CHAPTER 5

Potential energy yields of bioenergy crops in the tropics

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Abstract: Bioenergy can produce at least 25% of the global energy demand to combat climate change through reducing emissions in the energy sector. However, information on the bioenergy production potential of woody species and their suitability for silviculture on various soils in the humid tropics is limited. This slightly revised version of a short note published by Borchard et al. (2018) aims to identify tree species suitable for bioenergy production under these conditions. Data were compiled from 241 publications and nine freely available databases to assess environmental and silvicultural information on tropical tree species. Energy yield was derived from the estimated productivity of the reviewed species equivalent to an energy yield ranging between 2 and 444 GJ ha^{-1} yr^{-1}. As such, these bioenergy yields are within the range reported for the lignocellulosic biomass of energy crops cultivated in Europe, the USA and Brazil. Our review identified some high-yielding species (e.g., *Dyera polyphylla* (Miq.) Steenis, *Metroxylon sagu* (Rottb.), *Pongamia pinnata* (L.)) and leguminous species that could be beneficial in mixed stands (e.g., *Elaeis oleifera* (Kunth) and *Pongamia pinnata*) or are suitable species to grow on wet or re-wetted peatland (*Dyera polyphylla*). However, there are limitations to cultivating woody bioenergy species on wet peatland. Sustainable methods for managing and harvesting forests on wet or re-wetted peatland need to be developed.

Keywords: tropics, paludiculture, biomass, biofuel, biodiesel, bioethanol
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5.1 Introduction

It is predicted that global energy demand will increase substantially by 2040. Depending on the scenario, estimates range from 20% to 34% compared to consumption in 2018 (Newell et al. 2020), resulting in a massive CO_2 emission increase in case of neglecting renewable energy sources (IEA 2015). Evidently, achieving the 2°C limit on global warming requires new policies to reduce the energy sector's CO_2 emissions by replacing traditional and fossil fuels with renewable energies (Frei et al. 2013). Bioenergy, the energy produced from biological sources, is one such renewable energy (Brown and Feuvre 2017). Globally, bioenergy has the potential to produce 100–400 exajoules per year (EJ yr^{-1}) (Faaij 2006; Nijsen 2012), which is equivalent to 25%–100% of the total energy consumed in 2014 and 2017 (Brown and Feuvre 2017; IRENA 2017). According to Brown and Feuvre (2017), bioenergy from sustainable land use and forest management will be one of the most sustainable solutions among renewable energy options. Despite such enormous potential, in 2018, only around 1.9% of the electricity and 4.2% of the heat consumed were generated from biofuels (IEA 2021). Traditional use of biomass, although common in developing countries, remains inefficient and hazardous to health. However, bioenergy could provide clean and affordable energy to meet increasing demands in these countries (Faaij 2006; Balat M and Balat H 2009; IEA 2015). In the tropics, oil palm (*Elaeis guineenis* (Jacq.)) dominates biofuel production from tree species (Dislich et al. 2017; Proskurina et al. 2019). However, in comparison to forests, oil palm monoculture results in a loss of ecosystem functions (Dislich et al. 2017). This is less severe in mixed systems that may produce even higher yields per area (Zemp et al. 2019).

The aim of this study was to identify tropical tree species that could produce biological resources for bioenergy production and are able to grow on various types of soils. The potential biofuel and energy yields were estimated by assessing yields based on silvicultural information (e.g., stem density) and productivity (e.g., biomass per hectare per year), which were converted into energetic values (e.g., gigajoules per hectare per year (GJ ha^{-1} yr^{-1}). Due to the huge body of literature on species used and recommended for bioenergy production in the tropics, this study specifically focused on tree species for bioenergy production (Duke 1983; Biswas et al. 2011; Abel et al. 2013; Atabani et al. 2013).

5.2 Materials and methods

The aim of this narrative review (Uman 2011) was to identify tree species suitable for bioenergy systems in the tropics from the literature (Azam et al. 2005; Saito et al. 2005; Biswas et al. 2011; Abel et al. 2013; Atabani et al. 2013; Mekala et al. 2014) by combining their silvicultural information (Table 1) and potential energy yields per hectare per year (Table 2). A literature search using Google Scholar was conducted for silvicultural information using species names as keywords.

