Scenarios for oil palm expansion in degraded and deforested lands in the Brazilian Amazon to meet biodiesel demand

Cenários para expansão de palma de óleo em áreas degradadas e desflorestadas na Amazônia brasileira para demanda de biodiesel

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ABSTRACT

Palm oil production for biodiesel in Brazil is characterized by its high productivity in some environmental conditions, under the Sustainable Palm Oil Production Program. The program seeks to avoid deforestation for oil palm cultivation, recover degraded lands, and focus on social inclusion and family farming. This paper assesses the possible socio-environmental impacts of the expansion of palm oil until 2030, focusing on land-use change and impacts. Land-use data came from the TerraClass initiative for the analysis of degraded forests using geoprocessing. We produced two oil expansion scenarios. The first one reflects current trends in palm oil production expansion and deforestation in Pará State (S1). The second one considers the exclusive use of deforested/degraded land for oil palm crops (S2). The results demonstrate that degraded/deforested land in the current palm oil-producing municipalities is only sufficient for the projected level of expansion for 2020, requiring a stronger public policy to recover degraded areas for oil palm cultivation with social inclusion of family farming.

Keywords: Palm oil. Degraded land. Biofuels. Amazon region.

RESUMO

A produção de óleo de palma para biodiesel no Brasil é caracterizada por sua alta produtividade em algumas condições ambientais no âmbito do Programa de Óleo de Palma Sustentável. Esse programa visa evitar o desmatamento para o cultivo do dendê, recuperar áreas degradadas e ter como foco a inclusão social e a agricultura familiar. Este artigo objetiva uma avaliação dos impactos socioambientais da expansão do óleo de palma até 2030, com foco nas mudanças e impactos no uso da terra. Os dados de uso da terra foram obtidos pelo TerraClass para análise de desmatamento e áreas degradadas usando análise de geoprocessamento. Produzimos dois cenários para a expansão do óleo de palma, refletindo as tendências atuais de expansão da produção de dendê no estado do Pará (S1) e o desmatamento considerando apenas o uso de terras desmatadas/degradadas para o cultivo de palma (S2). Os resultados demonstram que as áreas degradadas/desmatadas localizadas nos atuais municípios produtores de dendê são suficientes apenas para o nível de expansão projetado para 2020, exigindo políticas públicas mais fortes de recuperação de áreas degradadas para o cultivo de dendê com inclusão social da agricultura familiar.

Palavras-chave: Óleo de palma. Áreas degradadas. Biocombustíveis. Região Amazônica.

1 INTRODUCTION

Biofuels can be a suitable option for replacing fossil fuels since their use promotes sustainable development and mitigates climate change, but benefits and/or contributions to sustainability and climate change mitigation depend on biofuel production practices, because the associated greenhouse gas (GHG) emissions could be equivalent to, or even greater than the corresponding fossil fuel emissions, especially when the land-use policies in place and the management of biofuel production are not efficient (FARGIONE *et al*., 2008; LAPOLA *et al*., 2010; SCHARLEMANN; LAURANCE, 2008; SILALERTRUKSA; GHEEWALA, 2012; WICKE *et al*., 2008; YUI; YEH, 2013). First-generation biofuels can be a threat to ecosystems when uncontrolled expansion occurs (IEA, 2013).

Oil Palm (*Elaeis guineenses Jacq.*) is one of the most productive oilseeds in the world, yielding 368 tonnes/km^2/year (VILLELA, 2009, 2014), whilst soy, for example, only produces 42 tonnes/km^2/year (BRITO, 2007). Palm oil is largely produced in Malaysia and Indonesia, and these countries are responsible for approximately 90% of worldwide palm oil production. However, as mentioned, the environmental impacts of inappropriate land-use management and intensive deforestation can result in a substantial level of GHG emissions. In addition, the consequent displacement of small farmers and local communities has been significant (CARTE *et al*., 2019; LORIS, 2017). Hence, internationally, social and environmental Non-Governmental Organizations (NGOs) have criticized palm oil expansion because of these negative impacts (BROWN; JACOBSON, 2005; STATTMAN; MOL, 2014), prompting the creation of the RSPO (Roundtable on Sustainable Palm Oil), an international multi-stakeholder organization created in 2006. The RSPO develops criteria for palm oil production considering sustainability in addition to the production and economic use of palm oil (RSPO, 2007). About 20% of palm oil production in the world was certified by the RSPO in 2017 (CARLSON *et al*., 2017). Compared to these major palm oil-producing countries, the level of production in Brazil is still incipient, only 0.5% of global production.

In 2003, the Brazilian government launched the National Program for the Production and Use of Biodiesel (PNPB) to increase energy security through the sustainable production of biodiesel from oilseeds. This program has focused on social inclusion and regional development, with an emphasis on job and income generation and the sustainable use of various oilseeds. The implementation of this program should also have led to a reduction in GHG emissions. Financial incentives have been provided to foster the production of various crops. A mandatory mix of 2% of biodiesel (B2) from oilseeds and/or animal fats into fossil fuel-based diesel was initially required in 2008. This amount was then raised gradually to 5% (B5) in 2010, completed 10% in 2018 and there are plans to increase the percentage to 20% by 2030 (B20) (BRAZIL, 2012). At the start of the PNPB program, most of the sources for biodiesel consisted of soybean and animal fats. This indicates that despite the increase in oilseed production, the multi-use potentials of various crops have not yet been fully explored (SILVEIRA, 2013). Brazil cultivates a large diversity of feedstocks, such as castor bean, oil palm, soybean (*Glycine max L.*), jatropha, and sunflower in the most favourable regions of the country (the northeast, north, central-west, south and southeast regions, respectively) according to the PNPB. Furthermore, the environment of the Amazon region is suitable for the cultivation of oil palm and is considered to provide an opportunity to increase biodiesel crop production to meet domestic and international demands (SILVEIRA, 2013).

Because of its high productivity and high adaptability to the edaphoclimatic conditions in northern Brazil, the oil palm plantations have expanded in Pará State from 2010 (522 km^2) (with the start of the Sustainable Palm Oil Production Program) to 2019 (1,644 km^2), an increase of 32% in oil palm plantations for cropping (125 km^2/year in the period 2010-2019), based on data from IBGE/Sidra (2021). Considering the accuracy of official data sources to be limited, Brandão and Schoneveld (2015) used remote sensing techniques and estimated there were 2,556 km^2 of oil palm plantations in Pará in 2014. In general, estimates from other data sources have varied from 2,069/km^2 (BRANDÃO; SCHONEVELD, 2015) to 3,300 km^2 (GLASS, 2013).

