Article

Spatial assessment of degraded lands for biofuel production in Indonesia

Wanggi Jaung [1,*], Edi Wiraguna [2,3], Beni Okarda [4], Yustina Artati [4], Chun Sheng Goh [5,6], Ramdhoni Syahru [3], Budi Leksono [7], Lilik Budi Prasetyo [3], Soo Min Lee [8] and Himlal Baral [4]

[1] Department of Biological Sciences, National University of Singapore, Singapore; dbsjw@nus.edu.sg
[2] University of Western Australia, Perth, Australia; ediwiraguna@gmail.com
[3] Bogor Agricultural University, Bogor, Indonesia; ediwiraguna@gmail.com; syahru.ramdhoni10@apps.ipb.ac.id; lbprastdp@yahoo.com
[4] Center for International Forestry Research, Bogor, Indonesia; b.okarda@cgiar.org; y.artati@cgiar.org; h.baral@cgiar.org
[5] Institute for the Advanced Studies for Sustainability, United Nations University, Tokyo, Japan; gohchunsheng@unu.edu
[6] Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan; gohchunsheng@unu.edu
[7] Center for Forest Biotechnology and Tree Improvement Research and Development, Yogyakarta, Indonesia; boedyleksono@yahoo.com
[8] National Institute of Forest Science, Seoul, Republic of Korea; lesoomin@korea.kr

* Correspondence: dbsjw@nus.edu.sg; Tel.: +65-9043-7565

Abstract: This study spatially estimates degraded lands in Indonesia that have limited functions for food production, carbon storage, and conservation of biodiversity and native vegetation, and examines their suitability to grow biodiesel species (*Calophyllum inophyllum*, *Pongamia pinnata* and *Reutealis trisperma*) and biomass species (*Calliandra calothyrsus* and *Gliricidia sepium*). Results showed that Indonesia has ~3.5 million ha of degraded lands potentially suitable for these species. With the all-five-species scenario, these lands had the potential to produce 1,105 PJ yr^{-1} of biomass and 3 PJ yr^{-1} of biodiesel. With the biodiesel-only-species scenario, these lands showed the potential to produce 10 PJ yr^{-1} of biodiesel. Despite this energy potential, however, the land sizes were too small to support economies of scale for biofuel production. The study findings contribute to identifying lands with limited functions, modeling biofuel-species growth on regional lands and estimating carbon stocks of restored degraded lands in Indonesia.

Keywords: degraded land; biodiesel; biomass; energy; Indonesia

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 [1]. In Indonesia, for example, energy demand is growing rapidly due to its urbanization, economic growth and population increase [2]. 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) [3]. Current biofuel production in Indonesia, however, is far from meeting these targets. In 2016, biofuel production was only 0.05% (or 3.66 billion liters) of the total fuel consumption for the year (or 70

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

billion liters) [3]. According to the Indonesian National Energy Council [4], 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 [5-8].

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 [9]. 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 [10-11]. Such expansion could also threaten—or destroy—rich biodiversity and native ecosystems in these lands [12]. 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 [1] and because of the many potential biofuel species available in Indonesia [5-8].

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)[5]; 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 [5,7,8,13-15]. However, investigation of these challenges first requires an understanding of the degraded lands available for biofuel production and potential biofuel species. Thus, this study analyzes these lands and species and estimates their potential energy production.

2. Species and land for biofuel production in Indonesia

2.1. 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 [8, 17-21]. 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.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

Table 1. Potential biofuel species in Indonesia.

Species	Indonesian name	Tolerable condition	Local use	Biomass type	Food consumption
C. calothyrsus [1]	Kaliandra	Drought Acidic soil Sandy soil	Firewood and animal feedstock	Wood	No
C. inophyllum [2]	Nyamplung	Salinity Sandy soil	Wood, medicine, and cosmetics	Seed oil	No
G. sepium [3]	Gamal	Acidic soil	Firewood, animal feedstock, medicine	Wood or seed oil	No
P. pinnata [4]	Malapari	Salinity Water logging Drought	Wood, firewood and medicine	Seed oil	No
R. trisperma [5]	Kemiri sunan	Sloping land	Pesticide and fertilizer	Seed oil	No

[1] [19, 22-25].

[2] [11, 20, 26-28].

[3] [23, 29-32].

[4] [16, 33-37].

[5] [24, 38-40].

C. calothyrsus is a fast-growing shrub of 5–6 m height [24]. 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 [18, 23]. The shrub is also used for animal feed [25, 41]. It grows in various soil types, including sandy clays and acid soil [22, 42]. 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 [18, 22-23, 43-44].

C. inophyllum is a medium-to-large tree of 8–20 m height [17]. Called "nyamplung" in Indonesia, the tree is used for its wood (e.g. building canoes) and seed oil (medicines and cosmetics) [17, 26]. The oil is slightly toxic for human consumption [17]. As it tolerates windy and sandy conditions, its major habitats include coastal areas, but it also grows inland at high elevations [11, 26]. Several studies have analyzed biofuel production from C. inophyllum oil because this species can yield up to 20 tons of inedible oil per hectare [17, 19-20, 26-28].

G. sepium is a medium-sized species of 2–15 m height [24]. In Indonesia, it is called "gamal" and is used for firewood, cattle feedstock and medicine [23, 31-32]. Its leaves, fruits, seeds, roots and bark can be toxic for human consumption [32, 45]. It tolerates various soil types, including slightly saline and clay soils [32]. 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 [23, 32].

P. pinnata is a fast-growing leguminous tree of 12–15 m height [46]. In Indonesia, it is called "malapari" and is used for wood, firewood and medicine [33-34, 37]. However, all parts of the plant are toxic for human consumption [47]. It tolerates salinity and drought and grows in a wide range of habitats from humid tropical and subtropical regions to cooler and semiarid zones [48]. Many studies

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

have analyzed biofuel production from *P. pinnata* as it is nitrogen-fixing, tolerates various habitats and has a high oil yield [16, 37, 48-49].

R. trisperma is a tree of 10–15 m height [50]. In Indonesia, it is called "kemiri sunan" and is used as a natural pesticide and fertilizer [40]. 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 [50-51]. There is interest in biofuel production from *R. trisperma* oil because of its high oil yield [40, 52-53].

2.2. Lands available for producing biomass in Indonesia

Several studies analyze available lands for biofuel production in Indonesia (Table 2). The studies employ different definitions of lands (e.g. degraded or suitable lands) and various methodologies (e.g. spatial or policy analysis), resulting in different land estimates. Several studies investigate degraded land for palm oil plantations. Colchester et al. (2006) indicate there are about 27 million hectares (Mha) of unproductive degraded forestlands in Indonesia [54]. Gingold et al. (2012) show about 7 Mha of degraded lands in the provinces of West and Central Kalimantan [55]. Harahap et al. (2017) demonstrate about 20.9 Mha of degraded land in Indonesia [9]. Other studies investigate non-palm-oil species for potential biofuel production in Indonesia. ICCC (2014) identifies about 23.78 Mha of degraded lands suitable for bioethanol species, such as sugarcane, cassava, sweet sorghum, corn and sago [5]. Milbrandt and Overend (2009) identify about 3.7 Mha of marginal lands for biomass production [56]. Nijsen et al. (2012) suggest approximately 30 Mha of lands with degraded soils for production of grasses and woody crops [57]. Wulandari et al. (2014) show about 0.9 Mha of potentially suitable lands on which to grow *R. trisperma* in the province of West Java [6]. None of these studies, however, examine the availability of lands that are degraded but potentially suitable for growing *C. calothyrsus*, *C. inophyllum*, *G. sepium*, *P. pinnata* or *R. trisperma* in Indonesia. Although Wulandari et al. (2014) analyze *R. trisperma*, the study only focuses on the province of West Java, and its objective is to estimate all suitable lands, including nondegraded lands [6]. Thus, our study contributes to analyzing the potential growth of multiple biofuel species on degraded lands at a national level in Indonesia.

