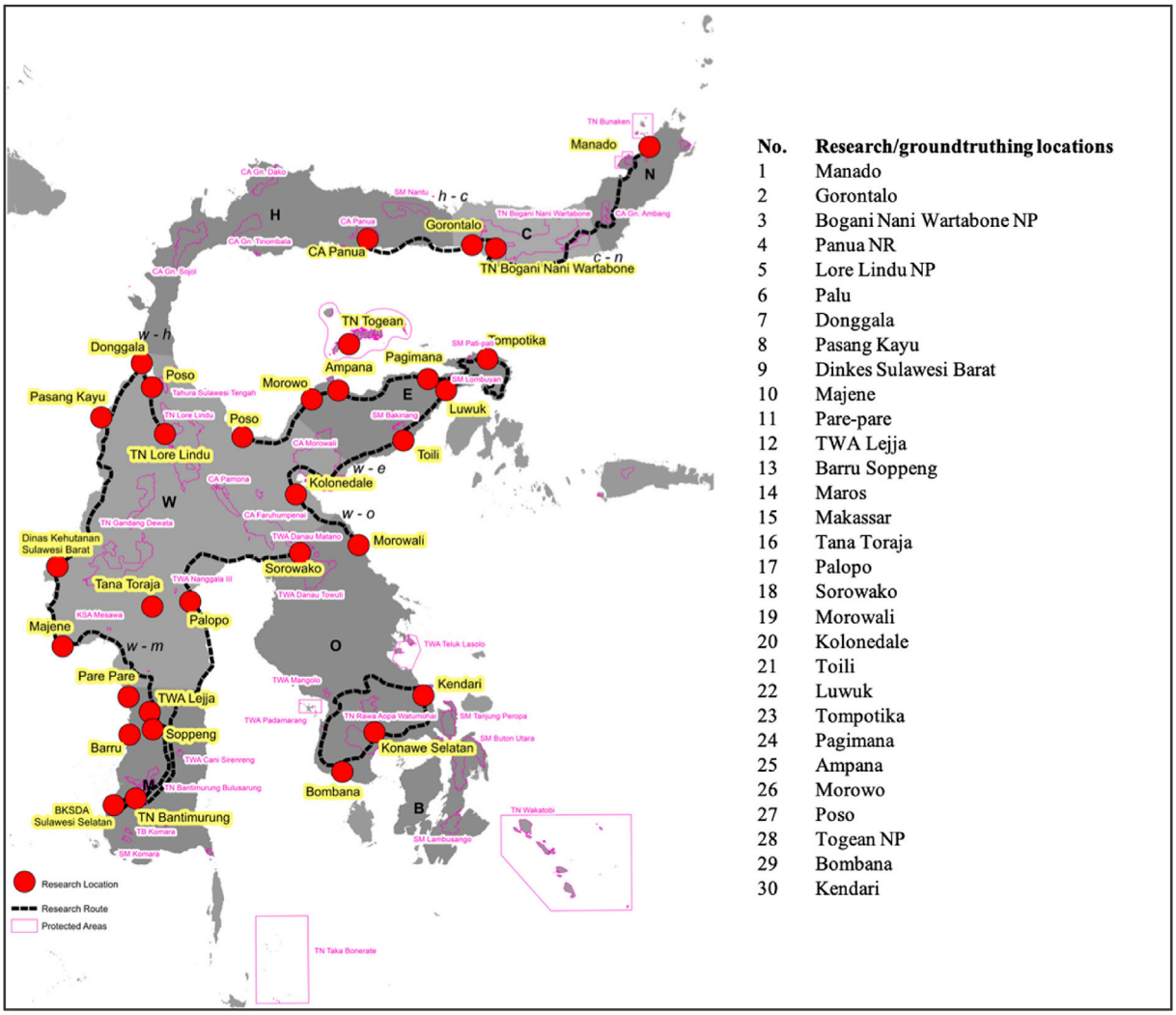

Fig. 1. Ground-truthing routes in Sulawesi.

understand the cause of deforestation on the ground and the likely future trends in deforestation. Different people have different land use practices and traditions. For example, the Bugis people, the main ethnic group on Sulawesi, are famous for their sea-faring and trading skills but have also proved to be excellent cocoa farmers (Ruf, 2001). The Bugis have strong social networks, which have an effect on land use decisions (Weber et al., 2007).

Based on primate distribution data from all of these sources, we plotted the current known distributions of each primate species. Evans et al. (2003a) identified 6 contact zones of *Macaca* spp. in Sulawesi based on MtDNA where there is gene flow between species that may lead to hybrids. Maps of these hybrid zones had been made previously by many scientists from the Sulawesi Primate Project, a collaboration between universities in Indonesia and the United States, including Supriatna (1991) who spent two years identifying the boundaries of the hybrid zone between *Macaca maura* and *M. tonkeana*. Bynum et al. (1997) and Bynum (2002) identified the contact zone between *Macaca tonkeana* and *M. hecki*. Riley et al. (2007) found the boundaries between *M. tonkeana* and *M. ochreata*. Groves (1990, 2004) identified the hybrid zone between *M. hecki* and *M. nigrescens*. We mapped the locations of these zones and measured forest loss in buffers of 10 km, 25 km, and 50 km around contact zones because previous studies predict gene flow up to 50 km (Supriatna, 1996). We then overlaid these geo-referenced distribution maps onto current forest cover maps and maps of forest lost between 2000 and 2017. In this way, we mapped changes in available habitat for all primate species and calculated current available habitat, defined as forest cover.