The search produced 241 documents and nine freely available databases (Borchard et al. 2018, Table S1). These were used to assess the following aspects of woody bioenergy crops: (i)

Table 1. Potential bioenergy species that tolerate unfavourable soil conditions

Soil conditions that are most relevant for species selection are presented. Potential ecological adaptations are also shown to inform about tolerances to, for instance, droughts and flooding. Primary data and their corresponding references are shown in Borchard et al. 2018.

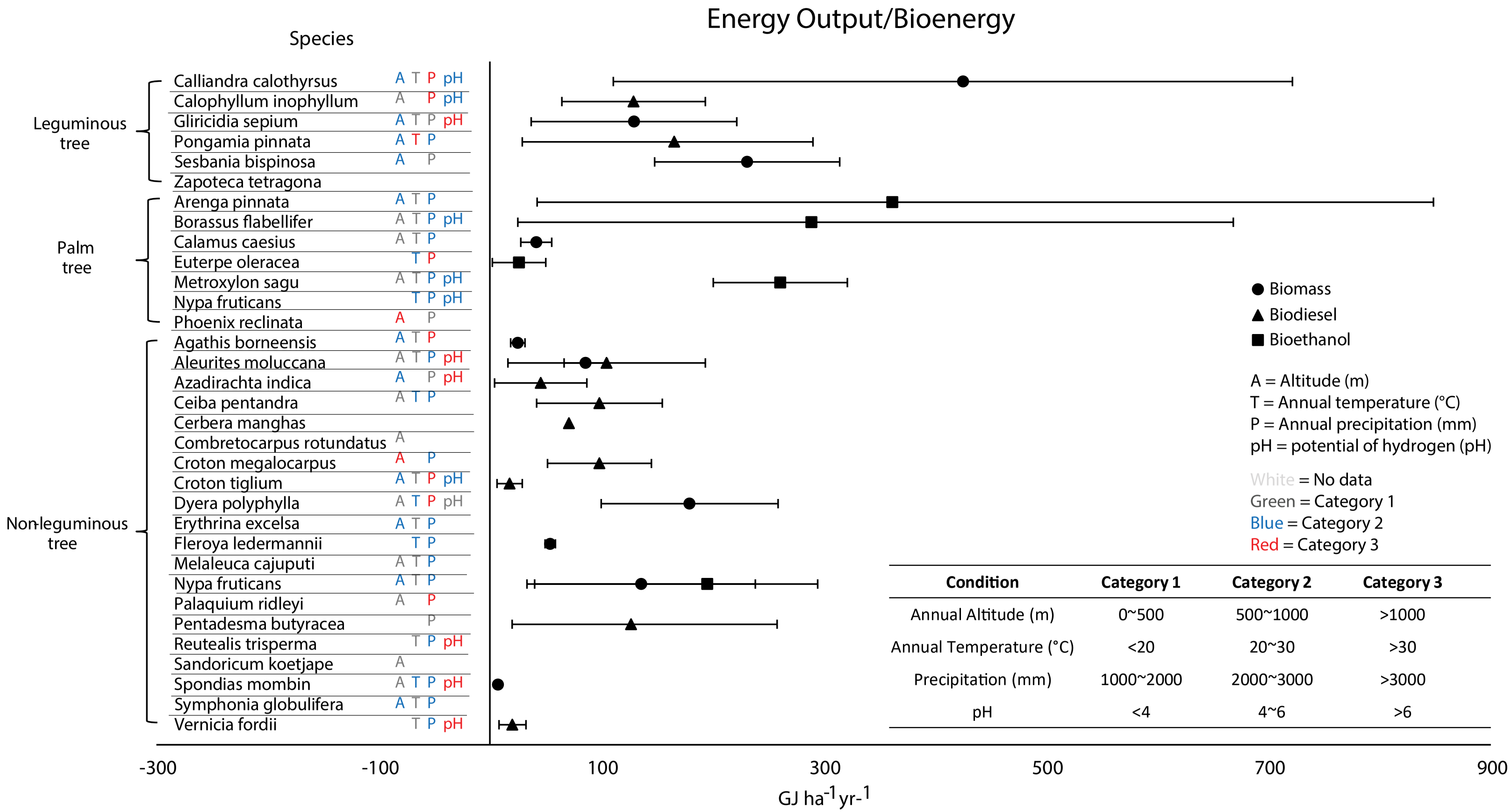
Species	Soil pH	Soil Texture	Soil Moisture	Soil Fertility	Additional Adaptations
Species that tolerate poor soils, moist and dry environments					
Agathis borneensis (Warb.)	<7	-/-	-/-	-/-	Deep, well-drained, acidic soil
Aleurites moluccana (L.)	5.0–8.0	-/-	Moist to dry	Poor	Tolerates droughts
Arenga pinnata (Wurmb.)	-/-	Sand	Moist to dry	-/-	Tolerates dry environments
Azadirachta indica (A. Juss.)	6.0–7.0	-/-	-/-	Poor	-/-
Borassus flabellifer (L.)	5.0–6.0	-/-	Moist to dry	-/-	Tolerates droughts and short-term flooding
Calliandra calothyrsus (Meisn.)	5.0–6.5	-/-	Moist to dry	Poor	Pioneer species, tolerates droughts
Calophyllum inophyllum (L.)	4.0–7.5	-/-	Moist to dry	-/-	Xerophytic species, tolerates droughts
Ceiba pentandra (L.)	-/-	Sandy	Moist	-/-	Deep, well-drained, light soil, Andosol
Croton megalocarpus (Hutch.)	-/-	Sandy	Moist	-/-	Pioneer species; deep, well-drained, light soil
Croton tiglium (L.)	4.5–7.5	-/-	-/-	-/-	-/-
Gliricidia sepium (Jacq.)	4.5–8.5	Various	Moist	-/-	Pioneer species, deep, well-drained soil
Neolamarckia cadamba (Roxb.)	-/-	-/-	Moist	-/-	Deep, alluvial soils
Pongamia pinnata (L.)	-/-	Sandy	Moist to dry	-/-	Deep soils, tolerates droughts and acidity