 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

Table 2. Studies on potential lands for biofuel production in Indonesia.

Study	Land condition	Land location	Area (Mha)	Biofuel species	Potential energy production	Method
[54]	Unproductive forestlands degraded by logging, cultivation and other activities	Indonesia	27	Palm oil	NA	Information from Dept. of Agriculture
[55]	Degraded lands that support sustainable palm oil production environmentally, economically, legally and socially	West and Central Kalimantan	7	Palm oil	NA	Spatial analysis and field survey
[9]	Administratively available lands; coherence to biofuel, agriculture, climate and forestry policies	Indonesia	21	Palm oil	NA	Policy analysis
[56]	Degraded lands that have poor climate, poor physical characteristics or difficult cultivation	Indonesia as a part of APEC countries	3.7	Biomass production potential	15 million tons of biomass per year/ 6 cubic hectometers of ethanol	Spatial analysis
[57]	Lands that have degraded soils	Indonesia as part of a global study	30	Grasses and woody crops	About 7,000 PJ yr–1 from grasses/ about 5,000 PJ yr–1 from woody crops	Spatial analysis
[6]	Lands with suitable climates and ecological conditions	West Java	0.9	*R. trisperma*	NA	Spatial analysis
[5]	Degraded lands that exclude high-carbon lands, lands with concessions and new permits, and lands with high slope and altitude	Indonesia	24	Bioethanol crops	NA	Spatial analysis

APEC: Asia-Pacific Economic Cooperation; Mha: million hectares; NA: not applicable.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

3. Materials and Methods

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

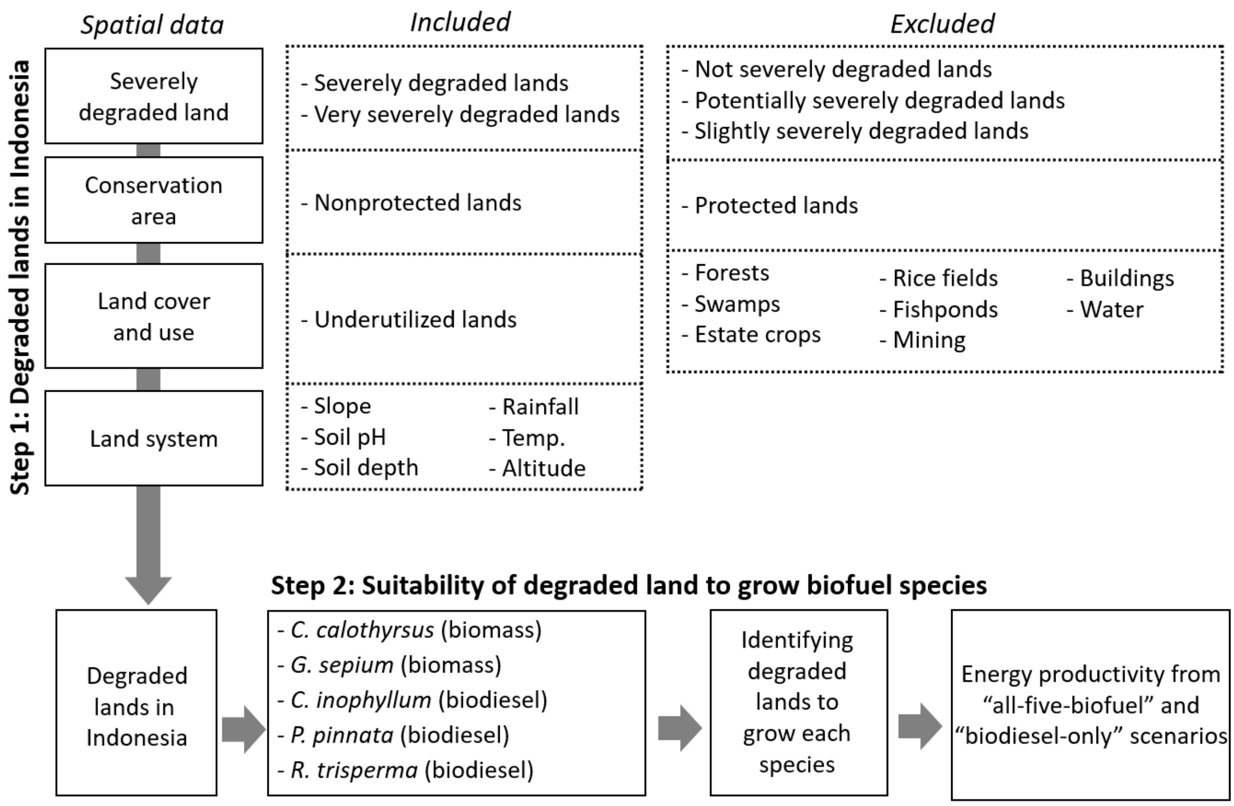


Figure 1. Research methods used to estimate degraded lands in Indonesia and their suitability to grow biofuel species.

3.1. 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 [58] 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 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 [59] were used to exclude protected and conserved forests that prohibit production activities on degraded lands. The data were used to identify protected forest (Hutan Lindung) and conservation forest (Hutan Konservasi) defined by the Basic Forestry Law, UU No. 41, 1999. The law defines protected forest as an area that protects life-support systems by

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

regulating water cycles, maintaining soil fertility, and preventing floods, erosion and salt water 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 [60] 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, fish ponds, water bodies and built-up areas. The data were collected from the Indonesian Ministry of Environment and Forestry. 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 [61].

Fourth, land system data [62] 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 [62]. In addition, missing data of the systems at a regional level were collected from the Land Resources Department (1989).

3.2. Suitability of degraded lands to grow biofuel species

The second step of the study analyzed the suitability of the degraded lands to grow potential biofuel species and estimated their energy production. Five biofuel species were analyzed: *C. calothyrsus, C. inophyllum, G. sepium, P. pinnata* and *R. trisperma* (Table 3). The study categorized suitable lands as highly and moderately suitable lands by modelling:

$$H_{score} = HS_{altitude} + HS_{rainfall} + HS_{tempt} + HS_{soil\ slope} + HS_{soil\ pH} + HS_{soil\ depth}$$

$$M_{score} = MS_{altitude} + MS_{rainfall} + MS_{tempt} + MS_{soil\ slope} + MS_{soil\ pH} + MS_{soil\ depth} \quad (1)$$

H_{score} and M_{score} were total scores of criteria for highly and moderately suitable lands, respectively. *HSs* were dummy variables of highly suitable (*HS*) land criteria for altitude, annual rainfall, temperature, slope, soil pH and soil depth of the biofuel species, whose values were 1 for a land meeting the species criteria and 0 for a land not meeting the criteria. Similarly, *MSs* were dummy variables of moderately suitable (*MS*) land criteria for altitude, annual rainfall, temperature, slope, soil pH and soil depth of the biofuel species. Highly and moderately suitable lands were determined only when H_{score} and M_{score} were 6, which indicates that a land meets all six criteria for the growth of biofuel species. Values of all dummy variables (*HCs* and *MCs*) were estimated by applying Monte Carlo analysis (e.g. [13]) to the spatial analysis results (Step 1 results in Figure 1) based on Gaussian distribution. The averages of 1,000 simulation results were used to estimate probabilities of each land to meet the growth criteria for all five biofuel species. The total areas of these suitable lands for these species were calculated by multiplying these probabilities and sizes of the lands.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

Table 3. Criteria for highly and moderately suitable lands.

