CHAPTER 3

Mapping degraded lands in Indonesia for bioenergy production potential

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Abstract: This study conducted a spatial analysis in Indonesia to estimate degraded lands potentially suitable for growing biodiesel species (*Calophyllum inophyllum, Pongamia pinnata* and *Reutealis trisperma*) and biomass species (*Calliandra calothyrsus* and *Gliricidia sepium*). Degraded lands have limited functions for food production, carbon storage, and conservation of biodiversity and native vegetation. Thus, identifying their potential to produce bioenergy can contribute to sustainable development by helping society to meet increasing energy demands and secure a new renewable energy source. The identified potential degraded lands were further examined with two scenarios: 1) an all-five-species scenario, examining the growth of all five species, and 2) a biodiesel-species-only scenario, analysing the growth of only biodiesel species. Study results illustrated approximately 3.5 million ha of degraded lands potentially suitable for these species in Indonesia. The all-five-species scenario indicated that these lands had the potential to produce 1,105 PJ yr^{-1} of biomass and 3 PJ yr^{-1} of biodiesel. The biodiesel-species-only scenario illustrated that these lands had the potential to produce 10 PJ yr^{-1} of biodiesel. In addition, many of these degraded lands were limited to support economies of scale for biofuel production due to their small land sizes. The study findings contribute to identifying lands with limited functions, modelling the growth of biofuel species on regional lands, and estimating carbon stocks of restored degraded lands in Indonesia.

Keywords: degraded land, biodiesel, biomass, energy, Indonesia
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3.1 Introduction

Bioenergy production from degraded lands might help society meet increasing energy demands and secure a new source of renewable energy for its sustainability. These potential benefits have attracted global attention to the feasibility of using degraded lands to produce bioenergy (Lewis and Kelly 2014). In Indonesia, for example, energy demand is growing rapidly due to its urbanization, economic growth and population increase (IRENA 2017). For these reasons, the Government of Indonesia set ambitious targets in 2015 to increase its biodiesel and bioethanol consumption to 30% and 20%, respectively, of total energy consumption by 2025 (Presidential Regulation No. 12/2015) (GAIN, 2017). Current biofuel production in Indonesia, however, is far from meeting these targets. In 2016, biofuel production was only 0.05% (or 3.66 billion litres) of the total fuel consumption for the year (or 70 billion litres) (GAIN 2017). According to the Indonesian National Energy Council (DEN 2017), moreover, its average energy demand would increase by around 4.9% per year from 2015 to 2025. This surge in expected demand has increased interest in the feasibility of using degraded lands to provide a new source of renewable energy in Indonesia (ICCC 2014; Wulandari et al. 2014; Baral and Lee 2016; Borchard et al. 2017).

In order to realize these potential benefits, however, bioenergy production must be sustainable in various ways. The expansion of biofuel production can result in reduced food production, which is particularly the case for palm oil. Indonesia is the largest palm oil producer and exporter in the world, and palm oil is a major feedstock for the production of liquid biofuels in the country (Harahap et al. 2017). In addition, the expansion of biofuel production through conversion of rainforests and peatlands would release large amounts of carbon from both aboveground and belowground reservoirs and create a biofuel carbon debt (Fargione et al. 2008; Goh et al. 2017). Such expansion could also threaten – or destroy – rich biodiversity and native ecosystems in these lands (Danielsen et al. 2009). Thus, for renewable energy to be sustainable, biofuel production from degraded lands should avoid compromising food production, carbon stocks, biodiversity and native vegetation. In many studies on degraded lands, however, data on the availability of such lands and their feasibility to deliver sustainable biofuel cannot be compared directly due to the diverging definitions of degraded lands used (Lewis and Kelly 2014) and because of the many potential biofuel species available in Indonesia (ICCC 2014; Wulandari et al. 2014; Baral and Lee 2016; Borchard et al. 2017).

To reduce this knowledge gap, this study (1) assesses degraded lands that have limited functions to produce food, to sequestrate carbon stocks on land, and to maintain vegetation and biodiversity, by adopting the definition of degraded lands from the Indonesia Climate Change Center (ICCC) (ICCC 2014); and (2) examines the suitability of the degraded lands to grow key species for biodiesel production (*Calophyllum inophyllum*, *Pongamia pinnata* and *Reutealis trisperma*) and biomass production (*Calliandra calothyrsus* and *Gliricidia sepium*). Indeed, biofuel production from degraded lands needs to overcome various obstacles as well, including improving the capacity of refineries, building business models for landowners and refineries, securing the property rights of the land, resolving potential conflicts among stakeholders, encouraging smallholder participation, competing with low-price fuels, and mitigating potential invasion by biofuel species (Bryan et al. 2008; Richardson and Blanchard 2011; ICCC 2014; Maraseni and Cockfield 2015; Baral and Lee 2016; Borchard et al. 2017). However, investigation of these challenges first requires an understanding of the degraded lands available for biofuel production and potential biofuel species. Thus, this study analyses these lands and species and estimates their potential energy production.

3.2 Potential biofuel species in Indonesia

While many energy crops exist in Indonesia, here we assessed five tree species with the potential for biodiesel production (i.e., *C. inophyllum*, *P. pinnata* and *R. trisperma*) or biomass production (i.e., *C. calothyrsus* and *G. sepium*) on degraded lands (Scott et al. 2008; Ong et al. 2011; Syamsuwida et al. 2014; Fadhlullah et al. 2015; Leksono et al. 2015; Hambali et al. 2016; Borchard et al. 2017). These species are native to Indonesia and tolerant to lands with harsh conditions that are normally unsuitable for agriculture; thus, these species have the capacity to not compete with food production (Table 1). The study intentionally excluded bamboo and other non-woody species as it mainly focuses on tree species for bioenergy production. Oil palm was excluded due to its large potential to compromise food production.