Reutealis trisperma (Blanco)	5.4–7.1	-/-	-/-	Poor	-/-
Vernicia fordii (Hemsl.)	6.0–6.5	Sandy	Moist to dry	-/-	Deep, well-drained, light soils
Zapoteca tetragona (Willd.)	-/-	-/-	-/-	-/-	-/-
Species that tolerate permanently wet and waterlogged or temporarily flooded soils					
Calamus caesius (Blume)	-/-	Peat, clayish, silty	Moist to wet	-/-	Margins of peat and swamp land, tolerates flooding
Cerbera manghas (L.)	-/-	-/-	Moist to wet	-/-	Riparian, swamp and mangrove environment
Combretocarpus rotundatus (Miq.)	3.0–4.5	Peat	Wet	-/-	Peat-swamp forest (*Shorea* spp.), tolerates waterlogged soils
Dyera polyphylla (Miq.)	3.0–4.5	Peat	Wet	-/-	Peat-swamp forest, wet soils, peat
Erythrina excelsa (Baker)	-/-	Various	Moist to wet	-/-	Riparian and swamp land, high water table
Euterpe oleracea (Mart.)	-/-	Sandy	Moist	-/-	Light soils, tolerates flooding
Melaleuca cajuputi (Powell)	-/-	Sandy	-/-	Poor	Poor, well-drained soils, brackish and acidic sulphate soils
Metroxylon sagu (Rottb.)	>4.5	Various	Moist to wet	-/-	Tolerates flooding
Fleroya ledermannii (K.Krause)	-/-	-/-	-/-	-/-	Anemochory, tolerates flooding
Nypa fruticans (Wurmb.)	5.0	Clayish	Moist to wet	-/-	Mangrove species
Palaquium ridleyi (King & Gamble)	3.0–4.5	Peat	Wet	-/-	Peat-swamp forest
Pentadesma butyracea (Sabine	-/-	-/-	-/-	-/-	Riparian forests, deep soils
Phoenix reclinata (Jacq.)	-/-	Various	-/-	-/-	Medium- to fine-textured soil, tolerates flooding
Sandoricum koetjape (Burm.f.)	≥7	Various	-/-	Poor	Pioneer species, riparian areas
Sesbania bispinosa (Jacq.)	<10	Various	Dry to wet	-/-	Alkaline soils, riparian areas, tolerates droughts
Spondias mombin (L.)	4.3–8.0	Various	-/-	-/-	Various mineral soils, tolerates flooding
Symphonia globulifera (L.f.)	-/-	-/-	Moist to wet	-/-	Lowland rainforest to swamp forest