	C. calothyrsus		*C. inophyllum*		*P. pinnata*	
Attributes [1]	**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
Temperature (°C)	22–30	18–22 30–34	28–35	10–28 35–42	16–40	10–16 40–50
Altitude (m)	0–1800	0–1800	0–200	0–200	0–1,200	0–1,200
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
Soil depth (cm)	50–150	20–50	20–50	20–50	>150	50–150
Soil slope (%)	<80 [2]	<80	<30 [3]	<30	<20 [4]	<20

	G. sepium		*R. trisperma*	
Attributes	Highly suitable	Moderately suitable	Highly suitable	Moderately suitable
Annual rainfall (mm)	1,200–2,300	600–1,200 2,300–3,500	1,500–2,500 [7]	700–2,500
Temperature (°C)	15–30	12–15 30–44	24–30	18–30 [7]
Altitude (m)	0–1,600	0–1,600	0–700	0–700
Soil pH	5.5–6.2	4.5–5.5 6.2–8.0	5.4–7.1	>7.1
Soil depth (cm)	>150	50–150	>100	50–100
Soil slope	<40 [5]	<40	<8 [6]	8–25

(%)

[1] [23, 41, 63].

[2] [64].

[3] Personal communication with Budi Leksono.

[4] [65].

[5] [66] Stewart (1996).

[6] [6].

[7] [67].

To analyze 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 production [55, 68]. In palm oil production, smallholder lands are up to 50 ha [68]; 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 [55]; 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 analyze 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-only-species scenario. The all-five-species scenario analyzed 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 4). 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-only-species scenario was treated using identical analytical procedures, but it only examined those species intended for biodiesel production.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

Table 4. Energy productivity of five potential biofuel species in Indonesia.

	C. inophyllum		*R. trisperma*		*P. pinnata*	
Attributes	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Moderately suitable**
Biofuel type	Biodiesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Energy productivity (TJ/ha/yr)	0.417	0.111	0.040	0.010	0.064	0.006
Caloric value (MJ/kg)	40.10 [1]	40.10	35.50 [3]	35.50	35.56 [5]	35.56
Biodiesel yield (kg/ha/yr)	10,400 [2]	2,773	8,000 [4]	6,000	1,800 [6]	180

	C. calothyrsus		*G. sepium*	
Attributes	**Highly suitable**	**Moderately suitable**	**Highly suitable**	**Highly suitable**
Biofuel type	Biomass	Biomass	Biomass	Biomass
Energy productivity (TJ/ha/yr)	0.704	0.264	0.089	0.034
Caloric value (MJ/kg)	17.60 [7]	17.60	16.85 [8]	16.85
Biomass yield (kg/ha/yr)	40,000 [8]	15,000	5,300 [9]	2,000

[1] [68].

[2] 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 × 150 kg of seeds) following [28]. It was also assumed that 65% of seed is oil, and 80% of the oil could be converted to biodiesel [69].

[3] [50].

[4] [53].

[5] [46].

[6] It was assumed that oil yield per hectare would be 2,250 kg for highly suitable land and 225 kg for moderately suitable land [70, 71], and that 80% of oil could be converted to biodiesel [69].

[7] Based on 4,205 kcal/kg for *C. calothyrsus* and 4,027 kcal/kg for *G. sepium* [23].

[8] [24, 44]

[9] Stewart et al. (1996).

3. Results

3.1. Degraded lands in Indonesia

The study results showed that Indonesia has about 5.8 Mha of degraded lands that have limited ability to produce food, to sequestrate carbon on land, and to maintain vegetation and biodiversity (Figures 2 and 3). Of them, 72% were categorized as severely degraded lands and 28% as very severely degraded lands. The largest area of degraded lands was located in Sumatra, totaling about 1.8 Mha. The second largest area of lands was in Kalimantan, totaling about 1.5 Mha. The smallest areas of land were in the Java and Bali regions, totaling about 0.1 Mha of degraded lands.

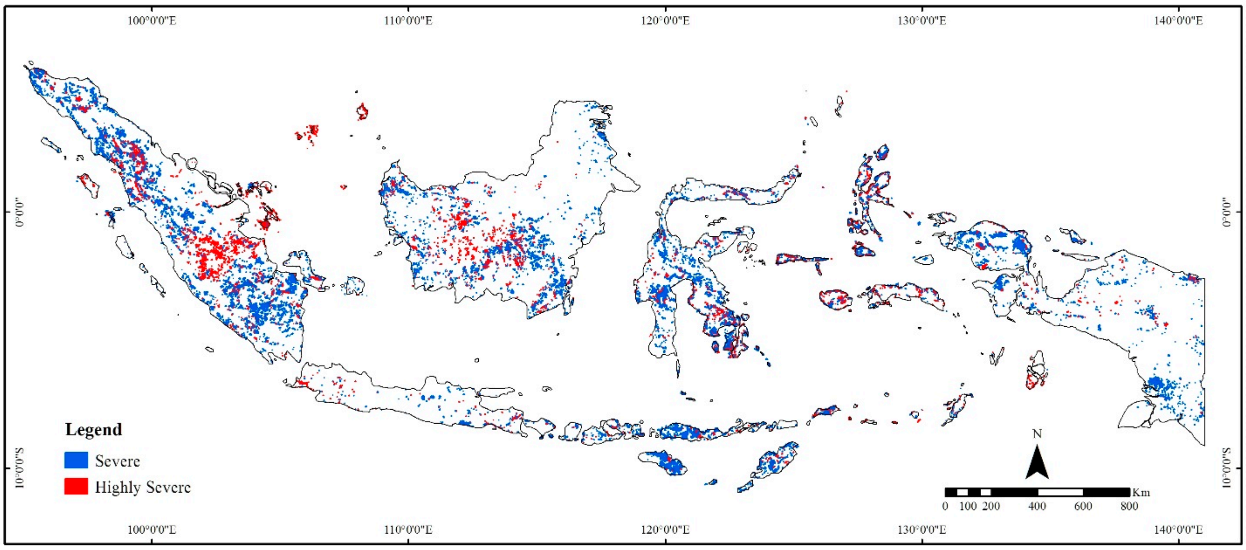


Figure. 2. Spatial distribution of degraded lands in Indonesia that have limited functions for food production, carbon storage, and conservation of biodiversity and native vegetation.

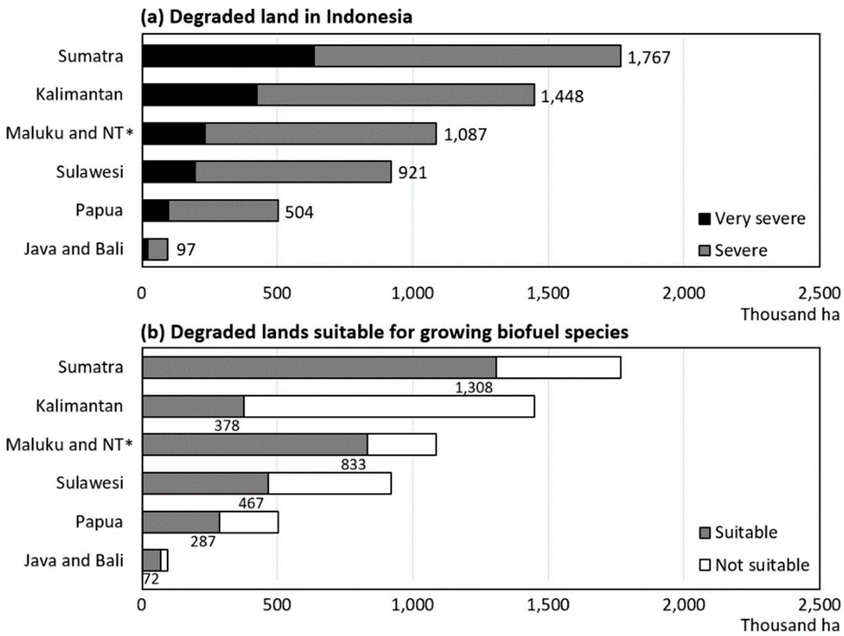


Figure 3. Distribution of degraded lands and lands suitable for growing biofuel species.