Table 1. Potential biofuel species in Indonesia

Species	Indonesian name	Tolerable condition	Local use	Biomass type	Food consumption
C. calothyrsus [a]	*Kaliandra*	Drought Acidic soil Sandy soil	Firewood and animal feedstock	Wood	No
C. inophyllum [b]	*Nyamplung*	Salinity Sandy soil	Wood, medicine, and cosmetics	Seed oil	No
G. sepium [c]	*Gamal*	Acidic soil	Firewood, animal feedstock and medicine	Wood or seed oil	No
P. pinnata [d]	*Malapari*	Salinity Water logging Drought	Wood, firewood and medicine	Seed oil	No
R. trisperma [e]	*Kemiri sunan*	Sloping land	Pesticide and fertilizer	Seed oil	No

a Adaganti et al. 2014; Amirta et al. 2016; Fadhlullah et al. 2015; Orwa et al. 2009; Palmer et al. 1994

b Bustomi et al. 2008; Chandra et al. 2013; Leksono et al. 2014, 2015; Ong et al. 2011

c Amirta et al. 2016; Atabani et al. 2013; Bhattacharya et al. 2003; Dahlanuddin et al. 2014; Knothe et al. 2015

d Al Muqarrabun et al. 2013; Aminah et al. 2017; Aunillah and Pranowo 2012; Hendra 2014; Scott et al. 2008; Syamsuwida et al. 2015

e Fuwape and Akindele 1997; Herman et al. 2013; Orwa et al. 2009; Riayatsyah et al. 2017

C. calothyrsus is a fast-growing shrub of 5–6 m height (Orwa et al. 2009). In Indonesia, it is called "kaliandra" and is used for firewood and land restoration due to its fast growth and good adaptability to a wide range of habitats (Syamsuwida et al. 2014; Amirta et al. 2016). The shrub is also used for animal feed (Palmer et al. 1994; Wulandari et al. 2015). It grows in various soil types, including sandy clays and acid soil (Adaganti et al. 2014; Herdiawan and Sutedi 2015). There is emerging interest in biofuel production from *C. calothyrsus* since it is highly cellulosic (46–48%), fast-growing, suitable for a short rotation and adaptable to diverse habitats (Fanish and Priya 2013; Adaganti et al. 2014; Syamsuwida et al. 2014; Yaliwal et al. 2014; Amirta et al. 2016).

C. inophyllum is a medium-to-large tree of 8–20 m height (Ong et al. 2011). Called "nyamplung" in Indonesia, the tree is used for its wood (e.g., building canoes) and seed oil (medicines and cosmetics) (Bustomi et al. 2008; Ong et al. 2011). The oil is slightly toxic for human consumption (Ong et al. 2011). As it tolerates windy and sandy conditions, its major habitats include coastal areas, but it also grows inland at high elevations (Bustomi et al. 2008; Ong et al. 2011). Several studies have analysed biofuel production from *C. inophyllum* oil because this species can yield up to 20 metric tons of inedible oil per hectare (Bustomi et al. 2008; Ong et al. 2011; Chandra et al. 2013; Leksono et al. 2014, 2015; Fadhlullah et al. 2015).

G. sepium is a medium-sized species of 2–15 m height (Orwa et al. 2009). In Indonesia, it is called "gamal" and is used for firewood, cattle feedstock and medicine (Dahlanuddin et al. 2014; Knothe et al. 2015; Amirta et al. 2016). Its leaves, fruits, seeds, roots and bark can be toxic for human consumption (Lim 2014; Knothe et al. 2015). It tolerates various soil types, including slightly saline and clay soils (Knothe et al. 2015). There is interest in biofuel production from *G. sepium* as it not only grows fast and tolerates harsh soil conditions, but also has low moisture content, high energy potency, and high carbon and volatile content (Knothe et al. 2015; Amirta et al. 2016).

P. pinnata is a fast-growing leguminous tree of 12–15 m height (Dwivedi and Sharma 2014). In Indonesia, it is called "malapari" and is used for wood, firewood and medicine (Al Muqarrabun et al. 2013; Syamsuwida et al. 2015; Aminah et al. 2017). However, all parts of the plant are toxic for human consumption (Sangwan et al. 2010). It tolerates salinity and drought and grows in a wide range of habitats from humid tropical and subtropical regions to cooler and semiarid zones (Jiang et al. 2012). Many studies have analysed biofuel production from *P. pinnata* as it is nitrogen-fixing, tolerates various habitats and has a high oil yield (Scott et al. 2008; Jiang et al. 2012; Syamsuwida et al. 2015; Siregar and Djam'an 2017).

R. trisperma is a tree of 10–15 m height (Kumar et al. 2015). In Indonesia, it is called "kemiri sunan" and is used as a natural pesticide and fertilizer (Riayatsyah et al. 2017). It is also used for land rehabilitation owing to its capacity to mitigate land erosion. Although one tree can yield about 25–30 kg of seeds per year, they are toxic and inedible (Kumar et al. 2015; Yohana et al. 2016). There is interest in biofuel production from *R. trisperma* oil because of its high oil yield (Holilah et al. 2015; Pranowo and Herman 2016; Riayatsyah et al. 2017).

3.3 Methods

The study methods consisted of two steps. The first step identified degraded lands in Indonesia. The second step analysed the suitability of growing five biofuel species on degraded lands and estimated their potential energy production (Figure 1).

3.1.1 Identification of degraded lands in Indonesia

The first step of the study identified degraded lands in Indonesia. The analysis employed four types of geographic information system (GIS) data to identify potentially degraded land in Indonesia using an overlaying analysis. These data included severely degraded land data, conservation area data, land cover data and land system data (Figure 1). Degraded lands were identified by overlaying these spatial data based on inclusion and exclusion criteria as described below. First, severely degraded land data (DPEPDA 2015) were used to define the initial scope of degraded lands in Indonesia. The data were developed by the Directorate General of Watershed Management and Social Forestry, under the Ministry of Environment and Forestry of Indonesia, based on technical guidelines for the development of spatial data on severely degraded land *(Petunjuk Teknis Penyusunan Data Spasial Lahan Kritis)* set out in Regulation No. P.4/V-SET/2013. These severely degraded lands indicate the degree of land degradation in Indonesia in terms of land cover, slope, potential erosion, land productivity