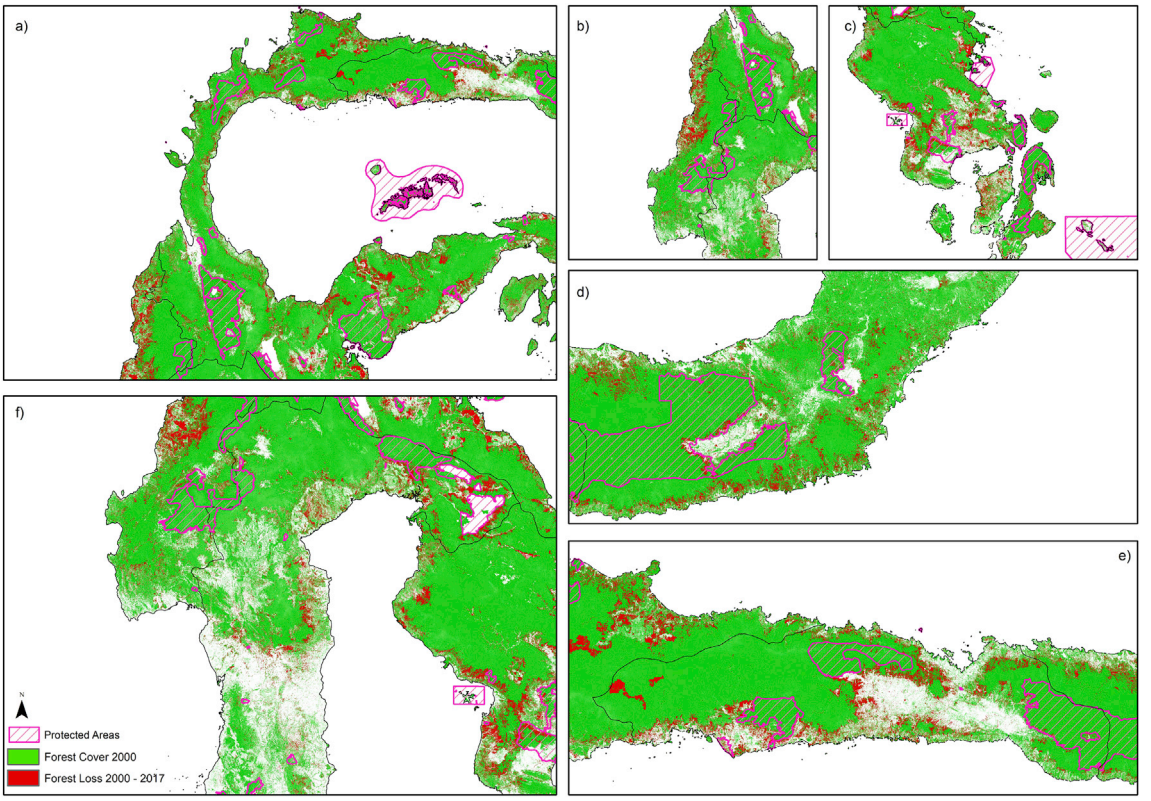

Fig. 2. Map of Sulawesi showing changes in forest cover between 2000 and 2017 (a. Central Sulawesi, b. West Sulawesi, c. Southeast Sulawesi, d. North Sulawesi, e. Gorontalo).

3. Result

Our results showed that deforestation was variable among the provinces. West Sulawesi and Southeast Sulawesi were the provinces which had the greatest extent of deforestation; both total deforestation and deforestation per year (Fig. 2, Table 1). The forest lost from the western part of West Sulawesi has been converted into agricultural land where it is mainly used for oil palm. In South-east Sulawesi newly cleared forest land is used for mixed agriculture including oil palm, maize and cocoa as well as nickel mining.

Table 1 shows that 2,069,016.66 ha of forest cover was lost in Sulawesi between 2000 and 2017, which is 10.89%. Every province was affected. The greatest forest loss, 737,516.52 ha was in Central Sulawesi Province. The average rate of deforestation in the provinces of Sulawesi ranged from 0.42% to 0.85% each year. The highest rate was found in Southeast Sulawesi Province with 0.85% each year. The overall average deforestation rate was 0.67%. Rijal et al. (2019) assessed forest loss on Sulawesi from 1990 to 2018 and found that overall Sulawesi experienced 18.90% forest loss during their study period in contrast to our 10.89% The difference may be ascribed to the decade of the 1990s when much of lowland Sulawesi was cleared for crops.

M. ochreata in Southeast Sulawesi and *T. pelengensis* on Peleng island of Central Sulawesi lost the most habitat at 14% but were closely followed by *M. hecki* and *M. tonkeana* (Table 2). *Tarsius niemitzi* on Togean Island, Central Sulawesi experienced

Table 1
Changes in Forest Cover in Sulawesi Between (2000) and 2017 with total deforestation and average rate of deforestation.

Province	Tree Cover 2000 (Ha)	Tree Cover 2017 (Ha)	Loss in 2017 (Ha)	Deforestation (%)	Average rate
Gorontalo	1,207,487	1,072,936	134,550	11.14	0.69
North Sulawesi	1,572,137	1,463,803	108,334	6.89	0.42
West Sulawesi	1,768,821	1,531,585	237,236	13.41	0.84
Southeast Sulawesi	3,859,144	3,342,803	516,341	13.37	0.85
South Sulawesi	3,917,567	3,582,528	335,038	8.55	0.52
Central Sulawesi	6,675,301	5,937,785	737,516	11.04	0.68
TOTAL	19,000,457.82	16,931,441.16	2,069,016.66	10.89	0.67

Table 2
The loss of primate forest habitat in and outside protected areas between 2000 and 2017 (NS: North Sulawesi, CS: Central Sulawesi, SE: Southeast Sulawesi, GR: Gorontalo, SS: South Sulawesi).