(* Nusa Tenggara)

Note: (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*.

3.2. Suitability of degraded lands to grow biofuel species

Of the degraded lands identified, about 3.5 Mha (or 57%) had the potential to grow at least one of the five biofuel species (Figure 3). The distribution of suitable lands was slightly different from the

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

distribution of degraded lands in general. For instance, Maluku and Nusa Tenggara had a larger suitable land area 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). For many of these species, the area of highly suitable lands was significantly smaller than that of moderately suitable lands. Moreover, the lands suitable for biomass species (*C. calothyrsus* and *G. sepium*) were approximately 11 times larger (or 4.49 Mha) than the lands suitable for biodiesel species (*C. inophyllum*, *P. pinnata* and *R. trisperma*) (or 0.4 Mha).

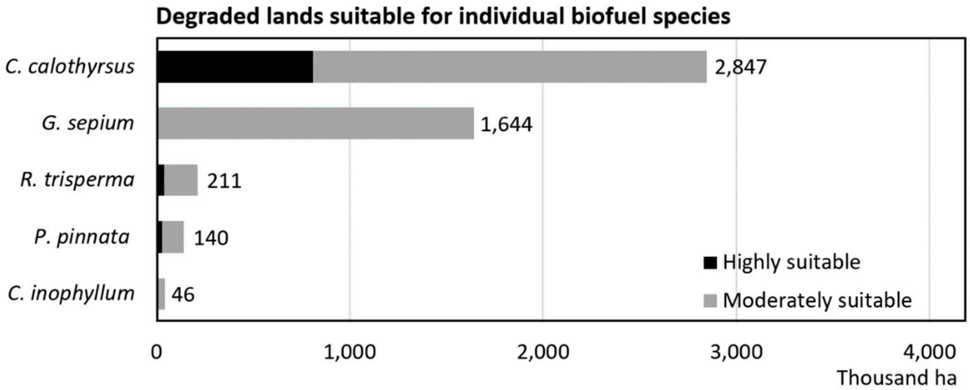
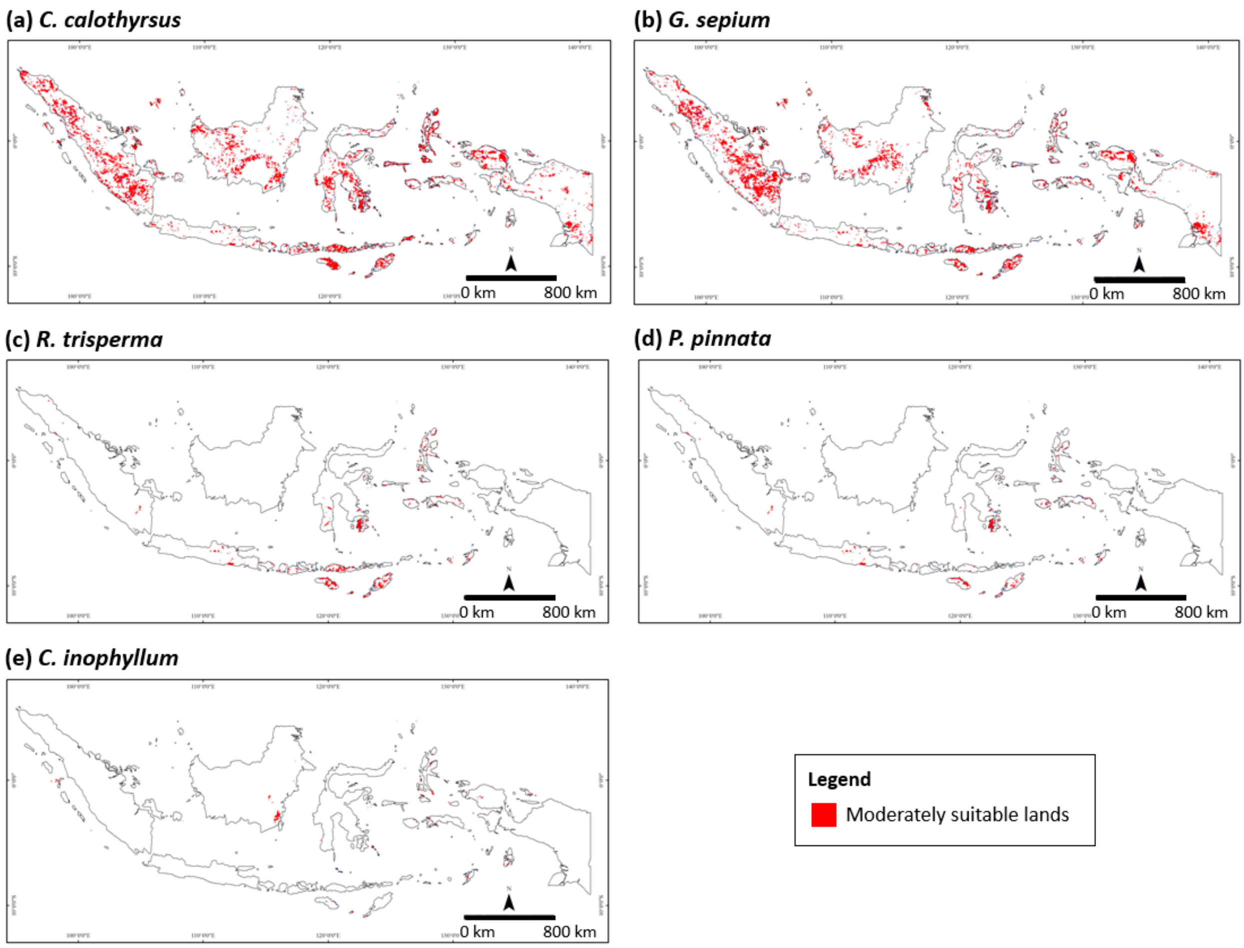


Figure 4. Total area of degraded lands in Indonesia identified as suitable for growing individual biofuel species.



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

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*,

The degraded lands were analyzed 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 lands. Medium-sized lands (between 50 and 5,000 ha) represented 19% of the total number of parcels, but their total area comprised 70% of the lands. Large-sized lands (larger than 5,000 ha) consisted of only 0.1% of the total number of land parcels, but their total area represented 22% of the degraded lands.