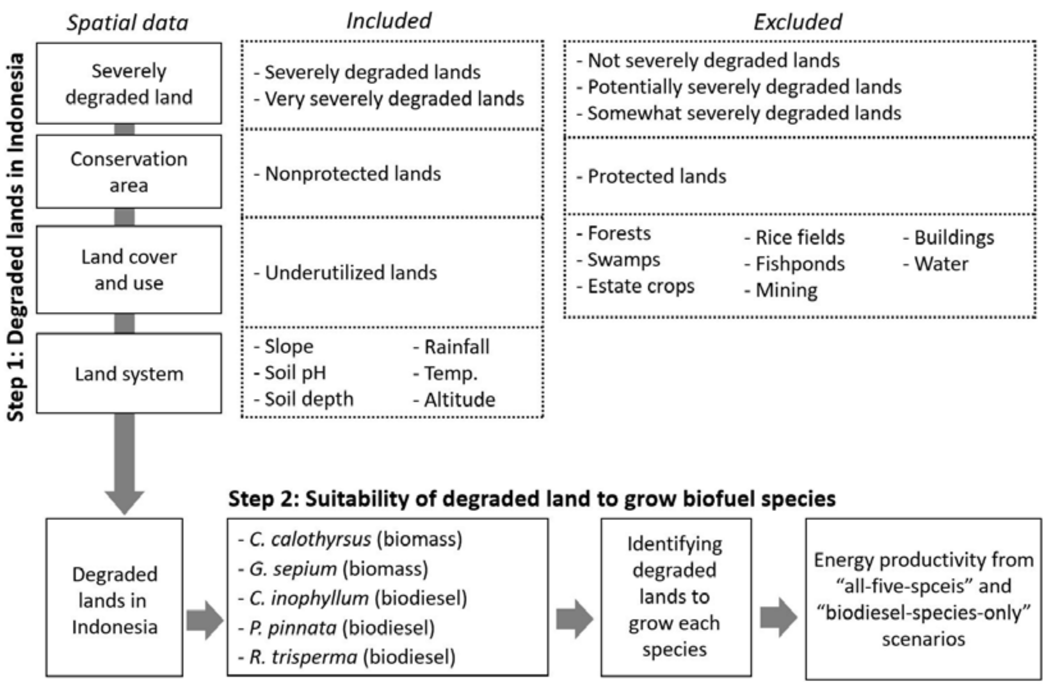

Figure 1. Research methods used to estimate degraded lands in Indonesia and their suitability to grow biofuel species

and land management. The regulation categorizes land degradation as follows: (1) not severe, (2) potentially severe, (3) slightly severe, (4) severe and (5) very severe. Of these categories, this study selected the categories of "severe" and "very severe" to identify the initial scope of degraded lands. Second, conservation area data (DPPKH 2015) were used to exclude protected and conserved forests that prohibit production activities on degraded lands. The data were used to identify protection forest (*Hutan Lindung*) and conservation forest (*Hutan Konservasi*) defined by the Basic Forestry Law, Law No. 41/1999. The law defines protection forest as an area that protects life-support systems by regulating water cycles, maintaining soil fertility, and preventing floods, erosion and saltwater intrusion. Conservation forest is defined as an area that protects life-support systems by preserving biodiversity and utilizing bio-natural resources and ecosystems sustainably. Third, land cover data (DIPSH 2015) were utilized to exclude lands that are used for other purposes and not feasible for biomass production, such as crop estates, forests, swamps, paddy fields, mining areas, fishponds, water bodies and built-up areas. The data were collected from the Indonesian Ministry of Environment and Forestry, where land cover is classified into 23 classes based on the physiognomy or appearance of biophysical cover, which is visually distinguished using the available cloud-free Landsat imagery. Visual classification is carried out by a digitizing on-screen technique using the key elements of image interpretation (MoF 2003). Fourth, land system data (RePPProT 1990) were used to obtain information on slope, pH, rainfall, soil depth, temperature and altitude of the degraded lands. The data were built by the Regional Physical Planning Programme for Transmigration (RePPProT). Land systems are natural ecosystems in which rocks, climate, hydrology, topography, soils and organisms are correlated in a specific way (RePPProT 1990). In addition, missing data of the systems at a regional level were collected from the Land Resources Department (1989).

3.1.2 Suitability of degraded lands to grow biofuel species

The second step of the study analysed the suitability of the degraded lands to grow potential biofuel species and estimated their energy production. Five biofuel species were analysed: *C. calothyrsus*, *C. inophyllum*, *G. sepium*, *P. pinnata* and *R. trisperma* (Table 2). The study categorized suitable lands as highly and moderately suitable lands by applying six conditions of degraded lands in relation to each of the five species: altitude, annual rainfall, temperature, slope, soil pH and soil depth. These lands were defined as being suitable only when the degraded lands fully met all six criteria. These criteria have also been employed by other studies analysing the potential growth of biofuel species on degraded lands in Indonesia (Gingold et al. 2012; Wulandari 2015). In addition, Monte Carlo analysis (e.g., Bryan et al. 2008) was used to estimate the probabilities of each of the degraded land areas to support species growth. The analysis adopted 1,000 simulations applying Gaussian distribution. Suitable lands for the biofuel species were calculated by multiplying the sizes of degraded lands and their probabilities of being suitable lands.

To examine land sizes and parcel numbers, the degraded lands were categorized into small, medium and large sizes. Size categories were developed based on the literature on palm oil