Pará is the focus of oil palm expansion because of the suitability of the climate and the agricultural conditions, besides land availability (BENEZOLI *et al*., 2021; VILLELA, 2014). From 2016 to 2019, production in Pará accounted for more than 90% of Brazilian palm oil production (FURLAN JÚNIOR, 2006; IBGE/SIDRA, 2021).

Considering Brazil's background in biofuel production and use, as well as the increased domestic demand for palm oil (OLIVEIRA *et al*., 2013), the Brazilian government has been struggling to launch and enforce guidelines for sustainable palm expansion through the establishment of environmental programs such as the Agroecological Zoning (ZAE) regulations (EMBRAPA, 2010) and the Sustainable Palm Oil Production Program (BRASIL, 2010), both launched in 2010. According to those guidelines, only lands mapped as deforested or degraded (after 2008) should be used for oil palm expansion, aiming to avoid massive deforestation and its related impacts. The ZAE indicates that 297,000 km^2 of deforested and degraded land is available for cultivation of oil palm crops (approximately 5% of the Amazon Region), and 128,000 km^2 of these lands are available in Pará (EMBRAPA, 2010; VILLELA, 2014), implying a high availability of land and potential for palm oil production. For comparison purposes, the total area of Brazil is 8,520,000 km^2 and that of Pará state is 1,240,000 km^2 (the second-largest state in Brazil).

The use of degraded lands for the cultivation of bioenergy crops reduces the production of negative environmental and social impacts because these lands are unsuitable and economically unattractive for agricultural production (HUNSBERGER *et al*., 2014; LIMA *et al*., 2011; RFA, 2008; SCHUBERT *et al*., 2009; STATTMAN; MOL, 2014). The expansion of palm oil production into deforested lands can bring environmental and socio-economic benefits, such as a reduction in the importation of diesel, the creation of jobs and income, the promotion of social inclusion and regional development, and a positive role for degraded land and abandoned areas (ALMEIDA *et al*., 2020; BRANDÃO, 2019; COSTA, 2004; GLASS, 2013; LEES *et al*., 2015; STATTMAN; MOL, 2014), albeit oil palm plantations have poor habitat value for birds and only support modest carbon stocks in the Amazon region (ALMEIDA *et al*., 2020; LEES *et al*., 2015).

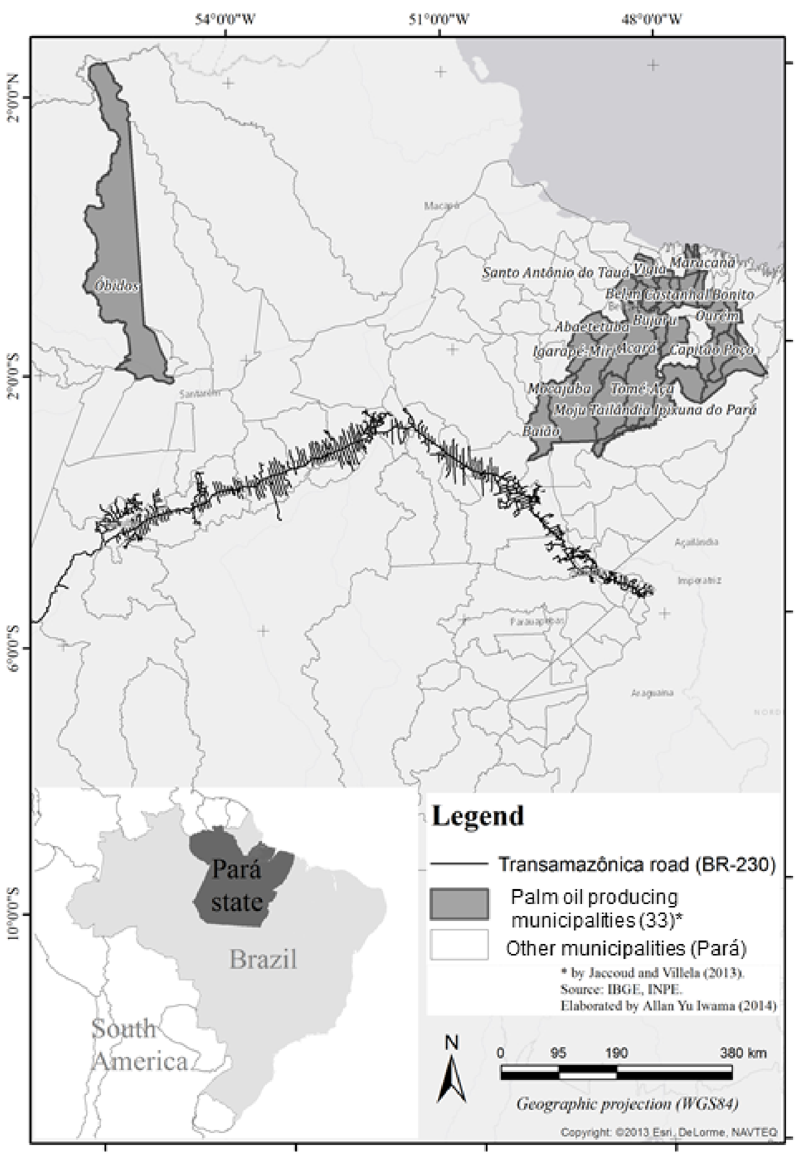
Given that context, the purpose of this paper is to develop and analyse two scenarios for palm oil expansion, focusing on the dynamics of the resultant land-use changes and their related GHG emissions, based on degraded forest and degraded land. Data provided by the TerraClass initiative (TERRACLASS, 2012), produced by remote sensing and GIS tools to identify potentially suitable land (KOH *et al*, 2011; RFA, 2008), can provide a strong background for evaluating available land for oil palm crops, considering current sustainability guidelines for the palm oil program in Brazil. Therefore, for each scenario, changes in land availability and distribution were analysed, aiming to assess multiple options to better support future decision-making in this field.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The Brazilian state of Pará is a focus for palm oil expansion because of the suitable environmental, social and economic conditions, especially in the palm oil-producing municipalities. Therefore, for this research, Pará and its producing municipalities were chosen as the study area. The state is in the eastern portion of the Amazon region, is Brazil's second-largest state and has 144 municipalities. The main economic activities are mining, logging, agriculture and cattle raising (BOLETIM REGIONAL DO BANCO CENTRAL DO BRASIL, 2013). The climate is tropical, with a mean annual temperature of 26°C and consistent rains throughout the year (see IBGE <http://www.ibge.gov.br/estadosat/>). The producing municipalities are in the north-eastern portion of the state, surrounding the capital city, Belém. Their main economic activity is agriculture (Figure 1), associated with the losses in ecosystem services in the last two decades because of the significant cropland changes (LI *et al.*, 2019). Figure 1 shows the study area which has been increasing during recent years (BRANDÃO; SCHONEVELD, 2015; EMBRAPA, 2010; FURLAN JÚNIOR, 2006; VILLELA, 2014).