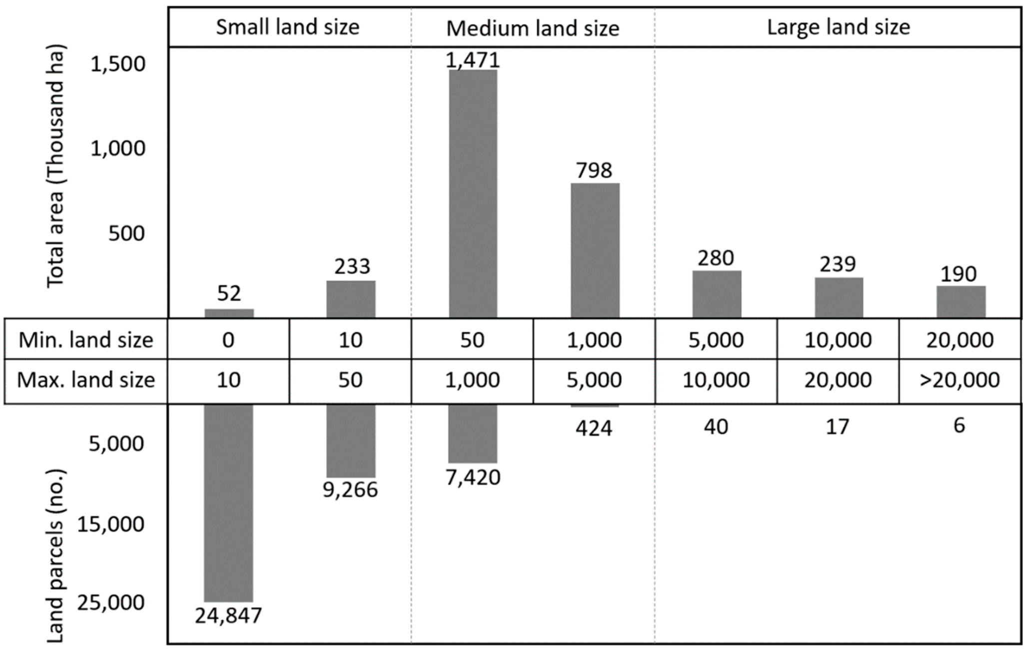


Figure 6. Total areas and number of land parcels for small, medium and large-sized degraded lands in Indonesia suitable for at least one of the biofuel or biomass species (*C. calothyrsus*, *G. sepium*, *C. inophyllum*, *P. pinnata* and *R. trisperma*).

3.3. Hypothetical maximum energy productivity

The all-five-species scenario, assessing all the biofuel species, resulted in the identification of suitable lands for *C. calothyrsus, P. pinnata, R. trisperma, G. sepium* and *C. inophyllum* (Figure 7). Of the species assessed, *C. calothyrsus* was the one that could grow well on the largest area of suitable lands (2.8 Mha) because it not only was the most suitable to the degraded lands (Figure 4), but also had the highest potential energy productivity compared with the other species (Table 4). Suitable lands for this species were largely located in Sumatra (0.93 Mha), and the smallest areas were identified in Java and Bali (0.07 Mha). Suitable lands identified for the other species in this scenario were smaller in area: *G. sepium* had 430,002 ha; *P. pinnata* had 30,559 ha; *R. trisperma* had 21,013 ha; and *C. inophyllum* only had 132 ha. This scenario resulted in about 1.105 EJ yr−1 of hypothetical maximum energy productivity (Table 5). 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.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

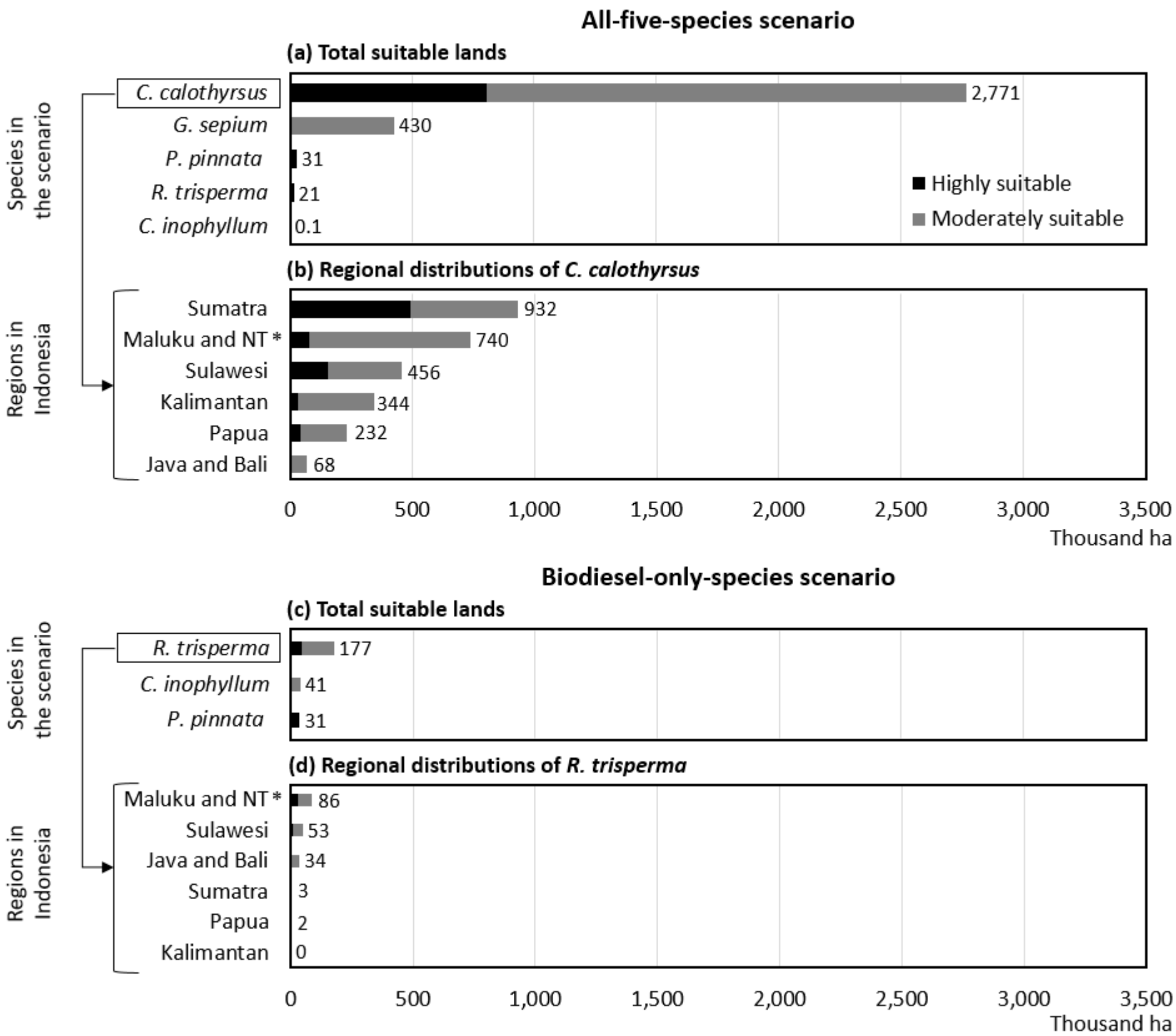


Fig. 7. Total area of degraded lands in Indonesia identified as suitable for the all-five-species and biodiesel-only-species scenarios.

(* Nusa Tenggara)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

Table 5. 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-only-species 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

The biodiesel-only-species scenario, assessing biodiesel species only, resulted in the identification of suitable lands for *R. trisperma, C. inophyllum* and *P. pinnata* (Figure 7). Of them, *R. trisperma* was the species with the biggest potential, having about 0.18 Mha of suitable lands. These lands were distributed across several regions in Indonesia, but no suitable land was found in Kalimantan. In this scenario, *C. inophyllum* and *P. pinnata* had only 40,625 ha and 30,739 ha of suitable lands, respectively. The scenario resulted in about 0.01 EJ yr−1 of hypothetical maximum energy productivity (Table 5).

4. Discussion

The study results showed that degraded lands in Indonesia might support bioenergy production by growing biodiesel species (by growing *C. inophyllum, P. pinnata* and *R. trisperma*) and biomass species (by growing *C. calothyrsus* and *G. sepium*). Indonesia potentially had about 3.5 Mha of severely degraded lands that not only have limited functions for food production, carbon storage, and conservation of biodiversity and native vegetation, but also might support the growth of these biofuel species. These degraded lands were smaller in area than other types of degraded lands identified in Indonesia, such as lands with degraded soils (about 30 Mha) [57], unproductive degraded forest lands (about 27 Mha) [54], degraded lands including forest covers with low carbon stocks (about 24 Mha) [5], degraded lands administratively available for biofuel production (about 21 Mha) [9], degraded lands for palm oil production in West and Central Kalimantan (about 7 Mha) [55] and degraded lands that have poor climate, poor physical characteristics or degraded lands on which cultivation is difficult (about 3.7 Mha) [56]. Moreover, the estimated biomass energy productivity from *C. calothyrsus* and *G. sepium* (about 1.1 EJ yr−1) in our study was smaller than the expected biomass energy from woody crops (about 5 EJ yr−1) and grasses (about 7 EJ yr−1) from degraded soil lands in Indonesia [57]. These differences stem from different definitions, different methods, different spatial data, and different species analyses among the studies.