Table 2. Criteria for highly and moderately suitable lands

Attributes[a]	*C. calothyrsus*		*C. inophyllum*		*P. pinnata*		*G. sepium*		*R. trisperma*	
	Highly suitable	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**
Annual rainfall (mm)	2,000–4,000	750–2,000 4,000–5,000	2,000–4,000	750–2,000 4,000–5,000	500–2,000	400–500 2,000–2,500	1,200–2,300	600–1,200 2,300–3,500	1,500–2,500 [g]	700–2,500
Temperature (°C)	22–30	18–22 30–34	28–35	10–28 35–42	16–40	10–16 40–50	15–30	12–15 30–44	24–30	18–30 g
Altitude (m)	0–1800	0–1800	0–200	0–200	0–1,200	0–1,200	0–1,600	0–1,600	0–700	0–700
Soil pH	5.0–6.0	4.5–5.0 6.0–7.5	5.5–7.0	5.0–5.5 7.0–8.0	6.5–8.5	6.0–6.5 8.5–9.0	5.5–6.2	4.5–5.5 6.2–8.0	5.4–7.1	>7.1
Soil depth (cm)	50–150	20–50	20–50	20–50	>150	50–150	>150	50–150	>100	50–100
Soil slope (%)	<80 [b]	<80	<30 [c]	<30	<20 [d]	<20	<40 [e]	<40	<8 [f]	8–25

a Adopted from Orwa et al. 2009; FAO 2007 and Wulandari 2015
b ACTI 1983
c Personal communication with Budi Leksono
d Miyake et al. 2015
e Stewart 1996
f Wulandari 2014
g CABI 2018

production (Gingold et al. 2012; Lee et al. 2014). In palm oil production, smallholder lands are up to 50 ha (Lee et al. 2014); this criterion was used to categorize small-sized lands for biofuel species production. For industrial palm oil production, 5,000 ha is considered to be the minimum land size (Gingold et al. 2012); this criterion was used to define large-sized lands for biofuel species production. In this study, therefore, “small-sized lands” were lands smaller than 50 ha; “medium-sized lands” were lands bigger than 50 ha but smaller than 5,000 ha; and “large-sized lands” were lands bigger than 5,000 ha. After categorizing the lands with their sizes, the numbers of land parcels were estimated for each land size.

To analyse energy productivity from degraded lands suitable for the selected biofuel species, we developed and investigated two scenarios: (1) the all-five-species scenario, and (2) the biodiesel-species-only scenario. The all-five-species scenario analysed all five of the biofuel species, including those for biodiesel production (*C. inophyllum*, *P. pinnata* and *R. trisperma*) and those for biomass production (*C. calothyrsus* and *G. sepium*). The scenario estimated potential energy productivity from each species assuming that their biomass or seed yields would be lower on moderately suitable land compared with highly suitable land (Table 3). Later, we chose only one species with the highest energy productivity when multiple species were suitable on the same degraded lands so that energy productivity could be maximized from these lands. The biodiesel-species-only scenario was treated using identical analytical procedures, but it only examined those species intended for biodiesel production.

3.4 Results and discussion

3.1.3 Degraded lands in Indonesia

The study results showed Indonesia has approximately 5.8 million hectares (Mha) of degraded land with limited capacity to produce food, sequestrate carbon on land, and maintain vegetation and biodiversity (Figures 2 and 3). Of this land, 72% was categorized as severely degraded and 28% as very severely degraded. The largest area of degraded land was in the Sumatra region, totalling approximately 1.8 Mha. The second largest area was in Kalimantan, totalling around 1.5 Mha, while the smallest area was in the Java and Bali region, at around 0.1 Mha in total.

3.1.4 Degraded land with potential for biofuel production

Of the degraded lands identified, around 3.5 Mha (or 57%) had the potential to grow at least one of the five biofuel species (Figure 3). The distribution of suitable land was slightly different from the distribution of degraded land in general. For instance, the Maluku and Nusa Tenggara region had a larger area of suitable land than Kalimantan. Of these degraded lands, 2.85 Mha were suitable for *C. calothyrsus,* 1.64 Mha for *G. sepium*, 0.21 Mha for *R. trisperma*, 0.14 Mha for *P. pinnata* and 0.05 Mha for *C. inophyllum* (Figures 4 and 5). The area

Table 3. Energy productivity of five potential biofuel species in Indonesia

Attributes	***C. inophyllum***		***R. trisperma***		***P. pinnata***		***C. calothyrsus***		***G. sepium***	
	Highly suitable	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**
Biofuel type	Biodiesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel	Bwiodiesel	Biomass	Biomass	Biomass	Biomass
Energy productivity (TJ ha^{-1} yr^{-1})	0.417	0.111	0.040	0.010	0.064	0.006	0.704	0.264	0.089	0.034
Caloric value (MJ kg^{-1})	40.10 [a]	40.10	35.50 [c]	35.50	35.56 [e]	35.56	17.60 [g]	17.60	16.85 [g]	16.85
Biodiesel yield (kg ha^{-1} yr^{-1})	10,400 [b]	2,773	8,000 [d]	6,000	1,800 [f]	180	40,000 [h]	15,000	5,300 [i]	2,000

a Ong et al. 2014

b It was assumed that seed yield per tree would be 150 kg on highly suitable land and 40 kg on moderately suitable land, and 133 trees could be planted per hectare (e.g., maximum 20 tons of seed yield per ha = about 133 trees x 150 kg of seeds) following Leksono et al. (2014). It was also assumed that 65% of seed is oil, and 80% of the oil could be converted to biodiesel (Mohibbe Azam et al. 2005).

c Kumar et al. 2015

d Pranowo and Herman 2016

e Dwivedi and Sharma 2014

f It was assumed that oil yield per hectare would be 2,250 kg for highly suitable land and 225 kg for moderately suitable land (Kumar and Sharma 2011; Atabani and César 2014), and that 80% of oil could be converted to biodiesel (Mohibbe Azam et al. 2005).

g Based on 4,205 kcal per kg for *C. calothyrsus* and 4,027 kcal per kg for *G. sepium* (Amirta et al. 2016)