Figure 1 | Study area – main palm oil producing municipalities in Pará state-Brazil



Source: Adapted from data by BRANDÃO; SCHONEFELD, (2015); JACCOUD; VILLELA, 2013.

Table 1 | Main palm oil producing municipalities in Pará state-Brazil

Municipality	*Abandoned pasture (ha)*	*Territory (ha)*	*% Aband. pasture*
Santa Luzia do Pará	18,320,1	132,487,3	13.8
Capitão Poço	26,518,5	281,720,2	9.4
Ourém	5,096,0	62,942,1	8.1
Garrafão do Norte	14,624,6	185,278,7	7.9
Ipixuna do Pará	24,646,9	539,715,3	4.6
Tomé-Açu	23,907,4	529,574,1	4.5
Baião	13,058,6	325,628,1	4.0
Bonito	2,235,6	58,766,0	3.8
Igarapé-Açu	3,110,3	83,157,5	3.7
Moju	32,427,4	996,099,9	3.3
Tailândia	13,979,1	456,799,0	3.1
Concórdia do Pará	1,754,2	73,631,6	2.4
São Domingos do Capim	3,991,6	174,170,9	2.3
Castanhal	2,426,2	107,239,0	2.3
São Francisco do Pará	1,051,1	49,803,2	2.1
Inhangapi	889,0	49,910,1	1.8
Santo Antônio do Tauá	916,4	56,402,2	1.6
Santa Maria do Pará	755,8	47,940,3	1.6
Terra Alta	330,9	21,651,8	1.5
Nova Esperança do Piriá	4,545,7	297,768,9	1.5
Santa Isabel do Pará	1,024,1	74,821,9	1.4
Bujaru	1,339,1	103,630,0	1.3
Nova Timboteua	575,1	51,672,0	1.1
Santa Bárbara do Pará	301,0	29,112,7	1.0
Acará	4,412,1	449,812,2	1.0
Abaetetuba	1,501,0	166,823,3	0.9
Mocajuba	754,4	88,373,1	0.9
Óbidos	22,595,1	2,841,885,6	0.8
Vigia	397,3	58,950,6	0.7
Igarapé-Miri	647,2	206,653,8	0.3
Benevides	29,4	18,428,9	0.2
Maracanã	66,6	81,075,5	0.1
Belém	43,7	111,910,2	0.0

Source: Adapted from data by BRANDÃO; SCHONEFELD, (2015); JACCOUD; VILLELA, 2013.

2.2 METHODOLOGY

To develop scenarios for oil palm expansion in degraded and deforested lands, the first step was to define these lands. For this paper, we assumed that degraded land that is suitable for oil palm cultivation is the land cleared of natural vegetation and is currently characterised by a low level of biodiversity (CÂMARA; VALERIANO; SOARES, 2006; FAO, 2013; GINGOLD *et al*., 2012); more specifically, land that the TerraClass initiative, based on data of the PRODES mapping of deforested areas in the Amazon, classified as 'abandoned pasture'. In other contexts, the concept 'degraded land' may be based on different criteria such as 'forest carbon', as in the case of oil palm expansion in Indonesia (GINGOLD *et al*., 2012).

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The methodology was organized into 3 steps: **Step 1** – geodatabase to produce overlay maps; **Step 2** – calculations of land conversion and carbon release; and **Step 3** – carbon release scenarios – Figure 2.

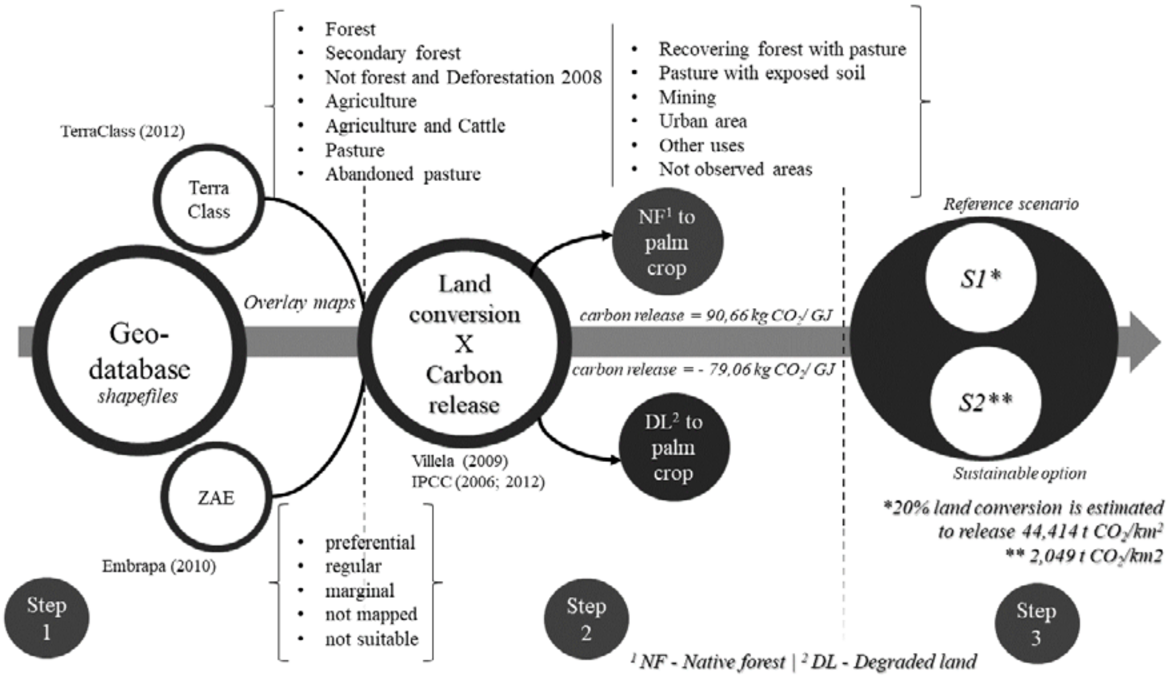


Figure 2 | Methodology following 3 steps for carbon release scenarios
Source: Prepared by authors.