English name	Scientific name	Total forest cover (ha) (% loss)	Non PA	Protected Area (PA) and National Park (NP)	Forest cover in PAs/NPs (% loss)
Tonkean Macaque	*Macaca tonkeana*	9,541,000 (11%)		Lore Lindu NP(CS), Morowali PA (CS)	981,000 (4%)
Supriatna Tarsier	*Tarsius supriatnai*	1,988,000 (12%)		Nantu PA (GR)	193,000 (3%)
Siau Island tarsier	*Tarsius tumpara*	12,000 (3%)	Siau Island (NS)	None	None
Peleng Tarsier	*Tarsius pelengensis*	265,000 (14%)	Peleng Island (CS)		1000 (1%)
Moor Macaque	*Macaca maura*	1,019,000 (5%)		Bantimurung Bulusaraung NP (SS)	68,000 (2%)
Heck's Macaque	*Macaca hecki*	2,674,000 (12%)		Gunung Dako PA (CS), Gunung Tinombala PA (SE), Nantu PA (GR), Pamona PA (CS), Panua PA (GR), Teluk Apar PA (NS)	269,000 (3%)
Great Sangihe Tarsier	*Tarsius sangirensis*	176,000 (3%)	Sangihe Island (NS)		33,000 (5%)
Gorontalo Macaque	*Macaca nigrescens*	803,000 (8%)		Bogani Nani Wartabone NP (GR)	297,000 (2%)
Crested Macaque	*Macaca nigra*	850,000 (7%)		Gunung Ambang PA (NS), Tangkoko Dua Sudara PA (NS), Gunung Manembo Nembo PA (NS)	70,000 (5%)
Booted Macaque	*Macaca ochreata*	3,438,000 (14%)		Rawa Aopa Watumohai NP(SE)	328,000 (8%)
Dian Tarsier	*Tarsius dentatus*	4,262,000 (10%)		Lore Lindu NP (CS)	655,000 (4%)
Wallace Tarsier	*Tarsius wallacei*	1,168,000 (10%)	Uwemaje (ST), Sigi (CS)		104,000 (4%)
Lariang Tarsier	*Tarsius lariang*	2,413,000 (11%)	Lariang river basin (CS)		212,000 (1%)
Sulawesi Mountain Tarsier	*Tarsius pumilus*	682,000 (12%)		Lore Lindu NP (CS)	168,000 (3%)
Makassar Tarsier	*Tarsius fuscus*	1,019,000 (5%)		Bantimurung Bulusaraung NP (SS)	68,000 (2%)
Selayar Tarsier	*Tarsius tarsier*	64,000 (6%)	Selayar (SS)	None	None
Togean Tarsier	*Tarsius niemitzi*	58,000 (1%)		Togean NP (CS)	58,000 (1%)

the lowest loss of forest habitat at only 1%. Some of the species that occur on small islands have lost a lower percentage of their habitat than others, for example, *T. tumpara*, *T. sangiriensis*, and *T. tarsier* (Table 2). However, the habitat available to them was already small, less than 10,000ha, so the loss is significant. There are no conservation management plans or protected areas covering the habitat of these small island or restricted area species. Others occur naturally in restricted habitat. For example, *T. pumilus*, occurs only on the top of Rano-rano and Lore Katimbu Mountains in Lore Lindu NP.

3.1. Macaque contact zones

All contact zones experienced forest loss. The zone between *M. tonkeana* west and *M. hecki* experienced the lowest loss, following by zone between *M. hecki* and *M. nigrescens*. The greatest losses occurred at contact zones between *M. tonkeana* west and *M. ochreata* (Fig. 3 and Table 3). Fig. 3 shows a contact zone between *M. tonkeana* east and *M. tonkeana* west. Evans et al. (2001, 2003a) split *M. tonkeana* into an eastern and a western population based on their mtDNA and Y chromosome microsatelites analysis, which indicated that the eastern and western populations of *M. tonkeana* diverge and may even be more divergent then adjacent populations of *M. tonkeana* west and *M. maura*.

To some extent, people growing commodities have been responsible for deforestation in and around protected areas in Sulawesi (Table 4). Corn, coffee, cocoa, and oil palm are the commodities that are now thriving in Sulawesi. Corn and coffee can be found mainly in highland areas, where most protected areas are, while cocoa can be found in non-protected mountain areas except where it is grown in Lore Lindu National Park. Oil palm is found mostly in West Sulawesi, Southeast Sulawesi and Gorontalo provinces where most plantations are run by big companies. Bugis people do not favor oil palm plantations but rather become small holders that mostly encroach on protected areas and mountainous parts of forests where they grow corn, cocoa and coffee.