h Orwa et al. 2009 and Yaliwal et al. 2014

i Stewart et al. 1996

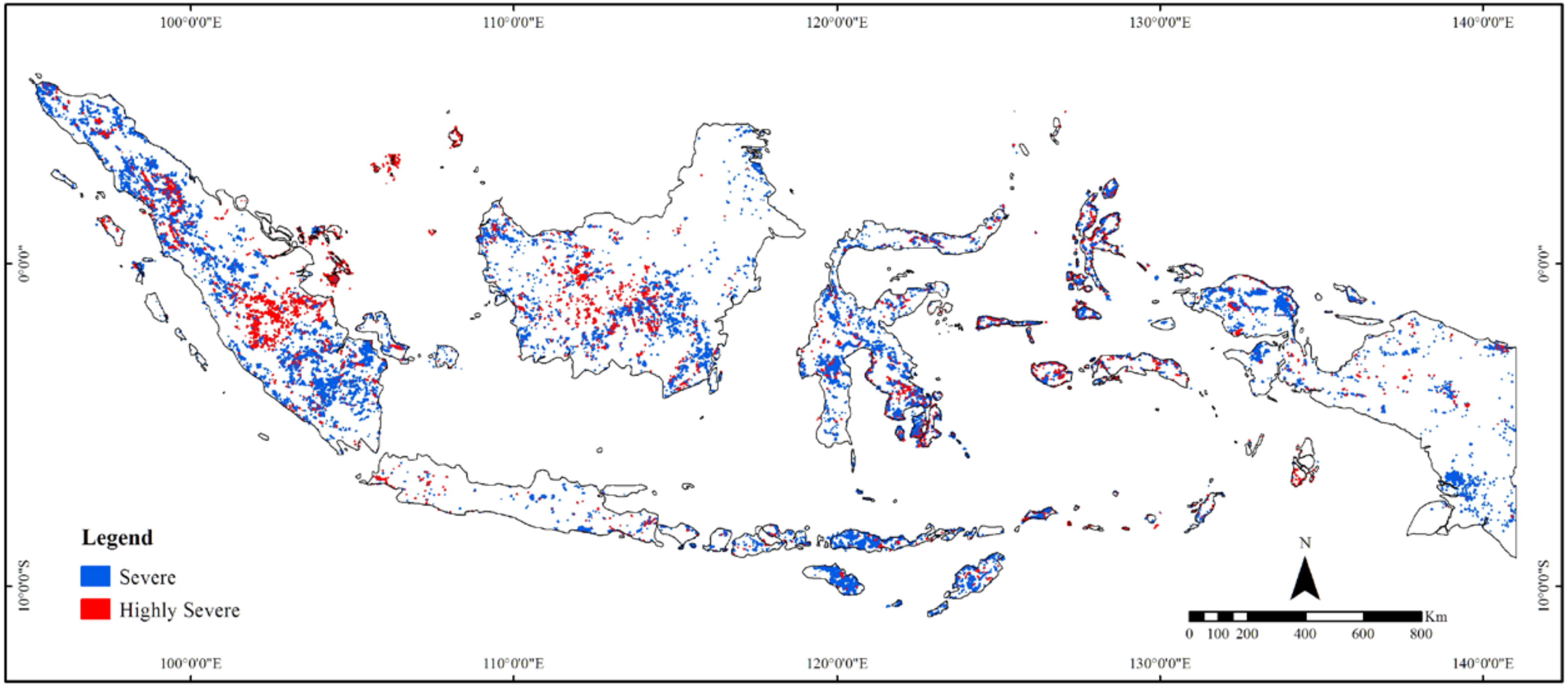

Figure 2. Spatial distribution of degraded lands in Indonesia that have limited functions for food production, carbon storage, and conservation of biodiversity and native vegetation

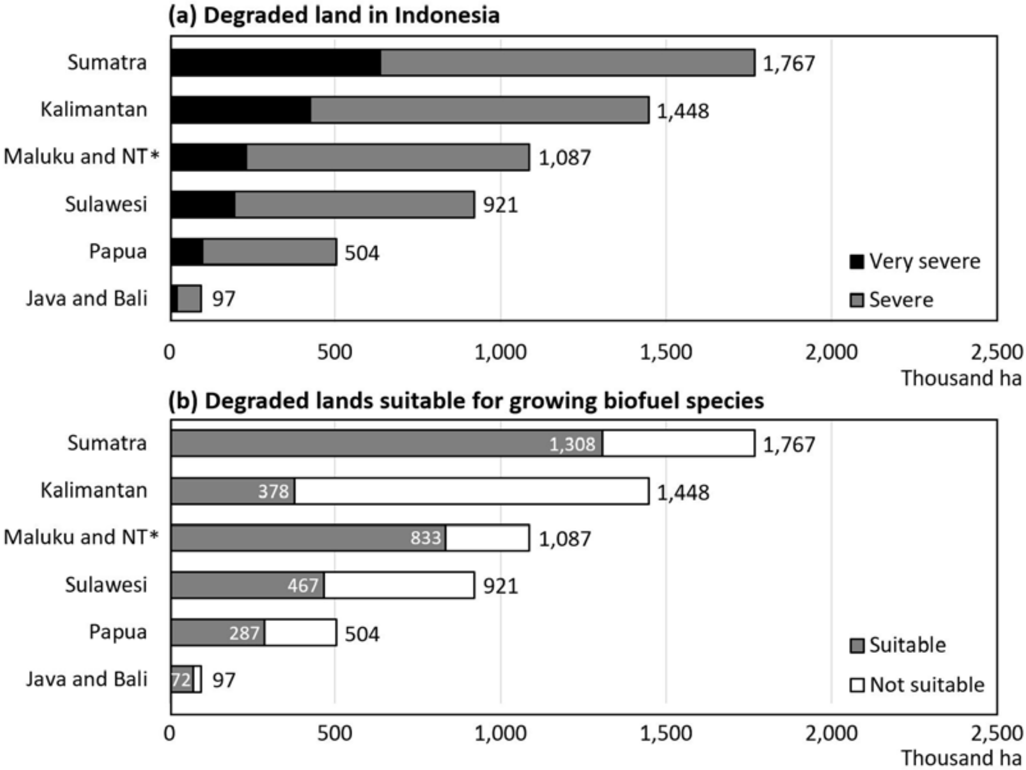

Figure 3. Distribution of degraded lands and lands suitable for growing biofuel species

Note: * Nusa Tenggara

(a) degraded lands in Indonesia identified as having limited functions for food production, carbon storage, and conservation of biodiversity and native vegetation; and (b) degraded lands identified as suitable for cultivating at least one of the following: *C. calothyrsus, G. sepium, C. inophyllum, P. pinnata* and *R. trisperma*.

of highly suitable land was significantly smaller than of moderately suitable land for these species. At 4.49 Mha, land suitable for biomass species (*C. calothyrsus* and *G. sepium*) was approximately 11 times larger than the 0.4 Mha of land suitable for biodiesel species (*C. inophyllum, P. pinnata* and *R. trisperma*).