Step 1. Data on deforested and degraded lands were collected from the TerraClass initiative (TERRACLASS, 2012). The TerraClass was developed by the Amazonia Regional Center (CRA) in partnership with the Brazilian Agricultural Research Corporation (Embrapa), which is responsible for qualifying deforestation in the Amazon as defined in Brazilian Law (Legal Amazon) and this provides important subsidies for a better understanding of land-use and land cover in the region. The land classification categories developed by TerraClass are: *Forest, Secondary forest, Not forest and Deforestation 2008, Agriculture, Agriculture and Cattle, Pasture, Abandoned pasture, Recovering forest with pasture, Pasture with exposed soil, Mining, Urban area, Other uses,* and *Non observed areas*. Abandoned pasture, which is deforested and/or degraded land according to the Sustainable Palm Oil Production Program, is the land class designated for oil palm expansion.

Step 2. Carvalho *et al*. (2015), with the support of geoprocessing techniques, analysed land-use availability to assess the real extent of land suitable for oil palm expansion available both in the current palm oil-producing municipalities and in Pará state as a whole. Their analysis served as support for scenario development. The land-use data were depicted in the form of polygons and were overlaid with the boundary of Pará state obtained from IBGE, enabling the spatial analysis of land-use.

Step 3. Two scenarios were developed based on these calculations. The oil palm plantation area reached 1,644 km^2 in 2019 (SIDRA/IBGE, 2021). Brandão and Schoneveld (2015) questioned the accuracy of data sourced from IBGE, considering its limited human and financial capacity and suggest the land demand of oil palm crops in 2014 was 2,556 km^2 (BRANDÃO; SCHONEVELD, 2015), and 3,300 km^2 through to 2020 (GLASS, 2013). Jaccoud and Villela (2013) estimated 6,000 km^2 of oil palm crops would be necessary to meet domestic demand in 2022. Based on that demand context and Villela (2014), the land demand for the scenarios was assumed to reach 10,000 km^2 by 2030 (Table 2).

Table 2 | *S1* (Reference) and *S2* (Sustainable) scenario assumptions based on several studies (BENAMI *et al*., 2018; BRANDÃO *et al*., 2021; BRANDÃO; SCHONEVELD, 2015; BRITO, 2017; GLASS, 2013; JACCOUD; VILLELA, 2013; LAPOLA *et al*., 2010; VIEIRA *et al*., 2014; VILLELA, 2014).

Scenario S1	*Scenario S2*
Land demand of 10,000 km2 up until 2030 (BRANDÃO; SCHONEVELD, 2015; GLASS, 2013; JACCOUD; VILLELA, 2013; LAPOLA et al., 2010; VILELLA, 2014)	Land demand of 10,000 km2 up until 2030 (BRANDÃO; SCHONEVELD, 2015; GLASS, 2013; JACCOUD; VILLELA, 2013; LAPOLA et al., 2010; VILELLA, 2014)
Commitment to deforestation reduction is not always fulfilled (VIEIRA et al. 2014); 20% of native forest is converted on private properties (BRITO, 2017)	Deforestation is forbidden, only degraded and deforested land is used (ALMEIDA et al., 2020; BENAMI et al., 2018; FURUMO; AIDE, 2017; WICKE et al., 2011)
Monoculture cultivation system	The monoculture cultivation system is avoided and replaced by intercropping techniques, favouring social inclusion; suitable for areas smaller than 0.1 km2 (ALMEIDA et al., 2020; BRANDÃO, 2019; BRANDÃO; SCHONEVELD, 2015; BRANDÃO et al., 2021)
Only the current producing municipalities are considered for the expansion due to the already implemented infrastructure	Other municipalities are considered

Source: Elaborated by the authors.

Based on Villela (2009, 2014) and IPCC Guidelines for National Greenhouse Gas Inventories (2006, 2012), the carbon release values were adopted for GHG emission calculations using the data organized in an Excel spreadsheet: GHG_r (reduction) = GHG_e (emission, fossil chain) – GHG_e. The models are the simplified calculation of the current model that favours market practices and product logistics close to the highways. Therefore, the discussion based on the analysis considers this limitation when analysing palm oil production and deforestation.

The land-use areas for each municipality, cross-checked with ZAE data. In addition, based on the analyses for scenario *S2*, new areas for oil palm expansion are proposed. As mentioned in the introduction, the ZAE has mapped the more suitable areas for palm oil production in Pará, according to the following land classifications: preferential, regular, marginal, not mapped, and not suitable; and considered two levels of development, B and C. Level B corresponds to agricultural development with fewer technology applications, whilst C represents a more highly technological approach to agriculture. The ZAE identifies the most suitable areas for planting these crops whilst taking into consideration the climate and soil characteristics, and the locations of native vegetation areas, conservation areas, Indigenous territories, and protected areas (BRASIL, 2010).

3 RESULTS AND DISCUSSION

3.1 CONCEPTUALIZING THE REFERENCE (S1) AND SUSTAINABLE OPTION (S2) SCENARIOS FOR GHG EMISSIONS

Scenarios are important tools to support public policy development. This approach is not intended to predict the future but to study various options for possible adoption and prepare palm oil stakeholders to take action to avoid negative impacts in the expansion process (MARCIAL; GRUMBACH, 2006). Scenarios are being used in climate change research according to the following classification: Business as Usual or reference situation, and other alternative scenarios that require different and innovative actions. Therefore, scenario development for palm oil is an important approach to study alternatives for the future and is being used for bioenergy expansion and feasibility research, aiming at reducing CO_2 emissions from land-use conversion and at fostering regional development (SACHS, 2007).