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

Although the two scenarios analyses showed their potential support for increasing the supply of biodiesel in Indonesia, however, there are still challenges to apply these scenarios to achieving the biodiesel consumption target of 30% of total energy consumption by 2025 (Presidential Regulation No. 12/2015) in Indonesia. First, 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 [55]. 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 [9]. Thus, the sizes of these degraded lands must be considered in analyzing their potential business models for bioenergy production in Indonesia.

In addition, the study results indicate the maximum energy productivity, as the study assumed that all degraded lands would be utilized for biofuel production by growing the five biofuel species. In reality, however, this bioenergy production would be discounted by many socioeconomic factors, such as the cost–benefit of the production to farmers and refineries [5, 13, 15], higher opportunity costs for bioenergy production compared with palm oil production [55], competition with low-price energy such as gasoline [4] and conflicted stakeholder interests [54]. Further this energy would be reduced further when it is converted into other types of energy, such as electricity, for final consumption. These factors are likely to reduce the biofuel production estimates from the study so that these factors must be analyzed further to understand how many of these degraded lands might in reality support bioenergy production in Indonesia.

Despite these challenges, the study findings might still contribute to analysis of potential biofuel species in Indonesia and the investigation of carbon sequestration from bioenergy production from degraded lands. First, the study results support identifying and comparing potential species for biodiesel production (e.g. *C. inophyllum*, *P. pinnata* and *R. trisperma*) and biomass production (e.g. *C. calothyrsus* and *G. sepium*). For instance, C. calothyrsus was more suitable on degraded lands compared with the other biofuel species in this study. Among the biodiesel species, *R. trisperma* had better suitability than *P. pinnata* and *C. inophyllum*. The identified lands suitable for these species would serve as input data for analyzing their potential growth on degraded lands by applying more sophisticated plant growth modeling (e.g. Bryan et al., 2010). Moreover, suitable lands for these five species can be reference data for studies on other biofuel species in Indonesia, such as sugarcane, cassava, sweet sorghum, corn and sago [5].

Second, the study findings might support investigating potential carbon sequestration from bioenergy production from degraded lands. The locations and sizes of the suitable lands support the modeling of carbon sequestration by the five species from above and below ground on degraded lands. Such carbon modeling would support analyzing net-positive carbon sequestration of the bioenergy production from degraded lands. Other required studies that the study findings might support are analyses of: conventionally consumed biomass species in Indonesia that might be replaced with biomass production from *C. calothyrsus* and *G. sepium*; increased carbon stocks by avoiding the harvests of replaced biomass species; impacts of climate changes on the growth of the five biofuel species on degraded lands and their capacities to store carbon stocks; saved carbon stocks from other uses of biomass from degraded lands; carbon emissions from diesel blended with biodiesel from *C. inophyllum*, *P. pinnata* and *R. trisperma*; and impacts of forest restoration of degraded lands on national carbon emissions in Indonesia as well as a scheme of reducing emissions from deforestation and forest degradation (REDD+) in Indonesia (e.g. [5]).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 November 2018 doi:10.20944/preprints201811.0298.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4595; doi:10.3390/su10124595

5. Conclusions

The study identified 3.5 Mha of degraded lands in Indonesia that not only might avoid compromising food production, carbon storage, biodiversity and native vegetation, but also might support bioenergy production by growing biodiesel species (*C. inophyllum, P. pinnata* and *R. trisperma*) and biomass species (*C. calothyrsus* and *G. sepium*). The study results revealed both opportunities and challenges for bioenergy production from these degraded lands in Indonesia. The two-scenario analysis showed that maximum biomass energy production from *C. calothyrsus* and *G. sepium* might support increasing the biofuel supply in Indonesia. However, the sizes of degraded lands were rather too small to support economies of scale for biofuel production, and the study results would be discounted by many socioeconomic factors in reality. The study findings support future studies on modeling the growth of biofuel species on degraded lands, comparing diverse potential biofuel species and modeling carbon sequestration from restoration of degraded lands.

Author Contributions: conceptualization, B.O., E.W., and H.B.; methodology, B.O., E.W., R.S., and W.J.; software, B.O., E.W., R.S., and W.J.; validation, W.J.; formal analysis, E.W., B.O., R.S., and W.J.; investigation, B.O., Y.A., and W.J.; resources, B.L., and L.B.P.; data curation, B.O., R.S., E.W., and W.J.; writing—original draft preparation, E.W.; writing—review and editing, W.J., C.S.G., H.B., and B.L.; visualization, W.J., B.O., and R.S.; supervision, H.B.; project administration, Y.A., and H.B.; funding acquisition, S.M.L. All authors contributed to the manuscript, read the final draft, and approved it.

Funding: This research was funded by the National Institute of Forest Science (NIFoS), Republic of Korea