Note: -/- no data available

botanical information (e.g., species and origin, synonyms, common name, typical use); (ii) ecological settings (e.g., temperature, mean annual precipitation, soil properties); and (iii) cropping and yields (e.g., stem density, biomass yield, bio-oil yield) (Borchard et al. 2018, Table S2). Data extracted from original resources were taken directly from the publication. Thus, our dataset represents original information without any conversion into a single system (e.g., FAO soil classification). Extracted soil pH values were mostly (i.e., 93%, Borchard et al. 2018, Table S2) published without further clarification on solutions used (e.g., H_2O, KCl, $CaCl_2$) or salt concentration, which affects the comparability of pH values (Edmeades and Wheeler 1990; Gavriloaiei 2012). Thus, due to the lower accuracy of pH values and ranges presented, this review can provide only approximate information on the soil pH values tolerated. Yield data in mass or volume per unit area were used as presented in surveys or calculations, based on single tree productivity (e.g., dry biomass, fruit yield, oil content) and stand density per unit area (Borchard et al. 2018, Table S2). Conversion factors used to derive energy yields (GJ ha^{-1} yr^{-1}) were: (i) carbon density of 0.5 in dry mass of wood (Penman et al. 2003); (ii) energy of 37 MJ stored per kg carbon or 19 MJ per kg dry biomass (German National Academy of Sciences Leopoldina 2012); (iii) a bio-oil – biodiesel conversion rate of 90% adapted from values published by Meher et al. (2006); (iv) biodiesel density of 0.9 g cm^{-3} (Meher et al. 2006; Hofstrand 2008); (v) energy of 33 MJ stored per litre of biodiesel (Meher et al. 2006; Hofstrand 2008); (vi) a sugar – bioethanol conversion rate of 51% (Demirbas 2005); (vii) bioethanol density of 0.8 g cm^{-3} (Hofstrand 2008); and (vii) energy of 21 MJ per litre of bioethanol (Hofstrand 2008).

5.3 Results

Although numerous woody species are suitable for forest-based bioenergy systems in humid tropical regions (Table 1), the estimation of potential bioenergy yields per unit of area (i.e., GJ ha^{-1} yr^{-1}) was limited to 33 species due to the scarcity of silvicultural and biorefinery data (Figure 1 and 2). This study provides species-specific information on environments preferred by each species, silvicultural information (e.g., stem density per hectare), and yield data (Mg dry biomass ha^{-1} yr^{-1}). Around 50% of the species ($n = 16$) are adapted to mineral soils and able to tolerate acidic and nutrient-poor soils (e.g., eroded Acrisols) and droughts (Table 1). Trees that can tolerate drought include *Aleuritis moluccana* (L.), *Calophyllum inophyllum* (L.) and *Pongamia pinnata.* Although their cropping on terrestrial soils potentially produces high yields, such yields will be reduced by flooding and wet soil conditions. In addition, soil wetness, soil acidity and low nutrient status may also limit plant productivity (Crosson 1997). In particular, biological nitrogen fixation by leguminous species that have been widely used to rehabilitate degraded land (e.g., *Calophyllum inophyllum*, *Gliricidia sepium* (Jacq.)) is drastically reduced in acidic soils. Based on tree productivity data and information on their silvicultural recommendations, species suitable for growth on mineral soils and (re)-wetted peatland (Table 1 and Table 2) can potentially produce between 0.2 Mg and 24.0 Mg biomass ha^{-1} yr^{-1}, 0.1 Mg and 9.0 Mg bio-oil ha^{-1} yr^{-1}, and between 0.2 Mg and approximately 20.0 Mg sugar ha^{-1} yr^{-1}, which is equal to an energy yield between 2 GJ and 444 GJ ha^{-1} yr^{-1} (Figure 1, Table 2).