The conversion of native forests into palm oil plantations, which has been observed in Indonesia and Malaysia in recent years, causes the release of huge amounts of CO_2 into the atmosphere. However, the conversion of deforested and degraded land into palm oil plantations releases substantially less CO_2. That difference is associated with the role of soils as a carbon reservoir and is strongly dependent on land use and management practices. Native forests have a greater amount of stored carbon than areas of degraded vegetation. When land is converted to another use, carbon is released into the atmosphere, contributing to the greenhouse effect (FARGIONE *et al*., 2008; GIBBS *et al*., 2008; IEA, 2009; LAPOLA *et al*., 2010; SCARLAT; DALLEMAND, 2011). Brinkmann (2009), IPCC (2006, 2012) and Villela (2014) have reported that the carbon stocks contained in the soil and biomass of native forest and degraded land are, respectively, 174.7 tonnes C/ha and 49.2 tonnes C/ha. According to several studies (ALMEIDA *et al*., 2020; BERNOUX; VOLKOFF; CERRI, 2002; HASSAN *et al*., 2011; SAATCHI *et al*., 2011; SISTI *et al*., 2004; SOMMER; DENICH; VLEK, 2000), native forest carbon stocks are approximately 158 tonnes C /hectare, whilst the soil carbon stocks of degraded land average 52 tonnes C /hectare. The carbon stock of an oil palm crop is estimated to vary between 35 tonnes C/ha and 55 tonnes C/ha (BRINKMANN, 2009; CARLSON *et al*., 2012; GERMER; SAUERBORN, 2008; HENSON; RUIZ; ROMERO, 2012; IPCC, 2006, 2012; YUI; YEH, 2013).

According to the IPCC (2006, 2012), a mean carbon stock value can be converted into units for emissions into the atmosphere by multiplying the value by 44/12, that is the ratio between the molecular weight of CO_2 and the atomic weight of C. Therefore, values, previously calculated by Villela (2009) and used as a basis to develop the scenarios calculations in this paper, are:

"Native forest conversion to oil palm crop, carbon release = 90.66 kg CO_2/ GJ

Degraded land conversion to oil palm crop, carbon release = - 79.06 kg CO_2/ GJ"

The first scenario (*S1*) was a Reference that limits the new forest conversion to palm crop to 20% on any given landholding in compliance with the Brazilian Forest Law (BRITO, 2017), even though there are major challenges in the determination of what is legally convertible or not in the management of secondary forests (BRANDÃO *et al*., 2021; VIEIRA *et al*., 2014). Based on that assumption, if the legal limit of 20% of the forest land on properties is converted to plant oil palm it is estimated to release 44,414 t CO_2/km^2, whilst the conversion of degraded land only releases an estimated 2,049 t CO_2/km^2.

These results can provide elements to orientate oil palm development, considering its indirect influence on other land uses. Despite the concern that developing pasture lands into oil palm may have induced cattle-raising activity to relocate to the forest frontier, and thus resulted in indirect deforestation (BENAMI *et al*., 2018; LAPOLA *et al*., 2010), our results may be overestimated, since intact forest and secondary vegetation conversion have been at a much lower rate than in other tropical regions of oil palm expansion (ALMEIDA *et al*., 2020; BENAMI *et al*., 2018; FURUMO; AIDE, 2017; WICKE *et al*., 2011).

The second scenario (*S2*) is a sustainable option, following the Sustainable Palm Oil Production Program and ZAE recommendation to only convert deforested and degraded land to oil palm crops. The identification of degraded land that is suitable for oil palm cultivation is at the core of sustainable expansion. In this scenario, the conversion of deforested and degraded land is estimated to release 2,049 t CO_2/km^2.

The GHG emissions under the *S1* and *S2* scenarios were presented as the total emissions of GHG from land-use conversion under the two scenarios up until 2030.

The conversion of 20% of land from native forest to palm cultivation, in the *S1* scenario, results in GHG emissions of 60.10^6 t CO_2 eq. in the year 2030, whilst the emissions for the *S2* scenario (no conversion of native forests) were calculated as 302.10^6 t CO_2 eq, less than the GHG emissions in the S1 scenario. Note that even in the *S2* scenario, deforestation is still considered a risk because the Sustainable Palm

Oil Production Program requirements do not guarantee by law that oil palm cultivation will be placed in deforested and degraded land. In addition, only the current 33 producing municipalities near Belém, the capital of the state, are considered for expansion because the infrastructure for palm oil production already exists so there are no extra investments required to create new processing plants (JACCOUD; VILLELA, 2013).

Scenario *S2* follows sustainable models of development, proving that palm tree cultivation on deforested and degraded lands can reduce the GHG emissions from land-use conversion, further reinforcing the benefit of reducing the level of deforestation for bioenergy purposes.

Both scenarios were created to reflect two current situations, without considering different decision-makers strategies for different uses of degraded areas or variations in deforestation monitoring. Therefore, these scenarios mainly serve to visualize different situations that could support the Sustainable Palm Oil Production Program.

3.2 SCENARIOS FOR PALM OIL PRODUCTION CONSIDERING THE SPATIAL DISTRIBUTION OF LAND-USE

Considering the *S1* scenario assumptions, palm oil production places considerable pressure on land use because the focus is on the 33 municipalities that already produce palm oil, which corresponds to the aforementioned 2,882.97 km^2 of degraded and deforested land mapped by TerraClass (of the entire 27,414.02 km^2 in Pará State). If only this amount of land is available, other lands that are not deforested or degraded will likely be used for expansion. However, there is sufficient degraded land that could be used for expansion located outside the producing municipalities. Land pressure is reduced under the *S2* scenario since those other lands could be used for expansion.

The *S1* scenario represents the current production model, which corresponds to a non-sustainable option. Despite the low forest conversion to oil palm plantation (BENAMI *et al*., 2018), there is a potential deforestation risk insofar as landowners may legally convert 20% of a given property (BRITO, 2017).

Conversely, the *S2* scenario represents a sustainable option due to the non-existence of deforestation to make way for palm oil crops, and the availability of sufficient land to meet the required demand for expansion. However, it should be considered that the use of more remote lands for production can create extra costs associated with changes in the palm oil production model, such as the construction of new processing plants in remote areas. The new infrastructure will be required because the available degraded and deforested lands are scattered throughout the state and outside the current producing municipalities (VILLELA, 2009, 2014). New processing plants can cause economic and environmental impacts and social conflicts in association with the development of infrastructures such as roads, the demand for new workers, the relationship with local communities, and even food security issues because small farmers are not capable of growing food crops together with oil palm, and consequently, food prices tend to increase (GLASS, 2013; HUNSBERGER *et al*., 2014; STATTMAN; MOL, 2014). An important factor influencing oil palm expansion is road proximity because new crops are more likely to be established near roads (YUI; YEH, 2013).

