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Recognizing social forestry's role in bioenergy optimization through geospatial fuzzy-multicriteria analysis

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ABSTRACT

Current bioenergy development has emphasized on degraded land, since the sustainability of bioenergy in the forest sector remains a subject of debate related with emissions and deforestation risk. Thus, this study aims to open new perspectives of how degraded land and social forestry can be potentially combined to significantly impact the energy transition and environmental-societal enhancement. Considering sustainability of Bali as a small island with its unique customary governance structure, a model of biomass energy optimization using geospatial fuzzy-multicriteria analysis was developed to select potential green energy source sites. Firstly, potential degraded land and social forestry were mapped to identify potential feedstock, then normalized using Euclidian Distance and Fuzzy Logic based on identified five sustainability criteria. They are availability of raw material, road, port, transmission, and demand proximities. Meanwhile, using identified three restriction criteria, i.e. protected area, slope and land-use restrictions, a restriction map was developed. The two maps were then integrated using Geospatial-based multicriteria analysis, fuzzy logic and Analytical Hierarchy Process (AHP) weighting method, to further identify potential green energy source map. The integration shown a significant increase of 60 % in land availability for bioenergy development. Results of study recognized potential 36,527 ha of degraded land; 21,671 ha of social forestry; and 40 optimal locations for bioenergy facilities, considering various spatial and temporal criteria. To conclude, the identified 120 social forestry sites in Bali involving 78,385 household provide opportunity to a community based socio-economic coupled with revitalizing environment efforts, which lead to massive net zero emissions community participation. Further, the integration of social forestry and degraded land should be highly recommended to policy maker in bioenergy development.

Introduction

Background and motivation of the study

The quest for sustainable energy sources gains relevance as the world addresses the climate crisis. Bioenergy stands as a promising renewable energy source required for attaining energy security and independence beyond the oil era (Chung, 2013; Hess et al., 2016; Lewandowski, 2015). Bioenergy, including traditional biomass usage, dominates the global renewable energy landscape, contributing about 12 % to final energy consumption, as reported by the International Renewable Energy Agency (IRENA, n.d.). IRENA projects a significant increase in bioenergy consumption, almost tripling from 54 EJ in 2018 to 153 EJ by 2050. Therefore, optimizing biomass energy production becomes an indispensable pathway forward in addressing energy needs sustainably.

The sustainability of bioenergy remains a subject of debate, emphasizing significant contrasts in perspectives on managing the entire supply chain. Especially when it comes to resource management. Wood-based biomass statistically to be the main resource globally, with the EU and UK being the major consuming regions (IRENA, n.d.). However, numerous studies continue to raise concerns about the long-term environmental impact of forest-based bioenergy production. This debate spans between studies suggesting that the risk of forest bioenergy escalates long-term greenhouse emissions due to carbon debt (Marland & Schlamadinger, 1995; Mitchell et al., 2012; Schlamadinger & Marland, 1996), and those advocating the opposite view that bioenergy considerably reduces emissions as an alternative to fossil fuels. (Bentsen, 2017;

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Nomenclature

AHP	Analytical Hierarchy Process
GIS	Geographic Information System
RUED	Rencana Umum Energi Daerah / Regional Energy General Plan
BPKH	Balai Pemantapan Kawasan Hutan / Forest Area Consolidation Agency
DKLH	Dinas Kehutanan dan Lingkungan Hidup / Forestry and Environment Service
DEM SRTM	Digital Elevation Model Shuttle Radar Topographic Mission
DEMNAS BIG	Digital Elevation Model Nasional Badan Informasi Geospatial
SHP	Shapefile
PLN	Perusahaan Listrik Negara / State Electricity Company
NGO	Non-Governmental Organization
IPP	Independent Power Producer
CR	Consistency Ratio
SARBAGITA	Denpasar, Badung, Gianyar, and Tabanan Metropolitan

Nabuurs et al., 2017). Nevertheless, continuous research efforts have actively addressed this issue over time, resulting in the emergence of contradictory evidence and innovation among studies that have effectively reduced the perceived risk of the initial hypothesis (Giuntoli et al., 2022). Hence, a new perspective has emerged in overcoming the bioenergy supply instability challenge by involving careful risk assessment of forests as a potential source of biomass.

Biomass raw materials instability has persistently hindered the bioenergy supply chain (IRENA, n.d.). Numerous studies aim to assess the sustainability of these raw materials. Previous research, primarily motivated by environmental concerns, heavily focused on degraded land as the key pathway for bioenergy development (Milbrandt & Overend, n.d.; Jaung et al., 2018; Nijsen et al., 2011). This focus on degraded land comes from its definition as areas affected by activities like deforestation, mining, or agriculture, contributing to perceived environmental benefits. However, there is still a lack of study in evaluating the potential of the forest sector to bioenergy. The growing clarity regarding the ambiguous risks associated with forest bioenergy in academic discourse (Bentsen, 2017; Nabuurs et al., 2017) presents an opportune moment. It opens a window to redefine the role of forest bioenergy in biomass development alongside degraded land, emphasizing a strict commitment to environmental sustainability criteria.

Numerous studies affirm that sustainable forest management stands as a viable solution. Research focusing on social forestry or community-based forest management consistently highlights its superior effectiveness, producing better environmental and socio-economic outcomes compared to other alternatives (Newton et al., 2015; Octavia et al., 2022). The success of social forestry has notably positioned it as a key element within Reducing Deforestation and Forest Degradation Emissions (REDD+) policy strategies across various nations (Newton et al., 2015; Octavia et al., 2022). Evidence from multiple studies further supports this premise; for example, in Tanzania, community-managed forests demonstrate greater efficacy in preserving forested lands compared to exclusive national government management (Blomley et al., 2008). Similarly, community forest management in Nepal is associated with significant growth in forest area (Gautam et al., 2002).

A multi-criteria decision analysis (MCDA) as a state-of-the-art method capable of considering various conflicting criteria is recognized in renewable energy planning, as a field laden with uncertainty and high complexity (Loken, 2007). Over the years, diverse MCDA methods have been proposed. This study delves into the specific MCDA method in the classification of Value Measurement Models categorized by Belton and Steward (Belton & Stewart, 2012). Through this approach, different criteria will be assessed in terms of their influence on the total score, combined by the Analytical Hierarchy Process (AHP) developed by Saaty (Saaty, 1990), as a method for assigning value functions with the use of pair-wise comparisons (Greening & Bernow, 2004; Jayarathna et al., 2022). Meanwhile, resource management in renewable energy planning compels MCDA to evaluate criteria involving spatial and temporal uncertainty (Rodríguez et al., 2017), such as leveraging geographical data for widely dispersed biomass, minimizing transportation costs, and other economic, social, and environmental criteria. Therefore, the use of Geographic Information Systems (GIS) serves as a valuable tool to assess the potential availability of biomass raw materials (Beccali et al., 1998), as well as the challenges of adapting the AHP method in dealing with spatially complex uncertainties (Jaung et al., 2018; Kordi & Brandt, 2012), prompting this study to integrates fuzzy logic with AHP to evaluate spatial and temporal uncertainty criteria. Studies such as Rodríguez et al. (Rodríguez et al., 2017) and Cebi et al. (Cebi et al., 2016) concluded that employing fuzzy logic theory for modeling enhances the accuracy of biomass energy plant location suitability analyses.