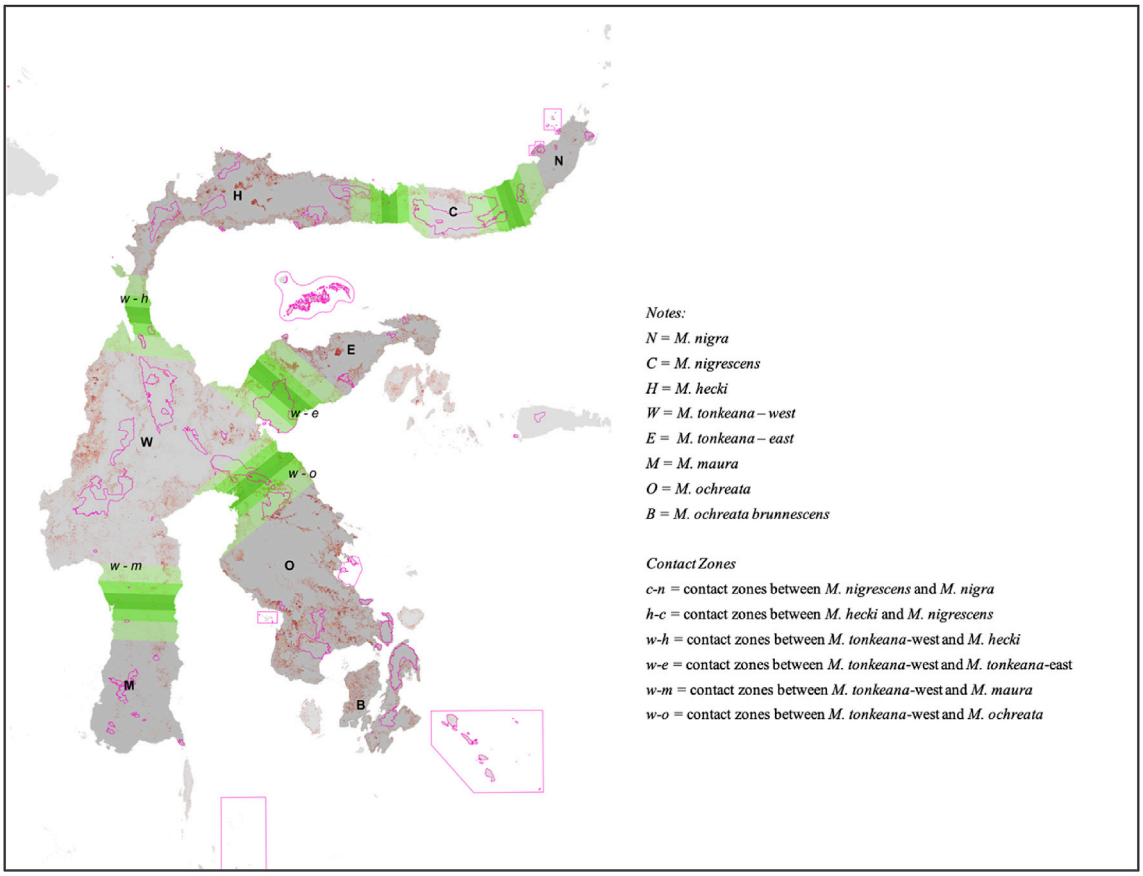

Fig. 3. Deforestation around contact zones of Macaca spp. in Sulawesi showing buffers of 10 km, 25 km, and 50 km in different green shades and protected areas (in pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussions

Preventing rapid biodiversity loss requires efficient allocation of conservation efforts (Pimm et al., 2001) within biodiversity hotspots—those areas where concentrations of endemic species clash with high levels of human activity (Myers et al., 2000). As with many large islands, the biota of Sulawesi is highly distinctive, but this island is too large to protect in its entirety. Therefore, designation of conservation areas requires a detailed understanding of species distribution patterns and patterns of endemism (Margules and Pressey, 2000). All 17 Sulawesi primates are endemic to the island and the contact zones between macaques are of particular interest to primatologists who regard the island as a natural field laboratory for the study of evolutionary biology. Primates are very good umbrella indicators of change in other species because they disperse the seeds of many trees (Lambert, 2010) helping to maintain diversity and healthy populations of those forest species. According to IUCN, the main threats to primates are loss of habitat due to clearing for agriculture (76% of species), logging and wood harvesting (60%), live-stock farming and ranching (31%), and direct loss due to hunting and trapping (60%) (Estrada et al., 2017). Other threats, such as habitat loss due to road and rail construction, oil and gas drilling and mining, affect 2–13% of primate species. There are also emerging threats, such as pollution and climate change.

The Government of Indonesia issued a moratorium in May 2011 to prohibit district governments from granting new forest concession licenses (President Instruction No. 10; Fajar, 2013), which was extended and is still in force today, despite some opposition from powerful palm oil interests (Butler, 2013). This moratorium covered licenses for three types of activities: (i) conversion of primary forests and peatlands to oil palm plantations (oil palm concessions); (ii) conversion of primary forests and peatlands to fast-growing tree plantations for pulp and paper (timber concessions); and (iii) logging of commercially valuable tree species in forests (logging concessions) (see also Supriatna et al., 2017). The current moratorium area of approximately 65 million hectares protects much smaller areas than the moratorium would suggest (Sloan et al., 2018). Around 4.5 million ha were removed from the moratorium for mining and agro-industries, and a further 5.5 million ha may also become exempt, and there are still overlaps with current forest licenses. This is likely due to a lack of clarity of maps of the moratorium areas. Even so, the moratorium is an important of government policy and will help to protect the forests of Sulawesi.

Table 3
Forest loss (ha) at macaque contact zones with different sized buffers.