Figure 3 depicts the TerraClass land classification for the municipalities in Pará State, cross-referenced with the ZAE. The preference (of producers) for oil palm cultivation in the preferential zoning areas, represented by scenario *S1*, can result in the overexploitation of these regions, causing soil erosion, deforestation and losses of biodiversity, as well as impacts on local communities. There is enough land located in preferential zones for palm oil expansion available outside of the producing municipalities, at both B and C development levels that can be used for expansion in scenario *S2* conditions.

Figure 3 | Deforested/degraded land, cross-referenced with the ZAE: (a) management level B (low technology) and (b) management level C (high technology) and municipalities with > 100 km² of available degraded land in ZAE-designated preferential areas for oil palm (São Félix do Xingu, Itaituba, Altamira and Tucumã). Family farming refers to municipalities registered in the palm oil programme in that category (GLASS, 2013).

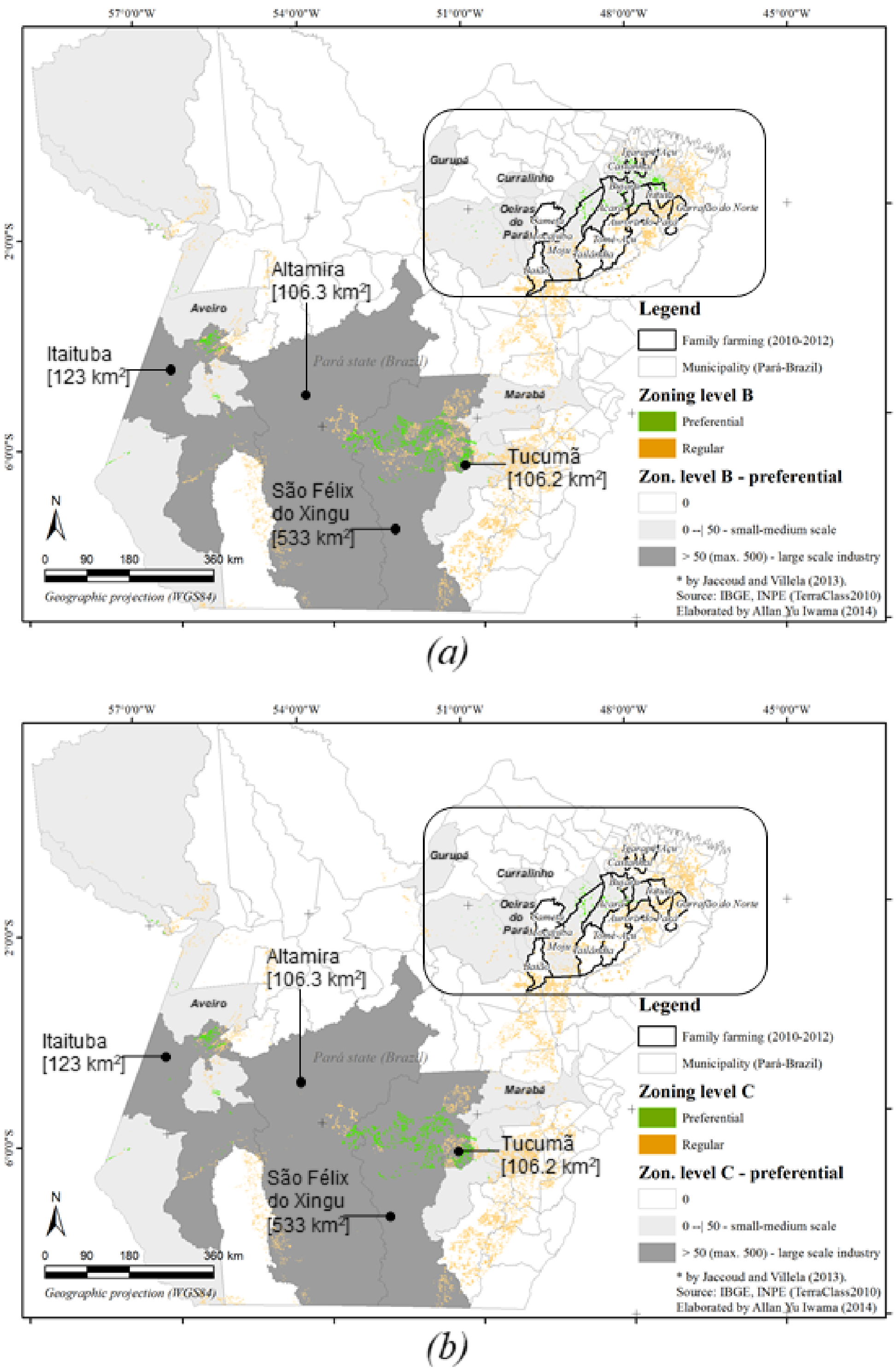
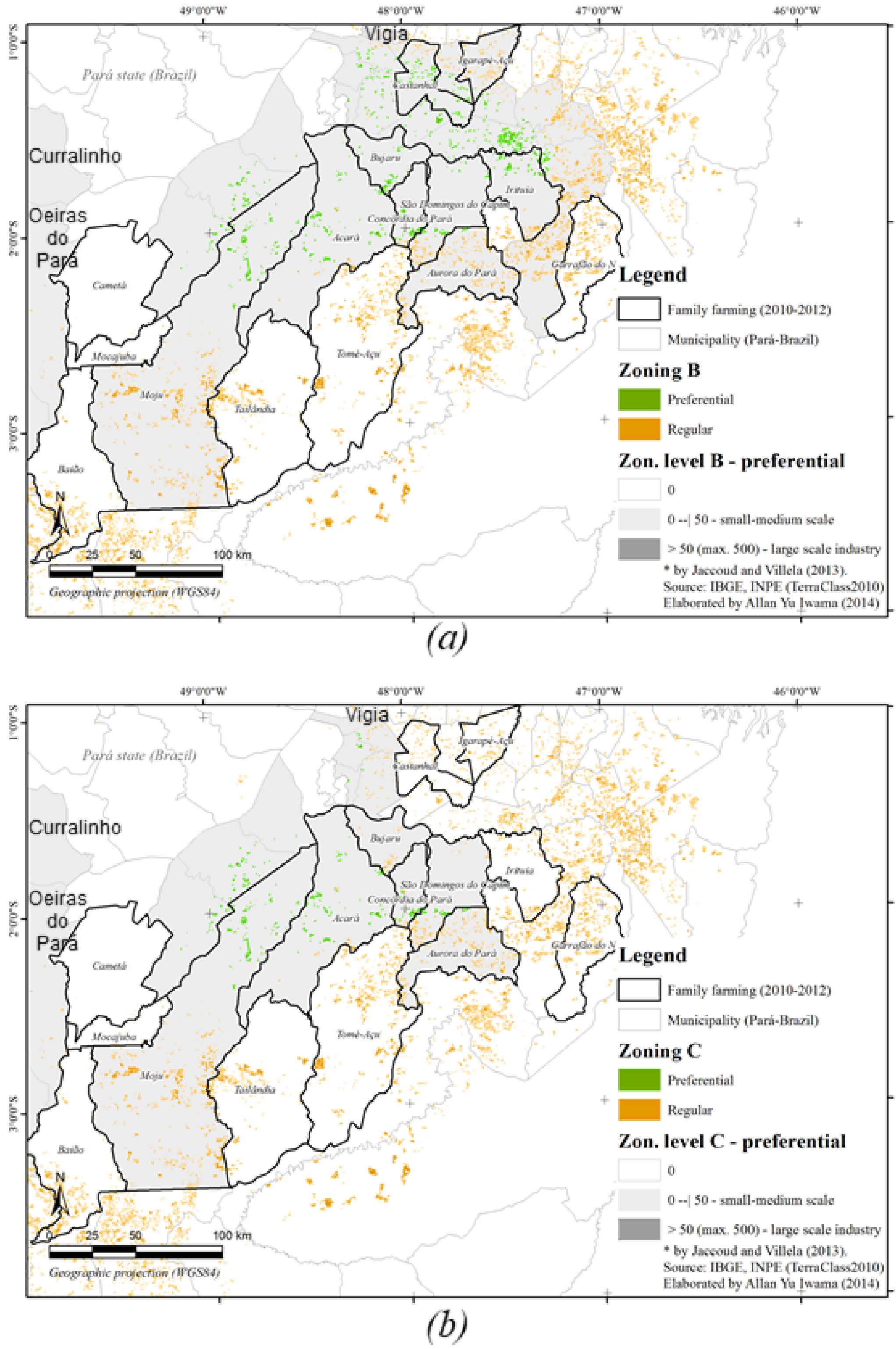