Condition	Category 1	Category 2	Category 3
Annual Altitude (m)	0~500	500~1000	>1000
Annual Temperature (°C)	<20	20~30	>30
Precipitation (mm)	1000~2000	2000~3000	>3000
pH	<4	4~6	>6

Figure 1. Potential bioenergy yield per tree species expressed in GJ ha^{-1} yr^{-1}

Table 2. Potential annual biomass, bio-oil, sugar (Su), and starch (St) productivity in Mg ha^{-1} yr^{-1} of species used/potentially suitable for forest-based bioenergy production in tropical regions.

Biomass data were also converted into volumetric values (mL ha^{-1} yr^{-1}) and energy values (GJ ha^{-1} yr^{-1}). A 'Yes' indicates a promising species, but due to a lack of information in the literature, yield could not be estimated. Primary data and their corresponding references are shown in Borchard et al. 2018.

Species	**Biomass**		**Bio-oil and Biodiesel**			**Sugar or Starch and Bioethanol**		
	Mg ha^{-1} yr^{-1}	GJ ha^{-1} yr^{-1}	Mg ha^{-1} yr^{-1}	kL ha^{-1} yr^{-1}	GJ ha^{-1} yr^{-1}	Mg ha^{-1} yr^{-1}	kL ha^{-1} yr^{-1}	GJ ha^{-1} yr^{-1}
Species that tolerate poor soils, moist and dry environments								
Agathis borneensis (Warb.)	1.0–1.7	19–31	-/-	-/-	-/-	-/-	-/-	-/-
Aleurites moluccana (L.)	3.6–5.7	67–105	0.5–6.0	0.5–6.0	16–194	-/-	-/-	-/-
Arenga pinnata (Wurmb)	-/-	-/-	-/-	-/-	-/-	20 (Su)	2.0–12.8	43–268
Azadirachta indica (A.Juss.)	-/-	-/-	0.1–2.7	0.1–2.7	4–87	-/-	-/-	-/-
Borassus flabellifer (L.)	-/-	-/-	-/-	-/-	-/-	20 (Su)	1.2–12.8	25–268
Calliandra calothyrsus (Meisn.)	6.0–24.0	111–444	-/-	-/-	-/-	-/-	-/-	-/-
Calophyllum inophyllum (L.)	-/-	-/-	2.0–6.0	2.0–5.9	65–194	-/-	-/-	-/-
Ceiba pentandra (L.)	-/-	-/-	1.3–4.8	1.3–4.8	42–155	-/-	-/-	-/-
Croton megalocarpus (Hutch)	-/-	-/-	1.6–4.5	1.6–4.5	52–145	-/-	-/-	-/-
Croton tiglium (L.)	-/-	-/-	0.2–0.9	0.2–0.9	6–29	-/-	-/-	-/-
Gliricidia sepium (Jacq.)	2.0–12.0	37–222	-/-	-/-	-/-	-/-	-/-	-/-
Neolamarckia cadamba (Roxb.)	1.8–12.9	33–239	-/-	-/-	-/-	-/-	-/-	-/-
Pongamia pinnata (L.)	-/-	-/-	0.9–9.0	0.9–8.9	29–290	-/-	-/-	-/-
Reutealis trisperma (Blanco)	-/-	-/-	Yes	-/-	-/-	-/-	-/-	-/-
Vernicia fordii (Hemsl.)	-/-	-/-	0.3–1.0	0.2–1.0	8–32	-/-	-/-	-/-
Zapoteca tetragona (Willd.)	Yes	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Species that tolerate continuously wet and waterlogged or temporarily flooded soils								
Calamus caesius (Blume)	1.5–3.0	28–56	-/-	-/-	-/-	-/-	-/-	-/-
Cerbera manghas (L.)	-/-	-/-	2.2	2.2	71	-/-	-/-	-/-
Combretocarpus rotundatus (Miq.)	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Dyera polyphylla (Miq.)	5.4–14.0	100–259	-/-	-/-	-/-	-/-	-/-	-/-
Erythrina excelsa (Baker)	Yes	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Euterpe oleracea (Mart.)	-/-	-/-	-/-	-/-	-/-	0.2–3.8 (Su)	0.1 –2.4	2–50
Melaleuca cajuputi (Powell)	Yes	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Metroxylon sagu (Rottb.)	-/-	-/-	-/-	-/-	-/-	15–24 (St)	9.6–15.3	201–321
Fleroya ledermannii (K.Krause)	2.7–3.2	49–59	-/-	-/-	-/-	-/-	-/-	-/-
Nypa fruticans (Wurmb.)	-/-	-/-	-/-	-/-	-/-	3–22 (Su)	1.9–14.0	40–295
Palaquium ridleyi (King & Gamble)	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Pentadesma butyracea (Sabine)	-/-	-/-	0.6–8.0	0.6–7.9	20–258	-/-	-/-	-/-
Phoenix reclinata (Jacq.)	Yes	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Sandoricum koetjape (Burm.f.)	-/-	-/-	-/-	-/-	-/-	Yes	-/-	-/-
Sesbania bispinosa (Jacq.)	8.0–17.0	148–315	-/-	-/-	-/-	-/-	-/-	-/-
Spondias mombin (L.)	0.2–0.6	4–10	-/-	-/-	-/-	-/-	-/-	-/-
Symphonia globulifera (L.f.)	Yes	-/-	-/-	-/-	-/-	-/-	-/-	-/-