The degraded lands were analysed in terms of their sizes and numbers of parcels (Figure 6). Small-sized lands (less than 50 ha) consisted of 81% of the total number of land parcels, but their areas were only 8% of the total area of degraded lands. Medium-sized lands (between 50 and 5,000 ha) represented 19% of the total number of parcels, but comprised 70% of the total land area. Large-sized lands (larger than 5,000 ha) comprised only 0.1% of the total number of land parcels, but represented 22% of the total area of degraded lands.

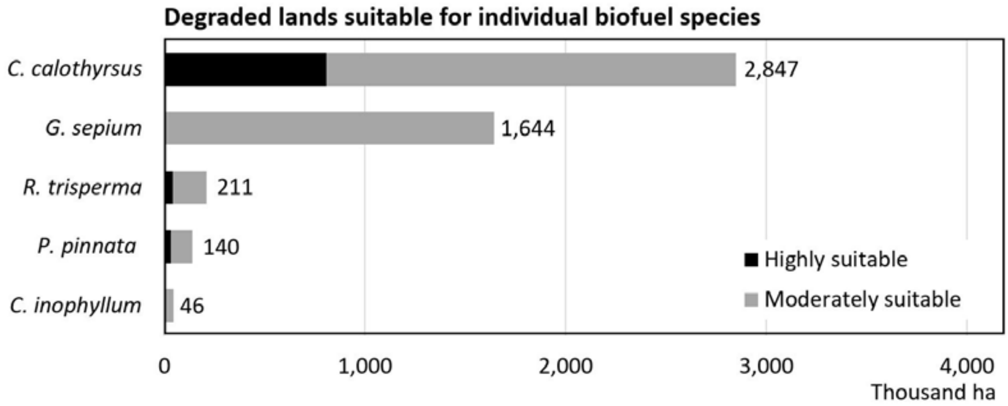

Figure 4. Total area of degraded lands in Indonesia identified as suitable for growing individual biofuel species

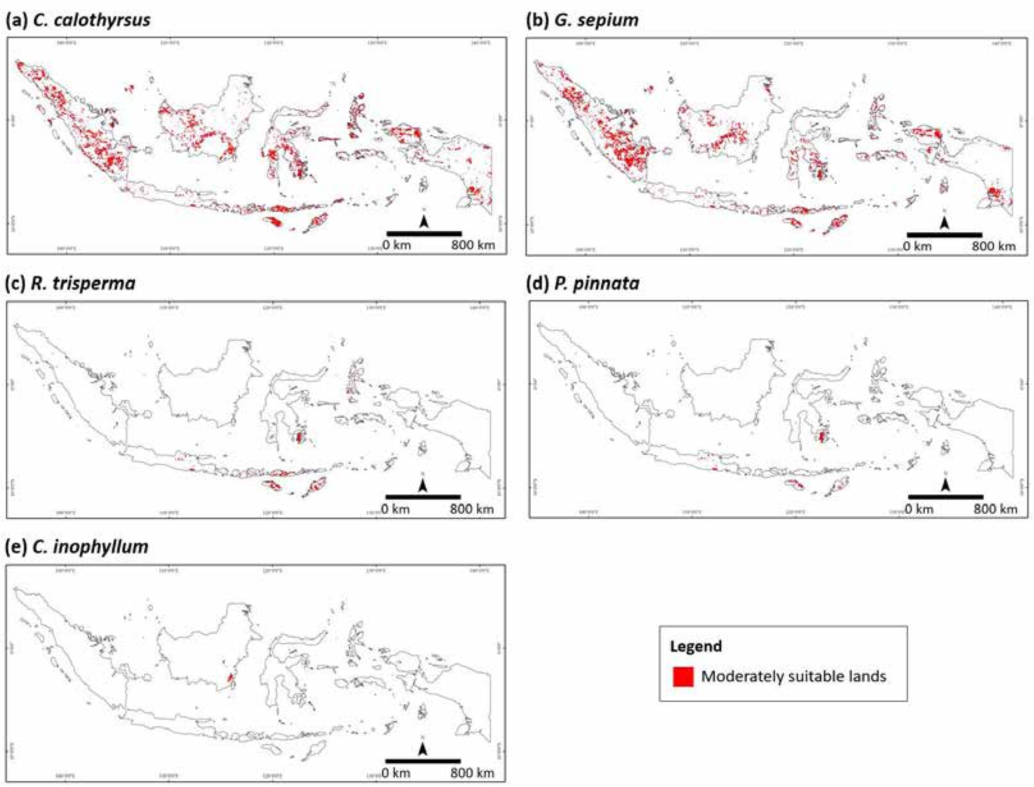

Figure 5. Comparison of degraded lands in Indonesia that are moderately suitable for cultivating *C. calothyrsus, G. sepium, R. trisperma., P. pinnata* and *C. inophyllum*