Figure 3 also shows that potential areas of land larger than 100 km² are located in just a few municipalities (São Félix do Xingu, 533 km²; Itaituba, 123.3 km²; Altamira, 106.3 km²; and Tucumã, 106.2 km²), including both ZAE levels, B and C (Figures 3a and 3b).

The mapping process shows that there are 862 km^2 of areas in the Preferential zoning category for smallholder oil palm crops, and 6,729 km^2 of degraded and deforested land in Regular zoning areas for the same crops. Therefore, altogether we found 7,591 km^2 of land available for small farmers (Figure 3 and Figure 4).

Figure 4 | Deforested/degraded land, crosschecked with ZAE: (a) land in municipalities in north-eastern Pará State (smallholder farming) under management level B and (b) land in municipalities in north-eastern Pará State under management level C.



Source: IBGE (2013) and TerraClass. Family farming municipalities are those registered as such in the palm oil programme (GLASS, 2013).

There are municipalities with areas of potential land ranging from 0-50 km2 located in the north-eastern part of Pará State (Figures 4a and 4b), with areas of varying ZAE management levels. Areas with less than 0.1 km2 (or 10 ha), suitable for small farmers are proposed for the S2 scenario. Municipalities with degraded land of less than 0.1 km2, Gurupá, Curralinho, Oeiras do Pará, Vigia and Aveiro show potential for small farmers and should be considered for palm oil production and small farmer activities expansion as well. Municipalities that are integrated with small farmers (family farms) are already notoriously subject to social conflicts (Figures 4a and 4b). According to Glass (2013), small farmers have improved their income by growing oil palm; however, their quality of life is still subject to question mainly because of the inconsistency between the initial discourse in the oil palm contracts and the later practices (TAVARES; MOTA, 2020).

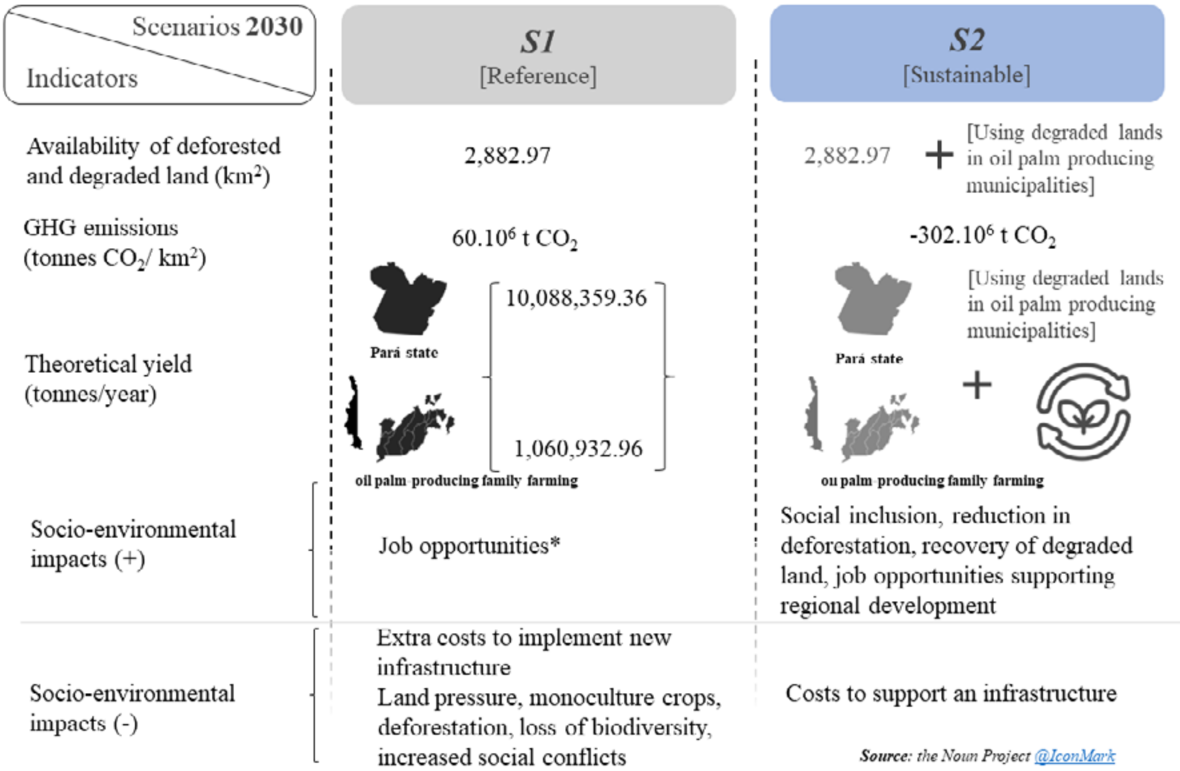
The use of degraded and deforested areas of land has implications beyond GHG emissions. A number of these areas are smaller than 0.1 km^2 and that can pose a challenge because they are fragmented, and it is costly to maintain small crops of oil palm. On the other hand, the use of degraded land for the expansion of palm oil production also has the potential for positive environmental impacts (UNEP, 2007), including recuperating the productive capacity of the degraded land, restoring its function as an ecosystem services provider (LI *et al*., 2019) and promoting an increase in the carbon stock of the cultivated land. In addition, small and scattered areas of degraded lands could be cultivated by small farmers, thereby improving livelihoods in rural areas by providing social and economic benefits (CBD, 2009). Examples of other problems that the cultivation of oil palm on degraded land can present include difficulties associated with the degradation of growing conditions, which may cause a requirement for greater amounts of fertilizers and longer periods to improve productivity because of the lower yields compared to production on newly deforested areas, and there may be difficulties associated with land ownership issues (WICKE *et al*., 2008).