Note: -/- no data available

Seventeen species are potentially suitable for bioenergy activities on wet land and land which is regularly flooded (Table 1). Three tree species tolerate brackish environments, namely *Cerbera manghas* (L.), *Nypa fructicans* (Wurmb.) and *Melaleuca cajuputi* (Powell). The energy yield potential of these species ranges between 71 GJ and 295 GJ ha^{-1} yr^{-1} (no data for *Melaleuca cajuputi*, Figure 1, Table 2). *Calamus caesius* (Blume) and *Symphonia globulifera* (L.f.) are adapted to wet soils rich in organic matter, while *Combretocarpus rotundatus* (Miq.) Danser*, Dyera polyphylla* and *Palaquium ridleyi* (King and Gamble) can grow on permanently wet organic soils (i.e., peatland). Although peatland species produce raw material for bioenergy activities, data on productivity and energy yields are rarely reported, with productivity data found only for *Dyera polyphylla* (Table 2). The remaining nine tree species presented in Table 2 tolerate flooding and produce biomass, bio-oil and sugar. Again, although information found on yields and productivity are minimal, the estimated energy output of some species may be too low for bioenergy activities (e.g., *Euterpe oleracea* (Mart.)*, Fleroya ledermannii* (K.Krause)*, Spondias mombin* (L.)), while the estimated productivity of *Pentadesma butyracea* Sabine and *Sesbania bispinosa* (Jacq.) seems to be promising for bioenergy activities (Table 2). Other species in this group are promising bioenergy crop candidates, but information on their productivity is not readily available (Table 2).