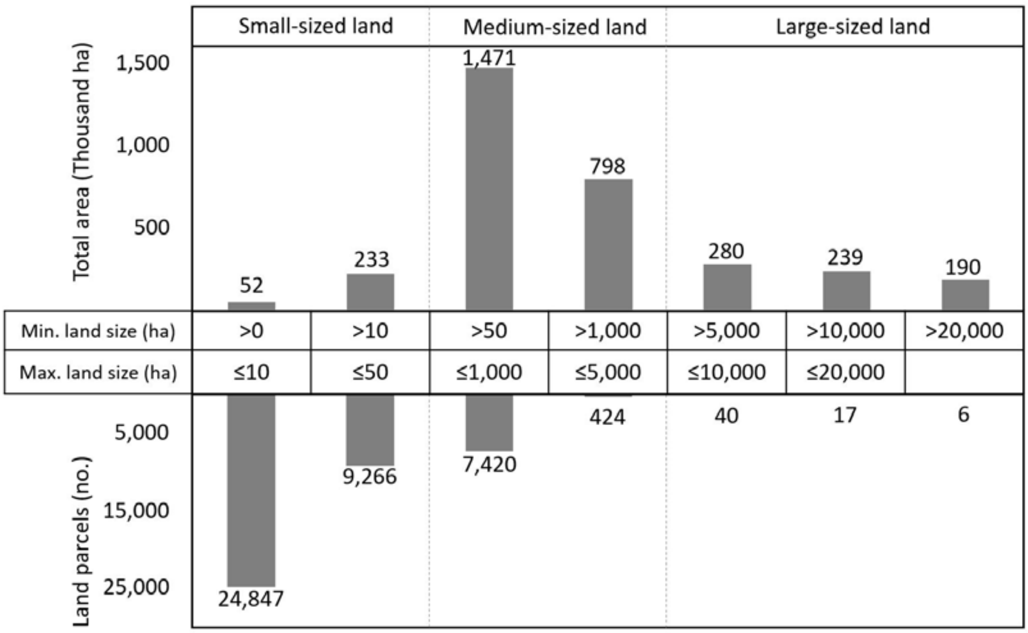

Figure 6. Total area and numbers of land parcels for small-, medium- and large-sized degraded lands in Indonesia suitable for at least one of the biofuel or biomass species (*C. calothyrsus, G. sepium, C. inophyllum, P. pinnata* and *R. trisperma*)

3.4.1 Scenario analyses

The all-five-species scenario, assessing all the biofuel species, resulted in the identification of land suitable for growing *C. calothyrsus*, *P. pinnata*, *R. trisperma*, *G. sepium* and *C. inophyllum* (Figure 7). Of the species assessed, *C. calothyrsus* had the largest area of suitable land (2.8 Mha), not only because it was the most suited to the degraded lands (Figure 4), but also because it had the highest potential energy productivity compared to other species (Table 3). The largest area of land identified as being suitable for this species was in the Sumatra region (0.93 Mha), while the smallest area was in Java and Bali (0.07 Mha). Degraded lands identified as suitable for other species under this scenario were smaller in area: *G. sepium* had 430,002 ha of suitable land; *P. pinnata* had 30,559 ha; *R. trisperma* had 21,013 ha; and *C. inophyllum* had only 132 ha. This scenario resulted in about 1.105 exajoules per year (EJ yr^{-1}) of hypothetical maximum energy productivity (Table 4). The energy productivity from biomass was about 1.102 EJ yr^{-1} (99%), while that from biodiesel was only about 0.003 EJ yr^{-1}. This biomass energy was equal to about 59% of the total biomass consumption in Indonesia in 2016 (ESDM 2017) (Table 5). With an assumption of 30% of this biomass being converted to electricity, it might produce 0.331 EJ yr^{-1}, which is equivalent to around 38% of Indonesia's electricity production in 2014 (0.865 EJ yr^{-1}) (IRENA and ACE 2016).

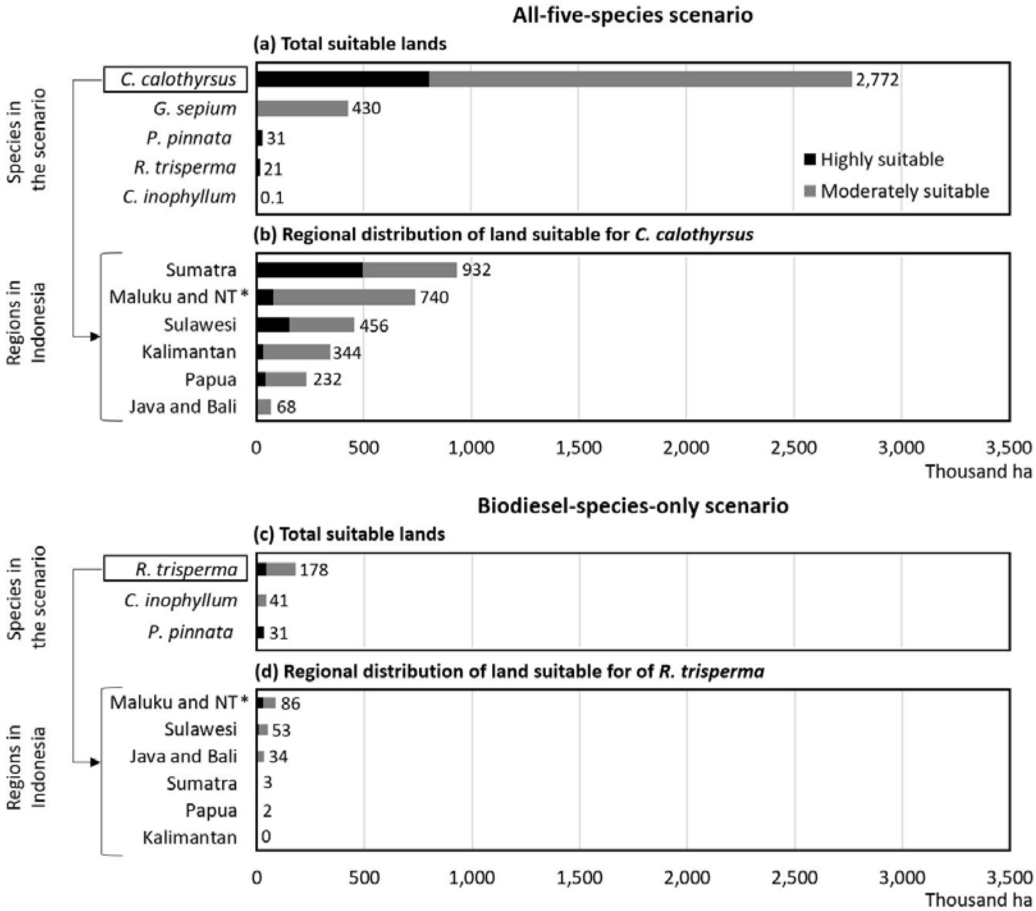

Figure 7. Total area of degraded lands in Indonesia identified as suitable for the all-five-species and biodiesel-species-only scenarios
(Note: * Nusa Tenggara)

The biodiesel-species-only scenario, assessing biodiesel species only, resulted in the identification of lands suitable for *R. trisperma, C. inophyllum* and *P. pinnata* (Figure 7). Of these species, *R. trisperma* had the largest potential, with around 0.18 Mha of suitable lands. These lands were distributed across several regions, though no suitable land was found in the Kalimantan region. Under this scenario, *C. inophyllum* and *P. pinnata* had only 40,625 ha and 30,739 ha of suitable lands, respectively. The scenario resulted in hypothetical maximum energy productivity of around 0.01 EJ yr^{-1} (Table 4). This energy is equal to around 2% of total automotive diesel oil consumption in Indonesia in 2016 and around 634% of total industrial diesel oil consumption (ESDM 2017) (Table 5).