Acknowledgments: Chun Sheng Goh is a JSPS International Research Fellow supported by Japan Society for the Promotion of Science.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lewis, S. & Kelly, M. 2014. Mapping the potential for biofuel production on marginal lands: Differences in definitions, data and models across scales. ISPRS International Journal of Geo-Information, 3(2), 430-459.
2. IRENA [International Renewable Energy Agency]. 2017. Renewable energy prospects: Indonesia, a REmap analysis. International Renewable Energy Agency, Abu Dhabi.
3. GAIN [Global Agriculture Information Network]. 2017. Indonesia biofuels annual 2017. USDA Foreign Agricultural Service, Jakarta, Indonesia.
4. DEN [Dewan Energi National]. 2017. Indonesia Energy Outlook 2016. Jakarta, Indonesia.
5. ICCC [Indonesia Climate Change Center]. 2014. Crops to energy on degraded land as a step toward energy independence, carbon sink agriculture and protection of REDD+ designated areas, Jakarta, Indonesia.
6. Wulandari, W. S., Darusman, D., Kusmana, C. & Widiatmaka. 2014. Land suitability analysis of biodiesel crop Kemiri Sunan (Reutealis trisperma (Blanco) Airy Shaw) in the Province of West Java, Indonesia. Journal of Environment and Earth Science, 4 (21):27-37.
7. Baral, H. & Lee, S. M. 2016. Sustainable bioenergy systems to restore and valorize degraded land. Center for International Forestry Research, Bogor, Indonesia.
8. Borchard, N., Artati, Y., Lee, S. M. & Baral, H. 2017. Sustainable forest management for land rehabilitation and provision of biomass-energy. Center for International Forestry Research, Bogor, Indonesia.
9. Harahap, F., Silveira, S., & Khatiwada, D. 2017. Land allocation to meet sectoral goals in Indonesia – An analysis of policy coherence. Land Use Policy, 61, 451-465.
10. Fargione, J., Hill, J., Tilman, D. & Polasky, S. 2008. Land clearing and the biofuel carbon debt. Science, 319, 1235.
11. Goh, C. S., Wicke, B., Potter, L., Faaij, A., Zoomers, A. & Junginger, M. 2017. Exploring under-utilised low carbon land resources from multiple perspectives: Case studies on regencies in Kalimantan. Land Use Policy, 60, 150-168.
12. Danielsen, F., Beukema, H., Burgess, N. D., Parish, F., Brühl, C. A., Donald, P. F., et al. 2009. Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate. Conservation Biology, 23(2), 348-358.
13. Bryan, B. A., Ward, J., & Hobbs, T. 2008. An assessment of the economic and environmental potential of biomass production in an agricultural region. Land Use Policy, 25(4), 533-549.
14. Richardson, D. M. & Blanchard, R. 2011. Learning from our mistakes: Minimizing problems with invasive biofuel plants. Current Opinion in Environmental Sustainability, 3(1), 36-42.
15. Maraseni, T. N., & Cockfield, G. 2015. The financial implications of converting farmland to state-supported environmental plantings in the Darling Downs region, Queensland. Agricultural Systems, 135, 57-65.
16. Scott, P. T., Pregelj, L., Chen, N., Hadler, J. S., Djordjevic, M. A. & Gresshoff, P. M. 2008. Pongamia pinnata: An untapped resource for the biofuels industry of the future. Bioenergy Research, 1, 2-11.
17. Ong, H., Mahlia, T., Masjuki, H. & Norhasyima, R. 2011. Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: A review. Renewable and Sustainable Energy Reviews, 15, 3501-3515.
18. Syamsuwida, D., Kurniaty, R., Putri, K. P. & Suita, E. 2014. Kaliandra (Calliandra callothyrsus) as a timber for energy: In a point of view of seeds and seedlings procurement. Energy Procedia, 47, 62-70.
19. Fadhlullah, M., Widiyanto, S. N. B. & Restiawaty, E. 2015. The potential of nyamplung (Calophyllum inophyllum L.) seed oil as biodiesel feedstock: Effect of seed moisture content and particle size on oil yield. Energy Procedia, 68, 177-185.
20. Leksono, B., Windyadni, E. & Hasnah, T. M. 2015. Growth, flowering, fruiting and biofuel content of Calopyllum inophyllum in provenance seed stand. Paper presented at the Proceeding of International Conference of Indonesia Forestry Researchers III-2015, Bogor, Indonesia.
21. Hambali, E., Nisya, F. N., Thahar, A., Nuryanti, A. & Wijaya, H. 2016. Potential of biomass as bioenergy feedstock in Indonesia. Journal of the Japan Institute of Energy, 95(8), 629-638.
22. Adaganti, S. Y., Yaliwal, V. S., Kulkarni, B. M., Desai, G. P. & Banapurmath, N. R. 2014. Factors affecting bioethanol production from lignocellulosic biomass (*Calliandra calothyrsus*). Waste and Biomass Valorization, 5(6), 963-971.
23. Amirta, R., Yuliansyah, A. E. M., Ananto, B. R., Setiyono, B., Haqiqi, M. T., Septiana, H. A., et al. 2016. Plant diversity and energy potency of community forest in East Kalimantan, Indonesia: Searching for fast growing wood species for energy production. Nusantara Bioscience, 8(1), 22-31.

24. Orwa, C., Mutua, A., Kindt, R., Jamnadass, R. & Anthony, S. 2009. Agroforestree Database: a tree reference and selection guide version 4.0. World Agroforestry Centre, Kenya.
25. Palmer, B., Macqueen, D. & Gutteridge, R. 1994. 2.4 *Calliandra calothyrsus* - a multipurpose tree legume for humid locations. Forage Tree Legumes in Tropical Agriculture, 65.
26. Bustomi, S., Rostiwati, T., Sudradjat, R., Kosasih, A. S., Anggraeni, I., Leksono, B., et al. 2008. Nyamplung (Calophyllum inophyllum L.) sumber energi biofuel yang potensial. Kementerian Kehutanan, Jakarta, Indonesia.
27. Chandra, B. B., Setiawan, F., Gunawan, S. & Widjaja, T. 2013. Pemanfaatan Biji Buah Nyamplung (Callophylum Inophylum) Sebagai Bahan Baku Pembuatan Biodisel. Jurnal Teknik ITS, 2, B13-B15.
28. Leksono, B., Windyarini, E. & Hasnah, T. M. 2014. Budidaya Tanaman Nyamplung (Calophyllum iInophyllum) untuk Bioenergi dan Prospek Pemanfaatan Lainnya. IPB Press, Jakarta, Indonesia.
29. Atabani, A., Silitonga, A., Ong, H., Mahlia, T., Masjuki, H., Badruddin, I. A. & Fayaz, H. 2013. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renewable and Sustainable Energy Reviews, 18, 211-245.
30. Bhattacharya, S., Salam, P. A., Pham, H. & Ravindranath, N. 2003. Sustainable biomass production for energy in selected Asian countries. Biomass and Bioenergy, 25, 471-482.
31. Dahlanuddin, Yanuarianto, O., Poppi, D. P., McLennan, S. R. & Quigley, S. P. 2014. Liveweight gain and feed intake of weaned Bali cattle fed grass and tree legumes in West Nusa Tenggara, Indonesia. Animal Production Science, 54(7), 915-921.
32. Knothe, G., de Castro, M. E. G. & Razon, L. F. 2015. Methyl esters (biodiesel) from and fatty acid profile of *Gliricidia sepium* seed oil. Journal of the American Oil Chemists' Society, 92(5), 769-775.
33. Al Muqarrabun, L. M. R., Ahmat, N., Ruzaina, S. A. S., Ismail, N. H. & Sahidin, I. 2013. Medicinal uses, phytochemistry and pharmacology of Pongamia pinnata (L.) Pierre: A review. Journal of Ethnopharmacology, 150(2), 395-420.
34. Aminah, A. A. M., Supriyanto, A. S. & Siregar, I. Z. 2017. Genetic diversity of Pongamia pinnata (Millettia pinnata, aka. malapari) populations in Java Island, Indonesia. Biodiversitas, 18(2), 677-681.
35. Aunillah, A. & Pranowo, D. 2012. Karakteristik biodiesel kemiri sunan [Reutealis trisperma (Blanco) Airy Shaw] menggunakan proses transesterifikasi dua tahap. Jurnal Tanaman Industri dan Penyegar, 3, 193-200.
36. Hendra, D. 2014. Pembuatan Biodiesel Dari Biji Kemiri Sunan. Jurnal Penelitian Hasil Hutan, 32, 37-45.
37. Syamsuwida, D., Putri, K. P., Kurniaty, R. & Aminah, A. 2015. Seeds and seedlings production of bioenergy tree species Malapari (Pongamia pinnata (L.)Pierre). Energy Procedia, 65, 67-75.
38. Fuwape, J. A. & Akindele, S. O. 1997. Biomass yield and energy value of some fast-growing multipurpose trees in Nigeria. Biomass and Bioenergy, 12, 101-106.
39. Herman, M., Syakir, M., Pranowo, D. & Saefudin, S. 2013. Kemiri Sunan (Reutealis trisperma (Blanco) Airy Shaw) Tanaman Penghasil Minyak Nabati dan Konservasi Lahan, Jakarta, Indonesia.
40. Riayatsyah, T. M. I., Ong, H. C., Chong, W. T., Aditya, L., Hermansyah, H. & Mahlia, T. M. I. 2017. Life cycle cost and sensitivity analysis of Reutealis trisperma as non-edible feedstock for future biodiesel production. Energies, 10(7), 877.
41. Wulandari, W. S. 2015. Strategi Pengembangan Biodiesel Kemiri Sunan (Reutealis Trisperma (Blanco) Airy Shaw) Di Jawa Barat. Institut Pertanian Bogor, Bogor, Indonesia.
42. Herdiawan, I. & Sutedi, E. 2015. Productivity of *Calliandra calothyrsus*, *Indigofera zollingeriana* and *Gliricidia sepium* on acid soil in the greenhouse. Indonesian Journal of Animal and Veterinary Sciences, 20(2), 105-114.
43. Fanish, S. A. & Priya, R. S. 2013. Review on benefits of agroforestry system. International Journal of Education and Research, 1(1), 1-12.
44. Yaliwal, V. S., Adaganti, S. Y., Kulkarni, B. M. & Desai, G. P. 2014. Production of renewable and sustainable fuel from *Calliandra calothyrsus* and its utilisation in compression ignition engines. International Journal of Sustainable Engineering, 7(1), 41-54.
45. Lim, T. K. 2014. *Gliricidia sepium*. In Lim T. K. (Ed.), Edible medicinal and non-medicinal plants (Vol. 7, 806-816). Springer Netherlands, Dordrecht, Netherlands.
46. Dwivedi, G. & Sharma, M. P. 2014. Prospects of biodiesel from Pongamia in India. Renewable and Sustainable Energy Reviews, 32, 114-122.