To complete the land availability analysis, the potential yield from oil palm cultivation was calculated based on the available area and an annual palm oil yield of 3.68 tonnes per hectare (368 tonnes/km^2) (BRITO, 2007). We determined that the potential yield is 10,088,359.36 tonnes/ for deforested and degraded land in Pará State. In 2019, the yield was 2,543,814 tonnes, while in the palm oil-producing municipalities, the potential yield is 1,060,932.96 tonnes/year. If the demand for palm oil production continues to increase until 2030, other lands could be converted to oil palm cultivation, so it is necessary to keep a close watch on adherence to principles of sustainability and the associated social conditions (BRANDÃO *et al*., 2021; TAVARES; MOTA, 2020).

Thus if, as in the case of the S1 scenario, land conversion is not restricted to the use of degraded/ deforested land only, there are serious are risks of deforestation, biodiversity losses and impacts on local communities occurring. Under the *S2* scenario, however, the land conversion target is achieved sustainably. The *S2* scenario corresponds to a possibility for the near future that envisages a real commitment to sustainable development – Figure 5.

This paper uses a spatially explicit exploratory model, considering the edaphoclimatic conditions and the availability of land. This limitation implies the spatial distribution of municipalities that mainly serve capital’s model and arguments to prioritise areas close to the roads, facilitating production and logistics. Despite the simplicity of the model for predicting the expansion of oil palm and the calculation of emissions, it provides elements for the discussion on the expansion of oil palm and degraded land use, especially with the incentives instituted by the Biodiesel Law in 2005 that started oil palm investments in Pará, focused largely on the municipalities south of Belém like Tailândia, Moju, Tomé-Açu, Acará, Concórdia do Pará, and São Domingos do Capim and led by large national and international corporations such as Biopalma, the ADM and a joint venture between Petrobras and Galp (BRANDÃO; SCHONEVELD, 2015).

Figure 5 | *Scenarios S1 (reference) and S2 (sustainable) to 2030 and socio-environmental impacts*



4 CONCLUSIONS

Scenarios for palm oil expansion were evaluated to support the development of a more sustainable path for palm oil expansion. Under the *S1* scenario, as a result of the conversion of native forest conversion to oil palm cultivation, accumulated GHG emissions would reach 60.10^6 t CO_2 by 2030. However, the *S2* scenario, based on the conversion of degraded and deforested land to palm, limits GHG emissions in 2030 to 302.10^6 t CO_2 less than the amount released in the *S1* scenario. These results show that there is a need for the development of new infrastructure for additional oil processing plants in the state to place palm oil crops in other lands outside the present producing areas and reduce the GHG emissions and other environmental impacts related to deforestation. Besides, the amount of degraded and deforested land located within the current palm oil-producing municipalities is only sufficient for the projected level of expansion in 2020. Therefore, under the *S1* scenario, other land areas, including native forest and protected areas, are at risk of being used to accommodate oil palm expansion, leading to further deforestation and various environmental and social impacts, showing that *S2* scenario is a sustainable option. In addition, the use of deforested and degraded land can help promote the social inclusion of small farmers and local communities, creating job opportunities and improving income levels, thus supporting regional development (BRANDÃO, 2019; BRANDÃO *et al*., 2021; CORDOBA *et al*., 2019; TAVARES; MOTA, 2020). However, field assessments are necessary to evaluate the processes required for the development of these degraded land areas.

The results also demonstrate the need for sound land-use policies for planning and monitoring the expansion of palm oil production, and the need to assess the quality and potential of lands that can be used for this expansion. In addition, the results reinforce the suitability of the *S2* scenario as an alternative for the sustainable development of palm oil production in Brazil. The development of scenarios for palm oil expansion based on the support and guidelines of the ZAE and the Sustainable Palm Oil Production Program has proved to be a beneficial tool for environmental planning. The *S2* scenario is a better option to follow if Brazil wants to become a leader in sustainable palm oil production. However, these scenarios require a transformation of the current production model for palm oil and depend on the support of public policies, especially regarding land-use dynamics, as pointed out by other studies (ALMEIDA *et al*., 2020; BENAMI *et al*., 2018; BRANDÃO, 2019; BRANDÃO; SCHONEVELD, 2015; BRANDÃO *et al*., 2021).

Further research on the development of degraded lands is required as well as on social aspects related to smallholder production. Environmental education programs must be developed involving all stakeholders to achieve sustainable palm oil development in Brazil.

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