Research gaps and aims of the study

A discourse on the integration of degraded land with community-managed social forestry, aiming to significantly impact the energy transition and environmental-societal enhancement, is recognized in this study. By focusing on the potential of these two land types as sources of bioenergy raw materials, the study aims to develop a model for determining suitable land areas, and identifying alternative sites for wood-biomass energy conversion facilities and power plants in the study area. Previous works commonly utilized GIS for potential assessment, however this study attempts to expands the integration of Fuzzy-AHP and Multi-Criteria Spatial Methodology by addressing limitations of the prior studies that failed to comprehensively consider all sustainability factors (Delivand et al., 2015; Jayarathna et al., 2022; Sharma et al., 2017).

Contribution of the study

The primary contribution of this study in a theoretical context is its initiation of a comprehensive discourse on the integration of degraded land and social forestry, serving as a catalyst to foster meaningful discussions and considerations in the realm of sustainable land use practices. Another practical contribution of this study lies in paving the way for future research advancements and policy frameworks within Indonesia's renewable energy landscape. It facilitates detailed studies and informed discussions concerning the tangible social, economic, and environmental effects linked to the production of biomass energy.

Degraded land and social forestry in Bali, Indonesia

Indonesia, a significant bioenergy exporter, mainly contributes 35 billion liters of palm-based biodiesel and 2390 thousand tonnes of solid biomass (IRENA, n.d.). Despite boasting a potential of 32,654 MW, the installed capacity stands at a mere 1671 MW, accounting for around 5 % (State Electricity Company (PLN), 2021). However, Indonesia has the characteristics of an archipelago. Bali Island, which is currently leading as one of the regions with the most aggressively pursuing energy transition, struggles to meet the target due to its condition as an isolated Island that wants to have its own clean energy security (Provincial Government, n.d.; Provincial Government, n.d.). Bali itself has a distinct advantage in its strategic approach to governance through strong customary villages (Desa Adat), setting it apart from other regions of Indonesia. This unique governance structure could potentially serve as a catalyst to enhance community engagement and alleviate tenure-related challenges, thus optimizing biomass production in social forestry. This distinctive attribute positions Bali to stand as a compelling location for biomass energy development.

Previous studies in Indonesia primarily defined potential land for bioenergy emphasizing degraded land as the remaining potential (Artati et al., 2019; Baral et al., 2022; Jaung et al., 2018). This is due to the limited room for land expansion or conversion into agricultural areas despite Indonesia possessing substantial landmass (Artati et al., 2019). Furthermore, this approach anticipates the consequences of deforestation in Indonesian tropical forests, particularly concerning palm oil cultivation (Jaung et al., 2018), which also holds potential for biofuel production, considering Indonesia's position as the world's largest palm oil producer and exporter. Nonetheless, given Indonesia's ambitious targets, especially for smaller islands like Bali, which are committed to independent clean energy, necessitates novel strategies to support sustainable transitions. Hence, despite debates regarding forest utilization for bioenergy, this study seeks to explore new dimensions of potential land worthy of consideration. It does so cautiously, addressing the risks outlined in academic discourse. Consequently, this study recognizes that integrating social forestry with degraded land could provide solutions to prevailing uncertainties.

Degraded land

Assessing the biomass energy potential depends on the availability and attainability of land area, with the role of degraded land in biomass energy production gaining increasing interest (Offermann et al., 2010). Degraded land refers to areas that have suffered damage from activities such as deforestation, mining, or agriculture. According to Jaung et al. (Jaung et al., 2018), bioenergy production in degraded lands offers a way to conserve critical resources by using lands that have limited roles for food production and other functions. However, measuring the biomass potential of degraded land and estimating achievable energy crops is a complex task (Campbell et al., 2008).

The availability of degraded land area holds significant importance as it ensures biomass production with minimal competing land uses (Offermann et al., 2010). Previous study (Jaung et al., 2018) shows that degraded land without a commitment to conservation, agriculture, mining, or built-up land can serve as potential biomass production sites. However, implementing this approach in Bali, where land availability is limited and most of the forestry sector is under protected status, was not without its challenges. A potential solution lies in the conversion of degraded lands previously used for mining and agriculture with the most severity. Research from Menéndez et al. (Menéndez et al., 2019) emphasizes the significance of landscape recovery through the restoration of degraded mining lands. They also argue that energy forests can be cultivated efficiently on agricultural land by utilizing agroforestry schemes to maintain an optimal land use balance and preserve ecological harmony.

Social forestry

Forest ownership in Indonesia is classified into four categories: state forests, non-state forests, areas for other purposes, and private-community lands (Rakatama & Pandit, 2020). State forest jurisdiction covers approximately 63 % of the total forested area. This area is then allocated for management by the government or community. Non-state forests include customary forests, which are managed by local communities based on their traditional practices and beliefs. Social forestry or community-based forest is a relatively new concept in Indonesia, which aims to formalize the traditional forest management practices of local communities and empower them to manage and benefit from forest resources.

Social forestry scheme (as shown in Fig. 1) encompasses community forestry, village forests, community plantation forests, forest partnerships, and customary forests (Moeliono et al., 2023). Among those five types of social forests, four are the state forests allocated to community forestry. Only customary forest is a non-state forest. Different characteristics occur, such as tenurial, contract terms, and permitted activities, which can influence their functions and outcomes. The role of Social Forestry within Indonesia's land tenure systems is to establish a legal framework and provide institutional support for local communities. This

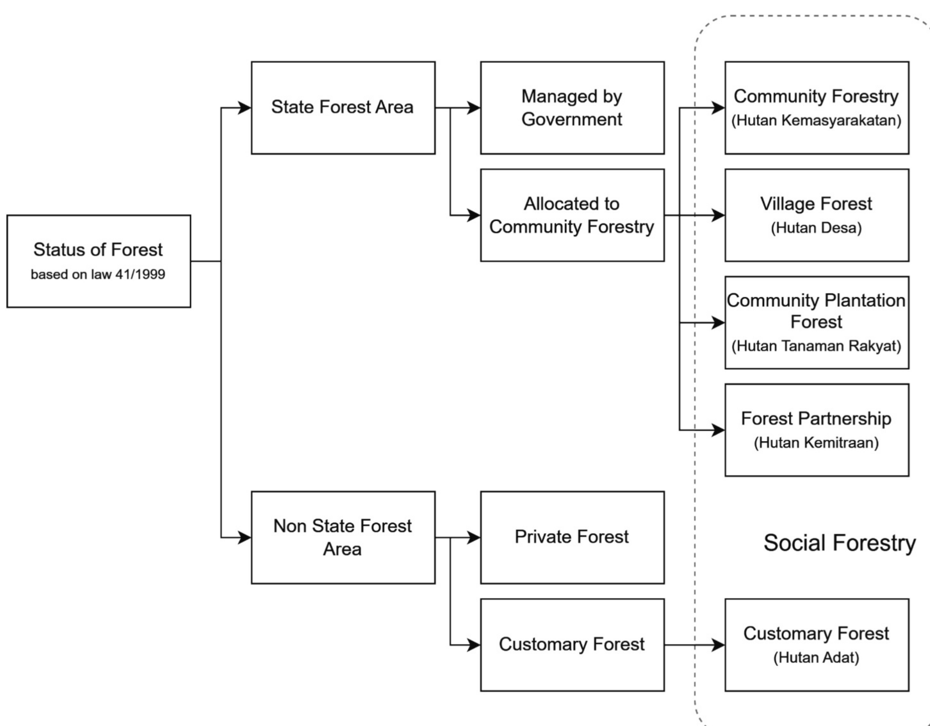

Fig. 1. Social Forestry Scheme in Indonesia.