Contact Zones	10 Km Buffer	25 Km Buffer	50 Km Buffer
c-n (*M. nigrescens* and *M. nigra*)	12,258	33,017	55,810
h-c (*M. hecki* and *M. nigrescens*)	10,198	36,121	69,905
w-e (*M. tonkeana*-west and *M. tonkeana*-east)	18,817	66,617	140,195
w-h (M. tonkeana-west and M. hecki)	4141	12,204	48,012
w-m (*M. tonkeana*-west and *M. maura*)	10,296	33,858	70,288
w-o (*M.tonkeana*-west and *M. ochreata*)	25,771	85,270	152,332

Table 4
Ecosystem types, commodities, and people living in and around deforested land who may influence future trends in deforestation, in the Provinces of Sulawesi (Migrant: People who migrated from Java and Bali, Bugis: Largest indigenous tribe from South Sulawesi; PA = Protected area; NP = National Park; APL = Area Penggunaan Lain (Area for Other Land Uses).

Location \ Landscape type	Land status	Ecosystem types	Dominant Crops/mining	Ethnic groups
North Sulawesi				
Tangkoko Batuangus	PA	Mountain	Corn	Minahasa (local)
Gunung ambang	PA	Mountain	Corn	Minahasa (local)
Manembo-nembo	PA	Lowland	Corn	Minahasa (local)
Gorontalo				
Boganiwartabone	NP	Lowland	Corn	Gorontalo (local), Minahasa (migrant)
Nantu	PA	Lowland	Corn/oil palm	Gorontalo, Java, Bali (migrant)
Bolahemo	APL	Lowland	corn	Gorontalo, Java (migrant), Minahasa (migrant)
Central Sulawesi				
Buol	PA and APL	lowland	Oil palm	Buol (local), Java (migrant)
Lore Lindu	NP	Mountain	Cocoa	Kaili (local), Bugis (migrant)
Bongka (Pangkonene)	PA	Lowland	Corn	Pangkonene (local), Bugis (migrant)
Luwuk	APL	Lowland	Corn/Palm oil	Kaili (local) and Java (migrant)
Morowali	PA and APL	Lowland	Palm Oil/Mining	Morowali (local)
Southeast Sulawesi				
Rawa Aopa	NP	Lowland	Corn	Bugis (migrant)
Tinangea	APL	Lowland	Oil Palm	Tolaki (local)
La Solo	APL	Lowland	Oil Palm/corn	Tolaki (local), Bugis (migrant)
West Sulawesi				
Pasang kayu	APL	Lowland	Oil palm	Mandar (local), Bali (migrant)
Mamuju Tengah	APL	Lowland	Oil Palm	Mandar (local) (migrant)
Mamuju Selatan	APL	Lowland	Oil Palm	Mandar (local)
Gandang Dewata	NP	Mountain	Corn	Bugis (migrant)
South Sulawesi				
Enrekang	APL and HL	Hilly	Coffee, Cocoa and Corn	Bugis (local)
Toraja	APL and HL	Hilly	Coffee, Cocoa, Corn	Bugis (local)
Palopo	APL	Lowland	Mixed Corn	Bugis (local)

5. Drivers of deforestation

5.1. Logging

Sulawesi has so far suffered less from the loss of forest cover than Sumatra or Kalimantan (FWI, 2014; Gaveau et al., 2009; Supriatna et al., 2017; Alamgir et al., 2019). This is due largely to the lack of the available lowland forest, fewer commercial tree species and large areas of rugged relatively inaccessible karst forest (Whitten et al., 2002; Bickford et al., 2007; Supriatna et al., 2015). However, Sulawesi is now on the cusp of major change. While logging itself does not necessarily cause deforestation, if it is followed by conversion to agriculture and plantations then deforestation occurs. Miettinen et al. (2011) suggested that logging is a main source of deforestation in Sulawesi because companies often cannot prevent local cooperatives, farmers' associations, village organizations, fake companies, and smallholders from encroaching on their logging concessions. Logging followed by conversion to agriculture has been widespread in Indonesia and continues to occur over and over again (Gaveau et al., 2009). This practice was identified in discussions with several stakeholders including the head of the Forestry Office in West Sulawesi and the head of Rawa Aopa National Park in Southeast Sulawesi during a visit in 2019. While logging occurs mostly in logging concessions, illegal logging constitutes a well-organized criminal enterprise, which is bold enough to put pressure to forestry law enforcement authorities (Supriatna et al., 2017). Illegal logging occurs in concession areas as well as expired concessions and protected areas.

Indonesia was the world's fourth-largest emitter of global warming pollution in 2016, and deforestation accounted for about 40 percent of those emissions (Wijaya et al., 2017). Indeed, for that same year Indonesia ranked second behind Brazil in the amount of global warming pollution it produced because of deforestation (Wijaya et al., 2017). Since the 1980s, the extraction of hardwoods has increased in Indonesia in response to an ever-expanding worldwide demand for tropical timber.

This has resulted in deforestation and new economic incentives to construct roads in forested areas (Alamgir et al., 2017). In Lore Lindu National Park of Central Sulawesi, the changing of subsistence livelihoods from farming to fishing has led to the loss of hardwoods, which are used to make dugout canoes (Riley, 2007). Although some primate species can survive temporarily in logged forests, both legal and illegal logging result in a decrease in canopy cover, reduced humidity in the sub-canopy and undergrowth that increases tree mortality and the incidence of ground fires. A decline in forest undergrowth inhibits the regeneration of large tree species that provide food, resting sites, and refuges for primates (Lewis et al., 2015; Peres, 1999, 2001; World Bank, 2016).