Both scenarios demonstrate opportunities and challenges for Indonesia in using degraded lands to help achieve its target of ensuring biodiesel accounts for 30% of total energy consumption by 2025 as mandated by Presidential Regulation No. 12/2015 (GAIN 2017).

Table 4. Potential energy production (TJ yr^{-1}) of selected biofuel species from degraded lands in Indonesia

Species	Type	Highly suitable lands	Moderately suitable lands	Total
All-five-species scenario				1,104,598
a) Biomass total		568,867	532,921	1,101,787
C. calothyrsus	Biomass	568,494	518,443	1,086,937
G. sepium	Biomass	373	14,478	14,851
b) Biodiesel total		2,796	15	2,811
R. trisperma	Biodiesel	1,956	0	1,956
P. pinnata	Biodiesel	841	0	841
C. inophyllum	Biodiesel	0	15	15
Biodiesel-species-only scenario				9,661
a) Biodiesel total		3,852	5,809	9,661
C. inophyllum	Biodiesel	229	4,448	4,678
R. trisperma	Biodiesel	1,655	1,361	3,016
P. pinnata	Biodiesel	1,967	0	1,967

Table 5. Comparison between the biofuel production scenarios and 2016 energy consumption in Indonesia

Energy consumption in 2016*		All-five-species scenario		Biodiesel-species-only scenario
Energy type	**Energy (TJ yr^{-1})**	**Biomass % (1,101,787 TJ yr^{-1})**	**Biodiesel % (2,811 TJ yr^{-1})**	**Biodiesel % (9,661 TJ yr^{-1})**
Biomass	**1,878,159**	**59**	**NA**	**NA**
Household	1,610,349	68	NA	NA
Industrial sector	259,611	424	NA	NA
Commercial sector	8,198	13,440	NA	NA
Automotive diesel oil	**567,812**	**NA**	**0.5**	**2**
Transportation sector	282,450	NA	2	6
Industrial sector	172,809	NA	11	39
Other sectors	87,671	NA	1	3
Commercial sector	24,882	NA	3	11
Industrial diesel oil	**1,523**	**NA**	**185**	**634**
Industrial sector	1,279	NA	220	756
Other sectors	190	NA	45,946	157,915
Transportation sector	49	NA	5,743	19,739
Commercial sector	6	NA	1,482	5,094

* Source: ESDM (2016)

Both scenarios showed potential to support Indonesia in achieving its biodiesel consumption target. The all-five-species scenario indicated the potential to produce biodiesel energy equivalent to around 0.5% of automotive diesel oil consumption in Indonesia in 2016 and in excess of industrial diesel oil consumption (Table 5). In addition, if 30% of the biomass produced were converted to electricity, it might produce 0.331 EJ yr^{-1}, which is equivalent to around 38% of Indonesia's electricity production in 2014 (0.865 EJ yr^{-1}) (IRENA and ACE 2016). The biodiesel-species-only scenario showed the potential to produce biodiesel energy equivalent to around 2% of automotive diesel oil consumption in Indonesia in 2016 and in excess of industrial diesel oil consumption. Considering Indonesia's biofuel production was only 3.66 billion litres in 2016 or 0.05% of its total fuel consumption (70 billion litres) (GAIN 2017), these study findings suggest producing biofuels on degraded lands might help Indonesia increase the biofuel percentages in its total energy consumption.

However, these lands might be limited in their ability to support economies of scale for biofuel production and only reflect a hypothetical maximum land area. The sizes of many degraded lands were smaller than 5,000 ha, which is considered the minimum land size on which economies of scale from palm oil production can be achieved (Gingold et al. 2012). Although palm oil is not solely used for biofuel production, lessons from palm oil production would support growth of other biofuel species since palm oil has been used as a dominant biofuel species in Indonesia (Harahap et al. 2017). Thus, the sizes of these degraded lands must be considered in analysing their potential business models for bioenergy production in Indonesia. Furthermore, study results indicate maximum energy productivity potential, as the study assumed all degraded lands would be utilized for biofuel production by growing the five biofuel species. In reality, however, this bioenergy production would be diminished by many socioeconomic factors, such as the production cost–benefit to farmers and refineries (Bryan et al. 2008; ICCC 2014; Maraseni and Cockfield 2015), higher opportunity costs for bioenergy production compared with palm oil production (Gingold et al. 2012) or other biofuel species such as sugarcane (ICCC 2014; Neupane et al. 2017), competition with low-price energy such as gasoline (ICCC 2014) and conflicted stakeholder interests (Colchester et al. 2006). Furthermore, this energy would be reduced further when converted into other forms, such as electricity, for final consumption. These factors are likely to reduce the biofuel production estimates from this study, and should be analysed further to fully understand how many of these degraded lands might in reality support bioenergy production in Indonesia.

3.5 Conclusions

The study identified 3.5 Mha of degraded lands in Indonesia that could be used for growing biodiesel species (*C. inophyllum*, *P. pinnata* and *R. trisperma*) and biomass species (*C. calothyrsus* and *G. sepium*) to support bioenergy production without compromising food production, carbon storage, biodiversity and native vegetation. Study results revealed both opportunities and challenges for bioenergy production from these degraded lands. The two-scenario analysis showed that maximum production from *C. calothyrsus* and *G. sepium* could produce biomass energy equal to 59% of Indonesia's total biomass consumption in 2016, while production from both scenarios could produce biodiesel energy equal to 0.5–2% of its 2016 automotive diesel oil consumption. However, the sizes of degraded lands were too small to support economies of scale for biofuel production, and in reality, these maximum production figures would be diminished by numerous socioeconomic factors. These findings may support future studies modelling biofuel species cultivation and comparisons with carbon sequestration potential from the restoration of degraded lands.

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