Social Forestry framework enables these communities to manage and derive benefits from forest resources, all while ensuring the conservation and protection of forest ecosystems. (Rakatama & Pandit, 2020).

Material and method

For the purpose of the study, a spatially analytical and multi-criteria approach was developed to map out and optimize biomass energy in the upstream and downstream processes. This study utilized a combination of primary and secondary data to ensure depth of information in the research. Primary data included expert opinions and a literature review, while secondary data encompassed diverse geographic and demographic information relevant to Bali. Secondary data, comprising spatial and demographic information, was acquired from various government institutions and agencies in Bali Province. These secondary data included:

1. Degraded land and social forestry from the Forest Area Consolidation Agency (BPKH) 8 Denpasar and the Forestry and Environment Service (DKLH) of Bali Province
2. Protected area from the Bali Provincial of Public Works
3. Slope classification 30-m DEM SRTM Bali Province DEMNAS BIG data
4. Land use data from BPKH 8 Denpasar
5. Road Network SHP data from the Bali Provincial Office of Public Works
6. Port SHP data from the Bali Province Spatial Plan
7. Transmission Network SHP data and Electricity Demand SHP data from PT PLN Bali Distribution Main Unit.

Data collection took place in June 2022, and all geospatial data were standardized to the WGS84_1984_UTM_Zone_50S projection system. Various types of data analysis were conducted within the ArcGIS Pro environment and Expert Choice Software. The analysis consisted of restriction area analysis, biomass feedstock analysis, sustainability criteria analysis, fuzzy membership normalization, Analytical Hierarchy Process, and weighted overlay analysis (as shown in Fig. 2).

Defining criteria

For optimal sustainability and efficiency, a broad range of criteria was considered, categorized into restriction criteria and sustainability criteria for suitable site locations in this study. Restriction is a criterion where the location of biomass facilities and power plants is not allowed. Meanwhile, sustainability is a criterion that brings sustainability to the development of bioenergy. The compilation of criteria incorporated Geographic Information System (GIS) approaches from seven previous studies (Delivand et al., 2015; Höhn et al., 2014; Jayarathna et al., 2022; Perpiña et al., 2013; Rodríguez et al., 2017; Sultana & Kumar, 2012; Zhang et al., 2011), laying the groundwork for this study's comprehensive assessment framework (Table 1). Table 1 presents the identified criteria for previous research and the position of this study, delineating the focus of criteria used for sustainability and restriction criteria. A total of 16 criteria were obtained from seven previous studies, which will be later synthesized as sustainability criteria and restriction criteria.

Based on the combination of these two criteria, an overall Sustainability and Restriction Criteria reference framework was developed as also shown in Table 1.

Sustainability criteria

Sustainability criteria were adopted from previous studies (see also to Table 1.), encompassing the availability of raw materials, industrial areas, population density, proximity to roads and ports, and distance to transmission networks. Subsequently, these sustainability criteria were amalgamated into five crucial components tailored specifically for the development of biomass energy in Bali: availability of raw materials, proximity to ports and road networks, proximity to demand load centers (comprising population density and industrial areas), and proximity to transmission networks.

Restriction area criteria

Optimizing biomass energy both in the upstream and downstream processes included environmental and regulatory considerations. The study focused on identifying restriction areas for biomass power plants and facilities. Guided by previous studies and customized for the unique context of Bali, six restriction criteria were selected: conservation areas, slopes, lakes, land cover, built-up areas, and airports. These criteria were chosen based on environmental considerations that required protection and areas unsuitable for biomass energy plant construction, as indicated in previous literature studies detailed in Table 1. These criteria were subsequently consolidated into three broader categories: restrictions on protected areas, slope, and land use. The land use restriction encompassed considerations of lakes, land cover, built-up areas, and airports. Further, a buffer zone was created for each restriction to calculate land availability, as demonstrated in Table 2.

Holistic selection criteria framework

A comprehensive multi-dimensional assessment framework was developed in this study, which aligned with Bali's unique environmental, economic, and social context, as shown in Fig. 3. The framework designed for biomass energy site selection in Bali was structured into four key levels. At the highest level, it outlined the overarching purpose: Biomass Energy Optimization Through Holistic Site Selection Criteria. This purpose was divided into two primary categories: sustainability criteria and restriction criteria, each with specific criteria tailored to

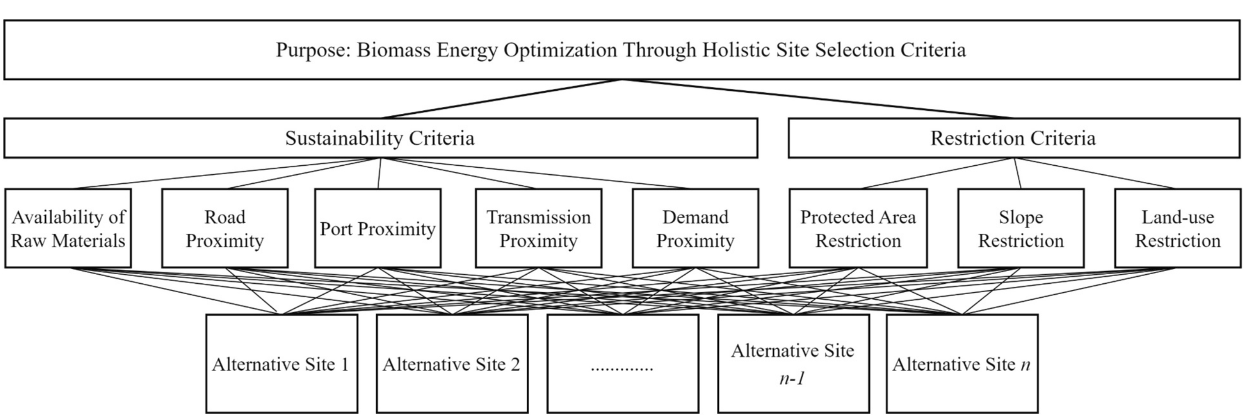

Fig. 2. Framework of the Study.

Table 1
Mapping Sustainability and Restriction Criteria from Previous Studies.