Many experts believe that the main actors in illegal logging are: (a) workers from communities around local forest areas; (b) investors, including traders, concession holders, or holders of legal timber cutting permits (IPK), and buyers of illegal timber; and (c) government and military officials including law enforcement personnel and certain legislators (Supriatna et al., 2002). Illegal land clearings are seen in many protected areas in Indonesia including in Sulawesi (Bickford et al., 2007). But currently the issue of logging has changed dramatically with a new policy initiative from China called the belt and road initiative (BRI). North and central Sulawesi are likely to be main destinations of BRI investment in Indonesia (Damuri et al., 2019). This may lead to increased road development, which increases access and provides opportunities for encroachment into the forests that remain (Venter et al., 2016; Sloan et al., 2019).

5.2. Oil palm

The recent high growth in palm oil production is likely to continue for the foreseeable future. Because of its high yield (about five to eight times more volume per hectare than the yields of its closest oil-crop competitors) and relatively low labour costs (sometimes due to forced or child labor), oil palm is the most inexpensive vegetable oil on the market today (Carter et al., 2007). In Sulawesi, oil palm is one of the industrial concessions responsible for forest loss although logging concessions are still considered to have the greatest impact (Abood et al., 2015). This study suggests that agricultural commodities grown in areas surrounding the forests, and which may increase forest loss by encroachment are primarily corn and oil palm (Table 4). Oil palm is mostly managed by companies while corn and cocoa are mainly planted by local communities especially Gorontalonese and Buginese. A most interesting finding was that most Buginese were not involved in palm oil plantations. Most of are proud owners not workers. Oil palm development in southern Sulawesi, where the Buginese mostly live, is locally owned and small scale. Emissions due just to oil palm cultivation in Indonesia accounted for an estimated 2 to 9 percent of all tropical land use emissions from 2000 to 2010 (Carlson and Curran, 2013).

5.3. Mining

Mining is a persistent threat to primates and their habitats. The mining of precious gems and minerals contributes to habitat destruction, fragmentation, deforestation, and the poisoning and pollution of soil and ground water (Alvarez-Berrıos and Aide, 2015). In Sulawesi, nickel accounts for most mining output, followed by gold and copper. Nickel is found in Central, South and Southeast East Sulawesi. Central and South east Sulawesi in particular are affected by large mining operations, especially nickel. IMIP, the International Morowali Industrial Park in Central Sulawesi, established with Chinese investments, hosts nickel mining industries from cradle to grave; from mining to smelter and end products for export to China (Song et al., 2018).

5.4. Corruption

Corruption is a major threat to primates because it distorts environmental laws, giving way to deforestation and land speculation and promoting poverty and illegal activities, including mining, poaching, logging, and the primate trade. Corruption and inequality interact by generating a vicious circle of greed, the unequal distribution of power in society, and the unequal distribution of wealth. The 2016 Transparency International Corruption Perception Index-CPI (0: highly corrupt to 100: very clean) profiling 176 countries (Transparency International, 2018) ranks Indonesia at 90, with a score 37. Corruption hampers efforts directed at wildlife conservation and weakens protected area capacity to prevent drivers of primate habitat loss and local species extirpation. Laws are often skirted around or ignored through bribery and extortion. For example, trading orangutans in Indonesia is a crime but 440 confiscations in the last 25 years have led to only seven convictions and sentencing was lenient (Nijman, 2017).

Complicity between businesses and politicians had led to the theft of billions of dollars in revenue from national economies, benefitting the very few at the expense of the many and impeding sustainable development (Baaz and Olsson, 2011; Transparency International, 2018). Given high levels of corruption and prevalent low human development, country-wide conservation of primate habitats and populations developing tropical countries remains a complex challenge. Moreover, measurements of the effectiveness of governance require a thorough causal analysis (with counterfactuals) to determine the degree to which the current status of individual primate species is best attributed to good policies that are poorly implemented, the continuation of ineffective policies, or the result of strong and effectively managed policies (see Baylis et al., 2016).

5.5. Impact of deforestation on primates

The last review of the distribution, population sizes, and conservation status of Sulawesi primates was carried out in 2013 by Supriatna et al. (2015) and there have been no published studies since then. However, information on the status of many species can be found in some local publications and student theses that were consulted here. Shekelle et al. (2013) found that tarsiers living on the offshore islands of Sulawesi (*T. pelengensis*, *T. sangiriensis, T. tarsier, T. tumpara*) do not occur in protected areas. The accidental exception is a new species described recently from the Togean islands (*T. niemitzi*), which occurs in a small pocket of forest in the Togean Marine National Park (Shekelle et al., 2019).

Another newly described species, *Tarsius supriatnai* (Shekelle et al., 2018), is also facing threats due to deforestation. Our results show that the species has suffered the loss of 12% of its habitat. Since 2008, it has been the policy of Gorontalo Province to boost the expansion of corn, which may well see the loss of more of this species' habitat in the near future. Conversely, *Macaca tonkeana*, is probably more secure than other Sulawesi primates due to its widespread distribution within central Sulawesi (Supriatna et al., 2015).