47. Sangwan, S., Rao, D. V. & Sharma, R. A. 2010. A review on Pongamia Pinnata (L.) Pierre: A great versatile leguminous plant. Nature and Science, 8(11), 130-139.
48. Jiang, Q., Yen, S.-H., Stiller, J., Edwards, D., Scott, P. T. & Gresshoff, P. M. 2012. Genetic, biochemical, and morphological diversity of the legume biofuel tree Pongamia pinnata. Journal of Plant Genome Sciences, 1(3), 54-67.
49. Siregar, N. & Djam'an, D. F. 2017. Pengaruh bahan tanaman terhadap keberhasilan setek kranji (Pongamia pinnata). Prosiding Seminar Nasional Masyarakat Biodiversitas Indonesia., 3(1), 23-27.
50. Kumar, K. R., Chandrika, K., Prasanna, K. T. & Gowda, B. 2015. Biodiesel production and characterization from non-edible oil tree species Aleurites trisperma Blanco. Biomass Conversion and Biorefinery, 5(3), 287-294.
51. Yohana, E., Yulianto, M. E., Ikhsan, D., Nanta, A. M. & Puspitasari, R. 2016. The development of the super-biodiesel production continuously from Sunan pecan oil through the process of reactive distillation. The AIP Conference Proceedings, 1737 (1), 1-10.
52. Holilah, H., Prasetyoko, D., Oetami, T. P., Santosa, E. B., Zein, Y. M., Bahruji, H., et al. 2015. The potential of Reutealis trisperma seed as a new non-edible source for biodiesel production. Biomass Conversion and Biorefinery, 5(4), 347-353.
53. Pranowo, D. & Herman, M. 2016. Potensi pengembangan kemiri sunan (Reutealis trisperma (Blanco) Airy Shaw) di lahan terdegradasi. Perspektif, 14(2), 87-101.
54. Colchester, M., Jiwan, N., Andiko, Sirait, M., Firdaus, A. Y., Surambo, A., et al. 2006. Promised Land: Palm Oil and Land Acquisition in Indonesia- Implications for Local Communities and Indigenous Peoples: Moreton-in-Marsh, Forest Peoples Programme, Perkumpulan Sawit Watch, HuMA and the World Agroforestry Centre.
55. Gingold, B., Rosenbarger, A., Muliastra, Y., Stolle, F., Sudana, I. M., Manessa, M. D. M., et al. 2012. How to identify degraded land for sustainable palm oil in Indonesia. World Resources Institute, Washington, DC.
56. Milbrandt, A., & Overend, R. P. 2009. Assessment of biomass resources from marginal lands in APEC economies: National Renewable Energy Laboratory (NREL), Golden, CO.
57. Nijsen, M., Smeets, E., Stehfest, E. & Vuuren, D. P. 2012. An evaluation of the global potential of bioenergy production on degraded lands. GCB Bioenergy, 4, 130-147.
58. DPEPDA [Direktorat Perencanaan dan Evaluasi Pengendalian Daerah Aliran Sungai]. 2015. Peta Digital Lahan Kritis Tahun 2011. Sub Direktorat Pemolaan Pengelola Daerah Aliran Sungai. Jakarta, Indonesia.
59. DPPKH [Direktorat Pengukuhan dan Penatagunaan Kawasan Hutan] 2015. Peta Digital Kawasan Hutan Tahun 2014. Sub Direktorat Pengukuhan Kawasan Hutan Wilayah I dan II. Jakarta, Indonesia.
60. DIPSH [Direktorat Inventarisasi dan Pemantauan Sumberdaya Hutan] 2015. Peta Digital Penutupan lahan Tahun 2014. Sub Direktorat Pemantauan Sumberdaya Hutan. Jakarta, Indonesia
61. MoF [Ministry of Forestry of Indonesia]. 2003. Pembakuan Standar Penafsiran Citra Satelit Resolusi Sedang. Badan Planologi Kehutanan Departemen Kehutanan dan Badan Informasi Geospasial (BIG). Jakarta, Indonesia.
62. RePPProT [Regional Physical Planning Program for Transmigration]. 1990. The land resources of Indonesia: A national overview. Government of Republic of Indonesia: Ministry of Transmigration, Directorate General of Settlement Preparation, and BAKOSURTANAL. Land Resources Department, Natural Resources Institute, Overseas Development Administration, Foreign and Commonwealth Office, United Kingdom.
63. FAO [Food and Agriculture Organization of the United Nations]. 2007. Ecocrop. Retrieved 27 July 2017 from http://ecocrop.fao.org/ecocrop/srv/en/cropSearchForm
64. Ad Hoc Pallel of the Advisory Committee on Technology Innovation Board on Science and Technology for International DevelopMent Office of International Affairs National Research Council. 1983. Innovations in Tropical Reforestation: Calliandra A Versatile Small Tree for the Humid Tropics. Washington, D.C.: NATIONAL ACADEMY PRESS.
65. Miyake, S., Smith, C., Peterson, A., McAlpine, C., Renouf, M., & Waters, D. 2015. Environmental implications of using 'underutilised agricultural land' for future bioenergy crop production. Agricultural Systems, 139, 180-195.
66. Stewart, J. L., Allison, G. E. & Simons, A. J. 1996. *Gliricidia sepium*: genetic resources for farmers. Oxford Forestry Institute, University of Oxford, United Kingdom.

Peer-reviewed version available at Sustainability 2018, 10, 4595; doi:10.3390/su10124595

67. CABI. 2018. Reutealis trisperma (Philippine tung). Retrieved from https://www.cabi.org/isc/datasheet/4125.
68. Lee, J. S. H., Abood, S., Ghazoul, J., Barus, B., Obidzinski, K. & Koh, L. P. 2014. Environmental impacts of large-scale oil palm enterprises exceed that of smallholdings in Indonesia. Conservation Letters, 7(1), 25-33.
69. Ong, H. C., Masjuki, H. H., Mahlia, T. M. I., Silitonga, A. S., Chong, W. T. & Yusaf, T. 2014. Engine performance and emissions using Jatropha curcas, Ceiba pentandra and Calophyllum inophyllum biodiesel in a CI diesel engine. Energy, 69, 427-445.
70. Mohibbe Azam, M., Waris, A. & Nahar, N. M. 2005. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass and Bioenergy, 29(4), 293-302.
71. Kumar, A. & Sharma, S. 2011. Potential non-edible oil resources as biodiesel feedstock: An Indian perspective. Renewable and Sustainable Energy Reviews, 15(4), 1791-1800.

Atabani, A. E. & César, A. d. S. 2014. Calophyllum inophyllum L. – A prospective non-edible biodiesel feedstock. Study of biodiesel production, properties, fatty acid composition, blending and engine performance. Renewable and Sustainable Energy Reviews, 37, 644-655.