No.	Criterion Components	Zhang et al. (2011)	Sultana & Kumar (2012)	Perpina et al. (2013)	Hohn et al (2014)	Delivand et al (2015)	Rodriguez et al (2017)	Jayarathna (2022)	This study
1	Biomass Raw Materials	Sustainability	Sustainability	Sustainability	Sustainability	Sustainability	Sustainability	Sustainability	Sustainability
2	Distance to Roads and Ports	Sustainability	–	Sustainability	Sustainability	–	Sustainability	Sustainability	Sustainability
3	Population Density	Sustainability	–	Sustainability	–	–	–	Sustainability	Sustainability
4	Economic Development	–	–	Sustainability	–	–	–	Sustainability	
5	Geomorphology	–	–	Sustainability	–	–	–	–	
6	Industrial Areas	–	Restriction	Restriction	–	Sustainability	Restriction	Sustainability	Sustainability
7	Distance to Transmission Network	–	Sustainability	–	–	Sustainability	Restriction	Sustainability	Sustainability
8	Railway Network	Sustainability	–	Restriction	–	–	–	Restriction	
9	Airports	–	Restriction	–	–	–	–	–	Restriction
10	Lakes and Rivers	–	Restriction	Restriction	–	Restriction	Restriction	Restriction	Restriction
11	Slope	–	Restriction	Sustainability	Restriction	Sustainability	–	Sustainability	Restriction
12	Land Cover	Restriction	Restriction	Restriction	Restriction	Restriction	Restriction	Restriction	Restriction
13	Built-up Area	–	Restriction	Restriction	–	Sustainability	Restriction	Restriction	Restriction
14	Conservation Areas	–	Restriction	Restriction	–	Restriction	Restriction	Restriction	Restriction
15	Mining Areas	–	Restriction	–	–	–	–	–	
16	Viewshed	–	–	–	–	–	–	Sustainability	

Table 2
Buffer Zone Restriction Criteria.

No	Restriction Criteria	Safe Area/ Buffer Zone (m)	Description
1	Protected Restriction Area		
	Conservation Areas	500	National parks, conservation parks, resource reserves, and native lands need a protective ring.
	Protected Areas in the Spatial Plans	All the area	Power plants cannot be built in protected areas
2	Slope Restriction Area		
	Slope Area	15 %	Construction of a biomass power plant is not permitted on a slope of more than 15 % and economically it is best to be at 0–5 %.
3	Land Use Restriction Areas		
	Lake and River	300	Plots of land within the buffer zone of lakes and rivers are limited to 300 m
	Airport	500	The main flight zone and the 500 m safety buffer area around it are restricted
	Built-up Areas	600	Restrictions apply to buildings, industrial zones, and a 600 m buffer safe area around the development area.

Bali's context. Sustainability criteria assessed factors such as raw material availability and proximity to essential infrastructure, while restriction criteria considered environmental and regulatory limitations. At the bottom level, the framework accommodated a series of alternative sites, each evaluated against the established criteria. This comprehensive framework guided the selection process, ensuring that chosen sites aligned with sustainability objectives and complied with crucial restrictions.

Biomass feedstock mapping

This stage, the mapping of biomass sources from degraded land and social forestry was conducted. The datasets were obtained from the Forest Area Consolidation Agency (BPKH) 8 Denpasar and the Forestry and Environment Service (DKLH) of Bali Province in June 2022. The degraded land data comprised five categories of land criticality levels: very critical, critical, moderately critical, potentially critical, and non-critical. Meanwhile, the social forestry data included the locations of five classifications of social forestry land: customary forests, partnerships, community plantations, community forests, and village forests. Two distinct maps were created to represent the potential biomass feedstock from these sources. Subsequently, these maps were integrated into one comprehensive map displaying the total potential biomass feedstock in Bali Province.

Fuzzy membership normalization

To ensure all datasets were standardized and normalized, each criterion was assigned a fuzzy value using the fuzzy membership function in ArcGIS. The fuzzy membership function took input data and assigned it a value between 0 and 1, indicating how likely it was to belong to a specific predefined category or set. This process ensured all datasets were within the same value standard, allowing for an accurate overlay analysis. In this study, fuzzy membership was employed to assign values to the outcomes of the Euclidean distance analysis, transforming them into relative distances between 0 and 1. Consequently, all spatial data of the criteria shared the same standardized values before the overlay process through the weighted overlay analysis.

Multiple types of fuzzy logic were utilized within this study, adjusted to the nature of the data within each sustainability criterion. The specification of each fuzzy logic was informed by prior research and stakeholder interviews relevant to biomass energy. This approach yielded determinations as presented in Table 3. Table 3 explained the specific fuzzy functions utilized for each criterion, along with their minimum and maximum values. The criteria using triangular fuzzy functions, such as road proximity and transmission line proximity, showed a range that represented the likelihood of suitability for each criterion's fulfillment. Meanwhile, criteria like port proximity and availability of raw materials employed decreasing linear fuzzy functions, describing the transition in suitability as values decreased from the desired conditions. This standardized dataset, harmonized through fuzzy membership functions, formed the foundation for the fuzzy membership and weighted overlay analysis in section 4.3.1.

The parameters for each criterion were chosen based on previous studies and expert input (Jayarathna et al., 2022; Rodríguez et al., 2017; State Electricity Company (PLN), 2021). For Road Proximity, suitability for PLTBm construction is highest between 100 m and 2000 m from the road, decreasing to zero at 4000 m, balancing accessibility with minimal environmental impact. Port Proximity optimizes transportation costs with a maximum ideal distance of 25 km, decreasing linearly as distance

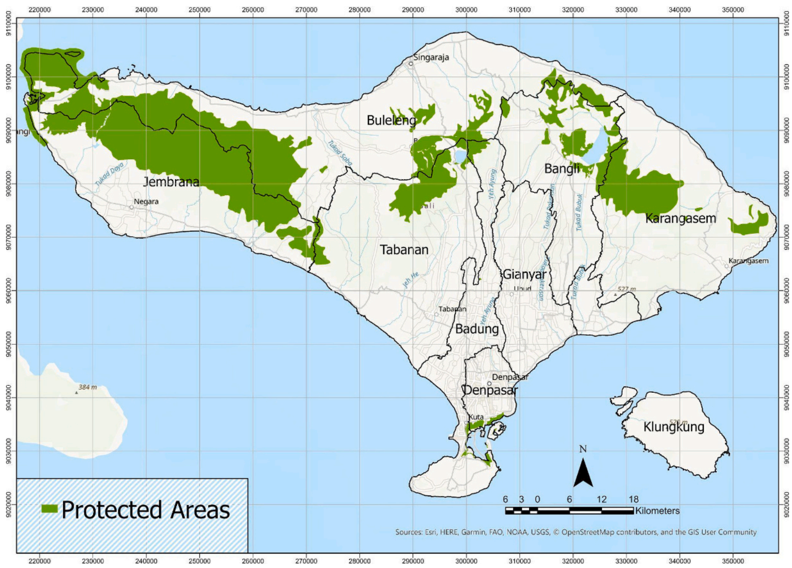

Fig. 3. Analysis Model for Holistic Site Selection Based on Synthesized Criteria.