Fragmentation may restrict the dispersal of primates. As their home ranges or territories become limited, sub-populations become more isolated from one another, and there is increased competition for habitat that has been reduced in area (Saunders et al., 1991; Monaghan et al., 2001; Supriatna et al., 2017). Limited home ranges and the isolation of sub-populations may lead to population declines. Small populations are less viable than large ones (Cowlishaw and Dunbar, 2000). The road construction which accompanies the development of plantations such as those described above indicate that habitat fragmentation will become increasingly widespread in the future. In Sulawesi, the largest infrastructure development is the railroad from Makassar in southern Sulawesi to Pare-pare, approximately 150 km to the north which is likely to expand to other areas. Accessibility created by deforestation will increase the probability of hunting success to the detriment of many primate species (Riley, 2008; Riley and Priston, 2010) and in turn will increases the number of primates in the market as well as affect the density of primate species in the forest (O'Brien and Kinnaird, 1996; Lee et al., 2005).

5.6. Deforestation in hybrid zones

Hybrid zones of many species in Sulawesi have been recognized by many researchers since 1984 (see Groves, 1984; Supriatna, 1992; Evans et al., 2001; Evans et al., 2003a; Evans et al., 2003b; Bynum, 2002; Bynum et al., 1997; Riley, 2007; Hamada et al., 2006; Hamada et al., 2012; Hamada et al., 2016; Ito et al., 2015; Schillaci et al., 2005). Many hybrid zones are in the contact zones between parapatric species with two possible consequences of contact. One is that they may eventually produce a new species. The other is that they continue to hybridize without significant changes in genetic compositions as long as gene flow is low (Evans et al., 2001). Some of the hybrid zones are narrow such as that between *M. tonkeana* and *M. hecki* (Watanabe and Matsumura, 1991; Bynum et al., 1997) and even so narrow that they could not be seen clearly, such as that between *M. nigra* and *M. nigrescens* in the Bogani Nani Wartabone National Park in Gorontalo. There, camera trapping has revealed that the two species do not have overlapping ranges (Johnson et al., 2019). Thus, it is possible that this may no longer be regarded as a contact zone with gene flow. Other zones are wide. Supriatna (1996) found the zone of the hybrid between *M. tonkeana* and *M. maura* to be approximately 35 km from north to south, which is the widest hybrid zone thus far found in the primates.

The greatest loss of forest occurred at the contact zone between *M. tonkeana* and *M. ochreata*. *M. ochreata* also suffered the greatest loss of forest habitat; 14%. *Ochreata-tonkeana* hybrids have been found in Faruhumpenai Nature Reserve close to villages. The reserve is surrounded by a cacao plantation (Riley et al., 2007). Deforestation may pose severe threats to the hybrids and their habitat as agriculture is continuing to expand in the contact zones.

The extent of deforestation in the hybrid zones is alarming. Deforestation will likely continue as none of the contact zones are represented in Protected Areas. In central Sulawesi, the project to widen a road through the very narrow contact zone between *M. tonkeana* and *M. hecki* will see even more people occupy this contact zone illegally. Table 4 shows that the forests of the Enrekang region, which are in the hybrid zone between *M. maura* and *M. tonkeana* are being replaced by corn, cocoa, and coffee. The Bugis people are likely to continue this process. Forest fragmentation is just as likely to have an impact on populations of hybrid macaques as on true species, as discussed above. It may also be affecting other species of hybrid animals such as toads (Evans et al., 2003a).

Endemism on Sulawesi is partitioned; because of this, to best preserve biodiversity, areas with complementary, non-redundant diversity should be targeted for protection (Margules et al., 1988; Vane-Wright et al., 1991; Margules and Pressey, 2000; Margules and Sarkar, 2007). Unfortunately, the current distribution of protected areas indicates that some large conservation areas such as Lore Lindu and Morowali National Parks may be restricted to a single area of genetic endemism (West Central) while other areas of genetic endemism such as East Central, Northwest, and Southwest Sulawesi are hardly protected at all (Table 2; Whitten et al., 2002). However, substantial portions of each of these regions have been proposed for protection including Bakiriang in East Central Sulawesi, Mt. Lompobatang in Southwest Sulawesi, and the Palu Mountains, Mt. Sojol, Mt. Dako, the Toli-Toli Mountains, and the Marisa complex in Northwest Sulawesi (Whitten et al., 2002). The addition of these sites would complement the biodiversity present in the existing reserve network improving its coverage of biodiversity greatly (Evans et al., 2003a).

Whenever new protected areas are created, it is necessary to balance the cost in foregone opportunities for profit making enterprises with the protection of biodiversity. This requires the simultaneous consideration of multiple, often conflicting

goals. Multi-criteria analysis (MCA) can be used to compare land use options and identify trade-offs (Sarkar and Illoldi-Rangel, 2010). In macaque contact zones this means trading off various forms of agriculture against the protection of macaques. Using MCA it would be possible to measure the cost in say, foregone opportunities for oil palm, corn or cacao plantations of creating protected areas and conversely, the cost to potential hybrid populations that would result from a given increase in the area of plantations. This is a decision support tool that would allow all stakeholders to examine alternative scenarios and possibly agree to an overall plan they can all live with.

5.7. Deforestation in national parks and other protected areas

Protected areas represent a potentially effective conservation tool in which local, state, and national governments can act to protect ecosystems and provide resources to conserve animal and plant populations, provided that these areas also contribute to alleviating rural poverty (Adams and Hutton, 2007). Globally, protected area networks tend to be located in ecosystems that have low value and low demand for land conversion, and are inexpensive to protect, meaning that many are located far from areas of high biodiversity (Joppa and Pfaff, 2009). In Sulawesi, many protected area have been encroached upon by small holders especially migrants from South Sulawesi to grow commodities such as coffee, cocoa and corn and to operate small local mines. As a result, where encroachment has degraded the forest, primate-rich lowland forests are at risk. This is because companies can argue that they are already degraded and lowland forests offer profitable opportunities to obtain land well-suited to industrial agriculture (Venter et al., 2016) or clear-cutting for timber and gold mining (Supriatna et al., 2015).