5.4 Discussion

The species presented that tolerate acidic soils and droughts are known and often used to produce raw material for bioenergy in tropical countries (Biswas et al. 2011; Atabani et al. 2013; Borchard 2017). However, initiatives that aim to produce bioenergy require silvicultural information and yield data. The information presented here can be used to assess the economic feasibility of bioenergy projects and cropping system types (Gruenewald et al. 2007; Ramachandran Nair et al. 2009; Vieira et al. 2009). Silvicultural and yield data are scarce for tropical tree species adapted to permanently wet and regularly flooded environments, but such data are required to develop feasible bioenergy strategies for wetlands (e.g., peatland). Two reasons could explain this knowledge gap: (i) limited interest in most of these tree species, except for sugar- and starch-producing palm trees (*Metroxylon sagu, Nypa fructicans*); and (ii) a lack of machinery for harvesting (Wichtmann et al. 2016). To avoid competition between food production and the production of raw materials for bioenergy, non-food crops should be cultivated on less productive land (e.g., eroded soil) (Balat M and Balat H 2009; German National Academy of Sciences Leopoldina 2012; Borchard et al. 2017).

The simplest approach to rehabilitating eroded land is the establishment of plantations (Chazdon 2003). Optimizing initial plant growth on eroded land for biomass production may require the application of fertilizer, which can cause the emission of N_2O (Popp et al. 2011; German National Academy of Sciences Leopoldina 2012). A less-assessed, but promising, way to reduce the amount of N-fertilizer is to mix non-leguminous and leguminous crops (e.g., *Elaeis oleifera* (Kunth) Cortés and *Pongamia pinnata*). Rehabilitation may require initial site preparation by planting species that can shade out weeds, fix nitrogen and improve soil organic matter (Chazdon 2003). Trees suitable for site preparation are fast-growing, nitrogen-fixing species, e.g., *Calliandra calothyrsus* (Meisn.), *Gliricidia sepium*, and *Zapoteca tetragona* (Willd.). The cultivation of non-native tree species risks invasive competition (Ziller and Howard 2008; Chimera et al. 2010; Richardson and Blanchard 2011). Thus, introducing for example species native to Africa (i.e., *Croton megalocarpus* (Hutch)) and America (i.e., *Spondias mombin*) to Southeast Asia and could have negative impacts on biodiversity and environmental services.

The rehabilitation of wetlands requires the selection of species that can tolerate wet soils and are adapted to natural conditions of peat swamp forests (e.g., *Dyera polyphylla*) (Wichtmann et al. 2016), yet there is limited information available on suitable trees for peat-swamp rehabilitation activities. In this study, bioenergy yields are compared to those of palm oil trees (*Elaeis guineenis*), which produce 3 Mg–6 Mg bio-oil ha^{-1} yr^{-1} (Wahid et al. 2005; Wicke et al. 2008; Verheye 2010), equivalent to an energy output of 90 GJ–194 GJ ha^{-1}. Most of the assessed species have the potential to produce raw material (*Palaquium ridleyi*, *Sandoricum koetjape* (Burm.f.)) generating the same level of energy. For some species, very high yields have been reported (e.g., *Dyera polyphylla*, *Metroxylon sagu*, *Pongamia pinnata*) (Azam et al. 2005; Manuri et al. 2016; Tata et al. 2017), potentially far above yields that are possible on degraded land. Other species with an estimated energy output of <90 GJ ha^{-1} yr^{-1} (i.e., the lowest energy output estimated for *Elaeis oleifera*) might not be feasible for bioenergy activities in tropical countries.

5.5 Conclusions

Tree species adapted to tropical wetlands and peatlands are potentially useful for bioenergy production, but published data are available only for a small number of species. The estimated bioenergy yields of the reviewed woody species are in the range reported for lignocellulosic biomass of energy crops cultivated in Europe, the USA and Brazil (110 GJ–370 GJ ha^{-1} yr^{-1}) (Faaij 2006; German National Academy of Sciences Leopoldina 2012). However, the values and coefficients used to estimate energy yields per unit area may fail to reflect the real variability of caloric values of biomass from various species (Demirbaş 1997; Günther et al. 2012). Thus, this study provides initial estimations, which should be verified by experiments to test the impact of silviculture and biorefinery methods on energy yields.

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