Table 3
Fuzzy Logic in each Sustainability Criteria.

Criteria	Fuzzy Function/ Membership value	Min	Max
Road proximity	Triangular Fuzzy	100, 4000	2000
Transmission Line Proximity	Triangular Fuzzy	100, 10,000	4000
Port Proximity	Decreasing Linear	2500	100
Demand Load Center Proximity	Triangular Fuzzy	100, 10,000	4000
Availability of Raw Materials	Decreasing Linear	25,000	100

increases due to logistical challenges. Demand Load Center Proximity shows highest suitability within 100 m to 4000 m, ensuring efficient power distribution, with suitability decreasing to zero at 10,000 m due to higher transmission losses. Transmission Line Proximity follows a similar pattern, with highest suitability within 100 m to 4000 m, decreasing to zero at 10,000 m to account for increased transmission losses. Lastly, Availability of Raw Materials considers a maximum distance of 25 km for optimal transportation costs, with suitability decreasing linearly as distance increases, reflecting the difficulty and cost of transporting biomass over longer distances. These justifications ensure that the selected parameters are robust and grounded in both practical and expert-informed considerations.

Pairwise comparison from analytical hierarchy process (AHP)

In this phase, the AHP methodology was utilized. A pairwise comparison matrix was employed to systematically assess the relative importance of the criteria. Values were assigned on a scale from 1 through 9, where 1 signified equal significance between two criteria, and 9 indicated a strong preference for one criterion over the other. This process allowed for a comprehensive understanding of the interactions between the selected criteria and their potential influence on the success of biomass plant development.

A strategic selection of experts, encompassing the public sector, private sector, academia, and NGOs, was made to ensure a diverse and comprehensive set of opinions. These included representatives from:

1. The Department of Labor and Mineral Resources Energy of Bali Province, representing provincial government services in the energy sector.
2. PT PLN (Persero) Bali Distribution Main Unit, representing the State-Owned Enterprises and the primary off-taker in the electricity sector.
3. CORE (Community-Centered Renewable Energy) at Udayana University, representing academia and acting as an NGO in the renewable energy sector.
4. PT Merauke Narada Energi, acting as an Independent Power Producer (IPP) and developer of a biomass generator in Wapeko, Merauke Regency, South Papua Province.

Pairwise comparison interviews were conducted based on the selected criteria such as road access, port proximity, load centers, transmission networks, and raw material availability, which were critical for optimizing biomass energy power plants.

In this research, pairwise comparisons were conducted using Expert Choice software to assess the criteria and their corresponding categories. Predefined values were given to each criterion using the pairwise matrices. The objective was to establish the final values for each factor in every hierarchy and compute the consistency ratio (CR). The CR serves as an indicator of the mathematical coherence of the values assigned in each matrix.

Suitability and alternative biomass energy power plants location

In this section, the suitability and alternative locations were determined using the weighted overlay method within ArcGIS. This involved utilizing fuzzy maps for each criterion and the AHP-derived weights from the earlier analysis. Through this process, a map representing suitability levels was generated based on the multicriteria analysis. Subsequently, an overlay was performed with predefined limitations from the restriction analysis to pinpoint locations with high suitability for potential biomass power generation projects. Once these suitable locations were identified, alternative location points were established as the central points of each high-suitability cluster, while excluding restricted zones.

Result and discussion

Restriction area analysis

The outcome of the restriction area analysis is the limitation of the land availability map. About 129.187 ha, roughly 23,09 % of Bali's total land area, are designated as protected areas. Additionally, the majority of Bali features slopes over 15 %, primarily concentrated in the central mountainous areas, resulting in slope restrictions (Fig. 5). Only white and light brown colors are suitable for biomass power plants. Moreover, around 259.752 ha (44 % of the total area), are subject to land-use restrictions (see Fig. 6). The colors yellow, red, black, and blue, in sequence, indicate residential areas, airports, and lakes. These restricted areas are mainly characterized by urban development, particularly in the SARBAGITA metropolitan region (Denpasar, Badung, Gianyar, Tabanan) (Figs. 4 and 7).

The road of degraded land and social forestry to forest bioenergy

This study focused on very critical and critical lands, including land previously allocated to forestry, agriculture (only with the highest degree of critical land), plantations, and mining, while excluding conservation areas and other protected areas. This selection aims to avoid land use conflicts, particularly those surrounding food security. For social forestry, this study also encompasses a diverse range of community-based management models within the scope of social forestry sites. As a result, this study produced a total of 36,527 ha of degraded land and 21,671 ha of social forestry land (see Fig. 8). The red color indicates the degraded land potential to be managed as an energy forest, meanwhile, the green color indicates areas of social forestry that have the potential to be developed into energy forests.

Potential location of biomass energy facilities

Normalization with fuzzy map analysis

Normalization through fuzzy map analysis employs sustainable criteria to identify potential locations for a biomass plant. Firstly, road access criteria (see Fig. 9c), specifically to national and provincial roads, is essential to transport the biomass feedstock and biomass energy products effectively. Based on the model, the red color shows high suitability that gradually decreases as the color changes towards green. The fuzzy map indicates high indexes along the coastlines in Jembrana and Buleleng Regencies, Central Bali, South Bali in the SARBAGITA metropolitan area, and areas scattered evenly from East to North.

Port proximity is also crucial (see Fig. 9e), with crossing ports between provinces and the main seaport being the focal points. The red color indicates high suitability that gradually decreases as the color changes towards green. The highest indexes are found in the northwest of Buleleng Regency and south in the Badung and Denpasar Regencies, plus the East and Southeast regions.

For the demand load centers (see Fig. 9a), this study identified five main areas: three industrial areas (Celukan Bawang, Pengambengan, Candi Kusumo) and two isolated areas (Tiga Nusa and Ban Karangasem Village). According to the model, the red color indicates a high level of suitability, which gradually decreases as the color transitions to green. High indexes are found in the West around industrial areas and the northeast in the Karangasem Regency.

Transmission networks (see Fig. 9d) are crucial for connecting the generator to the substation. The red color represents a high level of suitability, which gradually decreases as the color shifts towards green. High indexes are concentrated in central Bali to the west. Finally, this study considered raw materials availability from primary sources on critical land and social forestry (see Fig. 9b). The red color indicates high suitability that gradually decreases as the color changes towards green. High indexes are present in western, northern, eastern, and central Bali, excluding the SARBAGITA metropolitan area due to dominant settlements and lack of forest areas and critical land.

Land suitability analysis

The Analytic Hierarchy Process (AHP) was utilized with the Consistency Ratio (CR) achieved was 0.0091, indicating that the weight criterion was acceptable (see Fig. 10). Raw materials emerged as the highest criterion with a score of 0.487, followed by demand load centers, transmission networks, ports, and highways.