Protected areas in Sulawesi generally cover regions with extremely rugged terrain, or with slopes or elevations unsuitable for agriculture. Most of the largest national parks and protected areas are located in the mountain ranges in the middle of Sulawesi. The exception is Rawa Aopa Watumohai in south east Sulawesi. Most Sulawesi primates occur in lowland forest or forests of lower slopes, which are not well-represented in protected areas. Densities of fauna in most protected areas are therefore already low and will decline further unless dispersal between them is facilitated by, for example, corridors of natural habitat. Encroachment by people makes restoration and conservation of such corridors increasingly difficult. The protected areas themselves face a number of basic management problems, including poor staff morale and discipline; lack of incentives for good performance by staff; limited capacities and training; emphasis on park infrastructure rather than enforcement or awareness-raising activities; budget allocations made according to previous budgets rather than threats or needs on the ground at the present time; and emphasis on administration rather than field duties for park managers (Supriatna et al., 2002).

In addition, there is usually no support from local communities and decision-makers for national parks. There are many overlapping and conflicting claims to lands within protected areas. According to newspaper reports, this situation has worsened with decentralization and new perceptions of local community land rights. Many people have submitted claims to courts based on the perceived illegality of the original creation of national parks. If these claims are successful, up to 50% of high conservation lowland forest would be at risk (Supriatna et al., 2017). The purpose and intention of parks have usually been noted on the provincial spatial plan or forest land use map, but little action leading to official gazettal is evident. It is only when local governments (governor, regent) have passed decrees based on field-level consultations with local communities, that an area can be legally gazetted, as set forth in a final decree issued by the Minister of Forestry. There is little incentive for this to happen.

Changing production forests into national parks by converting the tenure of logged-over areas would seem, on the face of it, to be a secure and effective way of reducing deforestation. Issues with conflicting land tenure claims, imprecise boundaries and differences between adat (traditional) law and government law are recurring issues throughout Indonesia (for example, Riggs et al., 2016) that need to be resolved to secure primate habitat into the future.

5.8. Development policy

Forest loss is exacerbated by many factors including government policy on forest use. Since 1999, central government has decentralized the management of forests, except those in conservation areas, to local governments. This policy was renewed in 2004, although in 2014 management responsibility moved from regency to provincial governments. So between 1999 and 2014, regency governments have been allowed to allocate 100ha forest concessions to be logged by small-holders and communities without appropriate planning and without an understanding of forest ecology (Supriatna, 2019). Local access to local natural resources is an ethical imperative, but it is necessary to balance local interests with public goods (Sayer et al., 2017), which is a role of governments. It is not always clear how such trade-offs are made, if they are made at all. In response to the need to reduce poverty, the Province of Gorontalo has implemented what is known as an agropolitan policy (agriculture driven development), in which development is based on agribusiness systems (Bahua et al., 2013). This can be seen in the forest cover change of Gorontalo (Fig. 1). Industrial agricultural development has been followed by infrastructure development or vice versa. As discussed above, road infrastructure in particular has flow on effects by improving the accessibility of new land to both locals and migrants. Recently, since a new road was built close to Nantu Protected area in Gorontalo Province, oil palm has grown significantly compared to what it was 10 years ago.

6. Conclusions

Conflict between the need for human livelihoods and the need to protect primates, especially endangered species such as *M. maura* and *M. nigra*, will only continue to increase. We demonstrate here that deforestation rates have increased in the habitats of all of the primates of Sulawesi. Although not yet as severe or dramatic as deforestation rates in Sumatra, drivers of deforestation in Sulawesi are increasing in intensity. Deforestation is the result of legally converting natural forest into agricultural products, such as oil palm, corn and cocoa, and illegally logging the forests, even in protected areas and national parks. This problem is exacerbated by the fact that Indonesia remains largely an agricultural country. A significant proportion of the population relies on farming for survival. Population pressure and the lack of off-farm employment lead to demands for more agricultural land, which can only come at the cost of forests. With recent taxonomic revisions, some tarsiers such as *T. lariang* (Western Sulawesi), *T. tumpara* (Siau island), and *T. tarsier* are not found in protected areas at all. The remaining habitat of these three species, covering only a few thousand hectares, is not enough for them to survive unless the forest remnants in which they occur become protected and carefully managed.

Following Supriatna et al. (2017) we conclude with a call for greater effort to control the further loss of forest habitat, more careful integration of conservation and development by making trade-offs explicit, and conducting transdisciplinary research on social-ecological systems at the interface of policy and management at local scales (Langston et al., 2019). The results presented here now constitute a baseline against which improvements can be monitored. Habitat degradation cannot be allowed to continue if many of Sulawesi's primates are to survive. Enforcement of existing regulations, disentanglement of land claims and overlapping boundaries, phasing out logging in existing forests, a strategic approach to road building that avoids areas occupied by threatened species and minimizes forest fragmentation, clarification of how adat (traditional) law relates to protected areas, and the creation of new, enforceable laws protecting species from trade and exploitation will all be needed if Indonesia is to uphold its stated commitment to primate conservation in Sulawesi.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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