Before being synthesized, there is an interesting pattern that can be taken from the individual assessment. Parties representing government actors focused on sustainability criteria for raw materials and load centers, indicating their desire to fulfill areas that tend to need more electricity or are not yet met by state-owned enterprises or are isolated areas. This pattern is similar to state-owned enterprises. In contrast, the Independent Power Producers (IPP) focused on ensuring the sustainability of their biomass generation business without targeting specific demand fulfillment. Meanwhile, parties representing academia and NGOs had a broader preference, aiming for sustainability from various angles. The final pairwise comparison results, as synthesized from the expert assessments, are presented in Fig. 10. These results reflect the aggregated views of the experts on the relative importance of the criteria for biomass plant development.

Following the criteria weighting, a weighted overlay analysis was

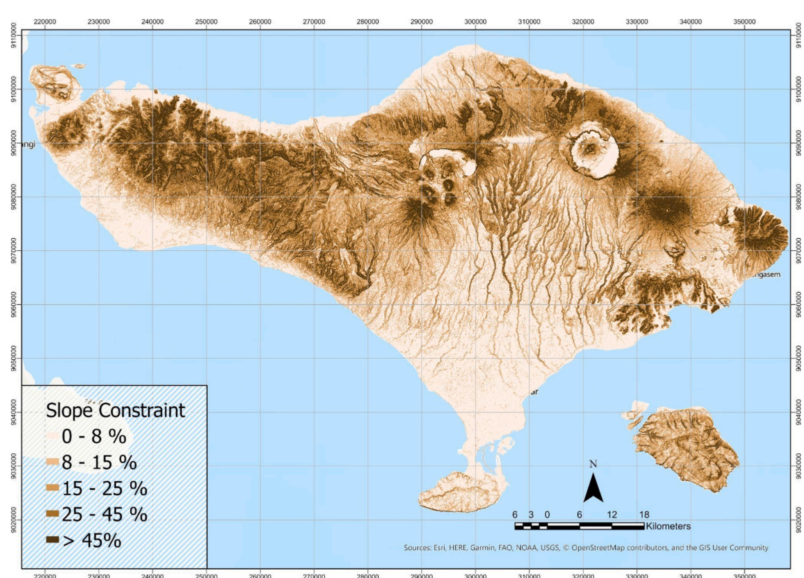

Fig. 4. Protected Area.

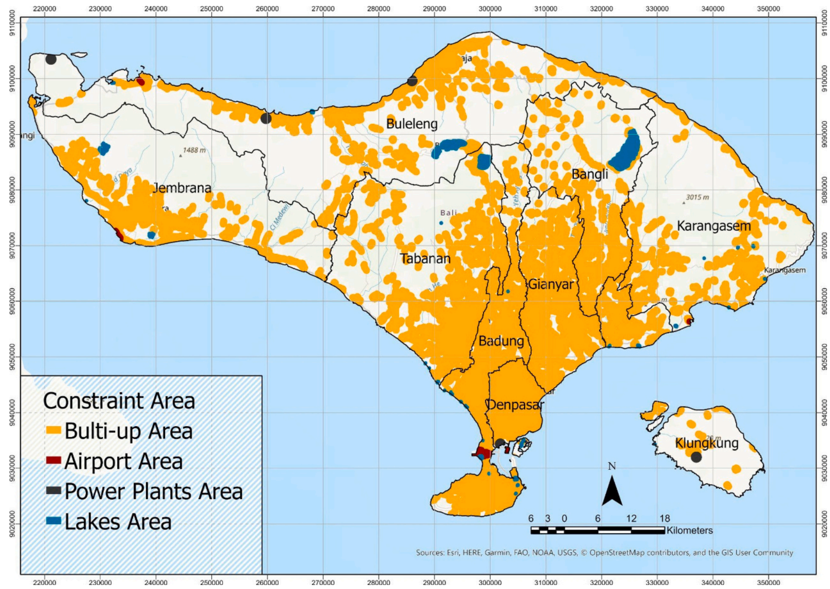

Fig. 5. Slope Restrictions.

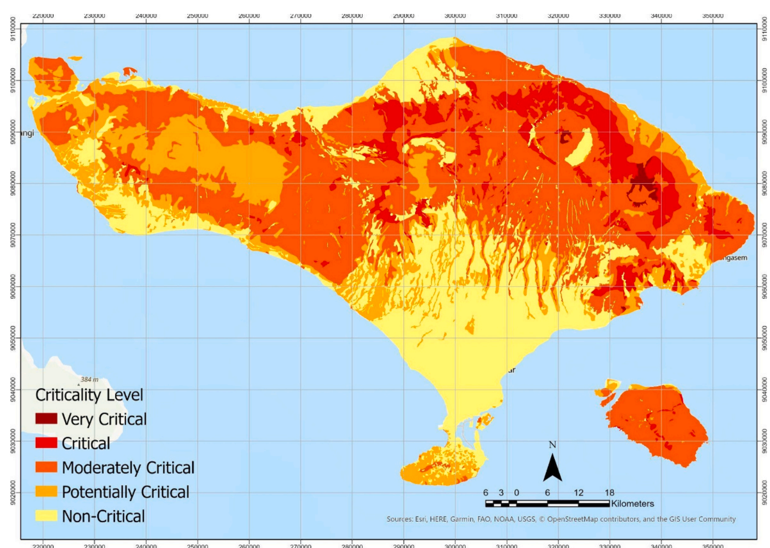

Fig. 6. Land-use Restrictions.

performed, taking into consideration the fuzzy maps of roads, ports, demand load centers, transmission networks, and raw materials, with each assigned its respective AHP weighting score. This analysis revealed that a classification of 'very high' was achieved for an area spanning 27,143 ha across the Jembrana, Buleleng, Karangasem, and Klungkung districts, with a particular focus on Nusa Penida. Dark green color indicates very high suitability, gradually decreasing as the color changes towards red (Fig. 11). This classification is indicative of these regions' robust potential for sustainable biomass plant implementation based on the selected criteria. It should be noted that this suitability analysis has not been overlaid with the restriction areas analyzed in section 4.1.

Alternative location biomass energy power plant

The final step involved pinpointing alternative locations by factoring in restricted areas, leading to the generation of a suitability map for biomass development. This involved overlaying the suitability analysis results from the previous section with the restriction areas described in section 4.1. The objective was to identify regions that not only possess a high degree of suitability but also do not overlap with the protected restriction areas.

Using Jayarathna (Jayarathna et al., 2022) criteria as a guide, areas with the highest compatibility were selected, with a minimum feasible area of 10 ha for a biomass power plant. Subsequently, this study will proceed to create a spatial mapping of alternative location points. This will involve performing a central point analysis for each cluster of high-suitability areas while ensuring that restricted zones are excluded. The outcome of this mapping exercise will be a set of specific location points. This will make it easier for policymakers to determine which location to build.

As a result, forty suitable locations were identified for Biomass Power Plant development, taking into account raw material availability, restricted areas, and sustainability criteria (Fig. 12). A clear clustering of areas in the Jembrana, Buleleng, and Karangasem districts, and Nusa Penida was observable. These locations stand as viable alternatives for sustainable biomass plant implementation, reflecting the successful integration of geospatial data and sustainability criteria in this endeavor. Nevertheless, there are limitations that in this study has not identified capacity at each point thus further research is needed.

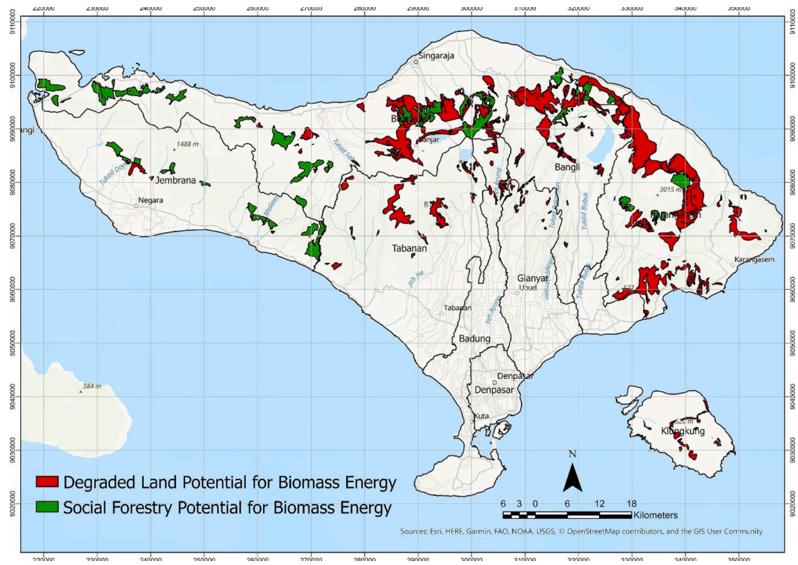

Fig. 7. Degraded Land Classification in Bali.

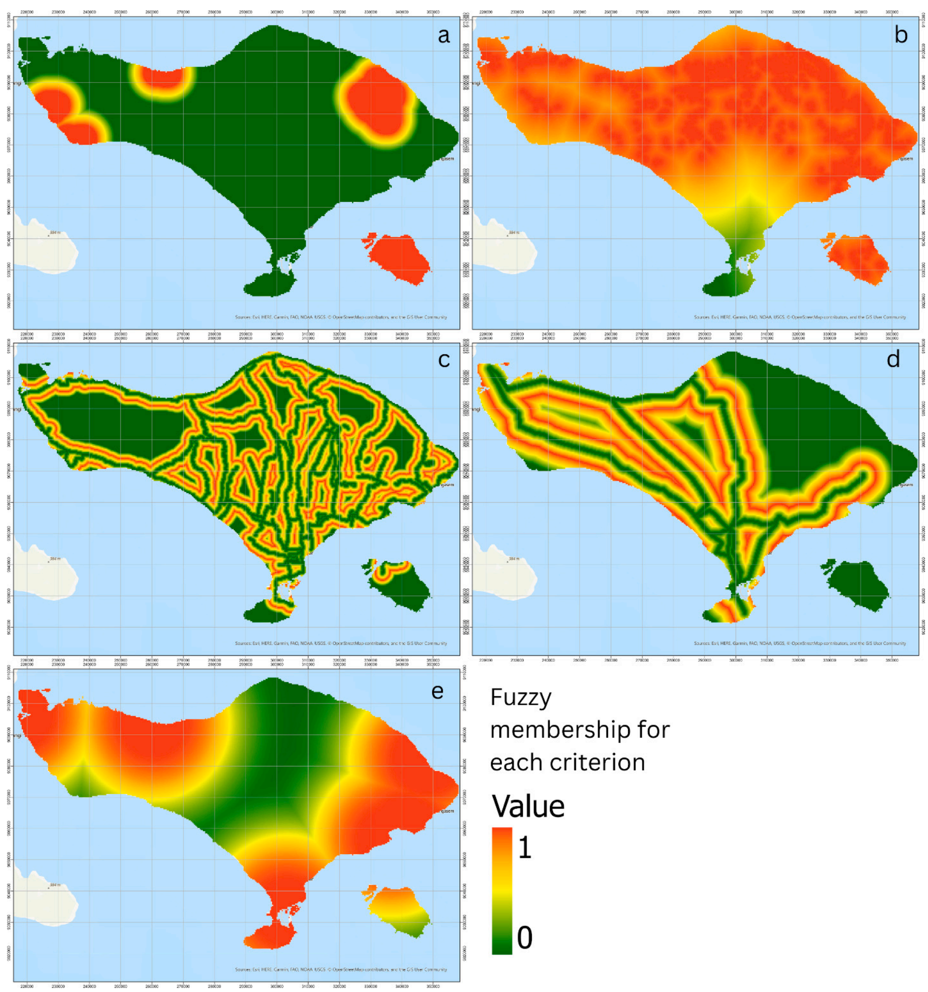

Fig. 8. Potential Degraded Land and Social Forestry.

This study demonstrates that when both land sources are combined, they complement each other. For instance, in the case of Jembrana, it was found that the degraded land covers a minimal area of only 347 ha, whereas social forestry dominates with an area of 5714 ha. Jembrana, being a major industrial center in Bali, receives significant benefits from the additional potential land found. A similar scenario exists in Buleleng, where there is potential demand arising from a partnership with the State-Owned Electricity Company (PLN), with surrounding land being

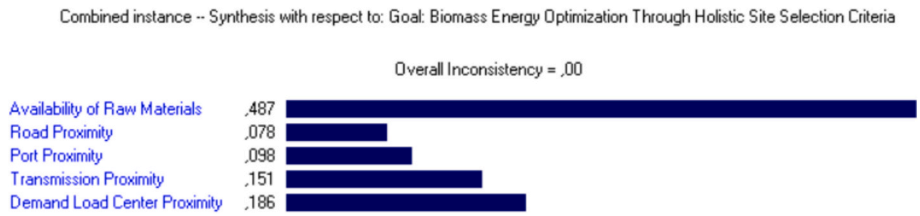

Fig. 9. Fuzzy Membership Analysis: (a) Demand Load Center (b) Availability of Raw Materials © Road Proximity (d) Electricity Transmission (e) Port Proximity.

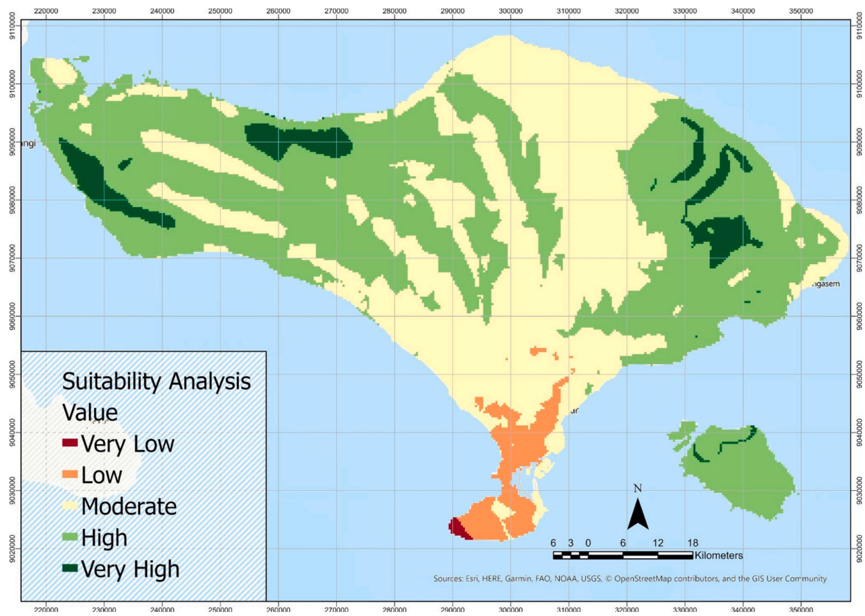

Fig. 10. Weighting Criteria Using AHP.

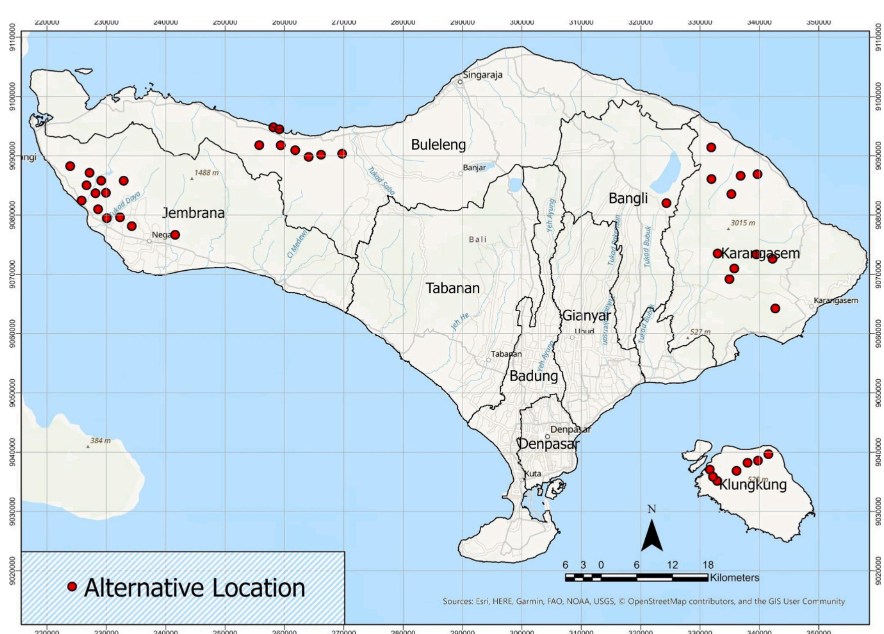

Fig. 11. Suitability Analysis for Biomass Energy Power Plant.

part of the co-firing program for coal-fired power plants in this area.

The role of social forestry

Additional potential land has been significantly discovered with social forestry. Several previous studies have mapped potential lands in

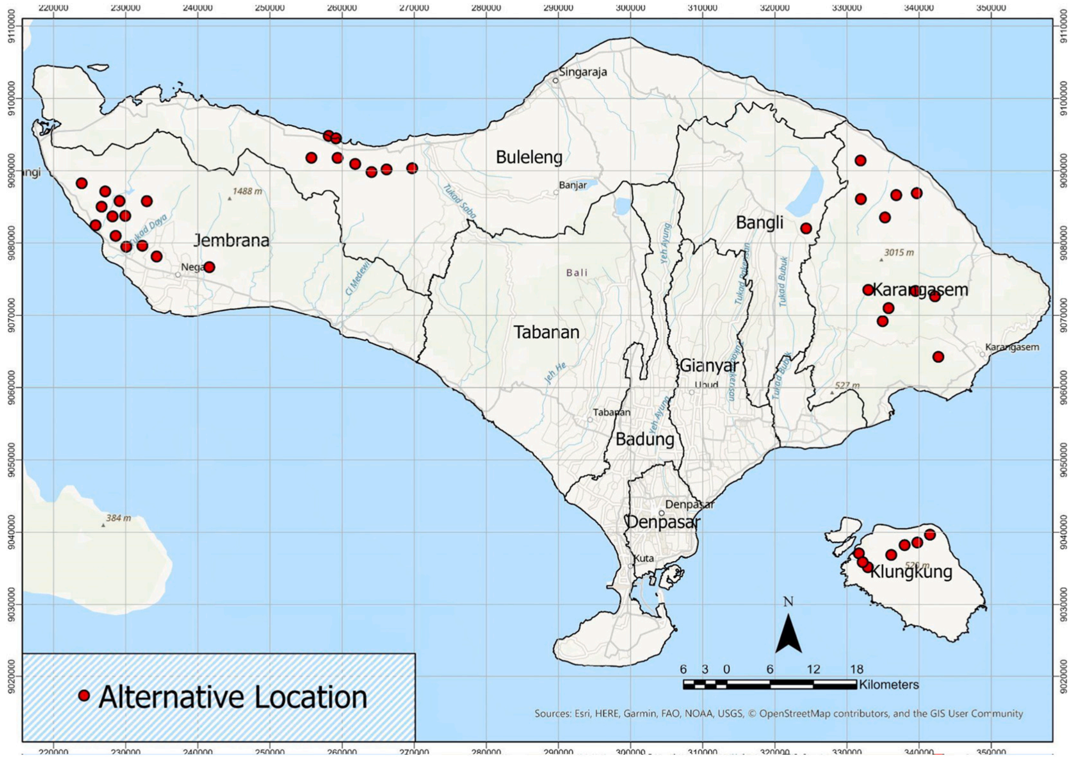

Fig. 12. Alternative Locations for Biomass Energy Power Plant.

Indonesia (Gingold et al., n.d.; Jaung et al., 2018; Nijsen et al., 2011). Jaung's research mapped 3 million hectares of potential degraded land for biofuel production in Indonesia. It is argued that this 3 million hectares area is still relatively small to support bioenergy at economies of scale, as suggested by Gingold's study (Gingold et al., n.d.) on palm oil, indicating a minimum parcel size of 5000 ha. However, the scale of the study which is subnational level could be a limitation in comparing the result. In aggregate proportion, the land area in Bali is considered small compared to previous degraded land mappings. The integration results in a significant increase of 60 % in land availability for Energy Forest development. This can be a significant consideration for further research by opening opportunities for social forestry to contribute to bioenergy development.

Moreover, this study identified 120 social forestry sites covering an area of 21,671 ha in Bali, involving approximately 78,385 households. The study focuses on the significant involvement of smallholder forest-dwelling communities as active local actors contributing to net-zero emissions, ensuring 'no one left behind.' However, this discourse is not without challenges. These household-based smallholders exhibit limited financial resilience (Zhunusova et al., 2019), preferring short-rotation plantations for quick cash flow (Cuong et al., 2020). Nonetheless, despite being beneficial for afforestation, large-scale monocultural short-rotation biomass conversion may negatively affect biodiversity (Favero et al., 2020). Therefore, this study advocates for agroforestry as a more viable solution. Bali's local community wisdom perceives agroforestry systems as an approach for sustainable land management, meeting daily needs while conserving natural resources, given their cultural ties with forests. Among the identified social forestry sites, 16 sites actively engage in agroforestry partnerships that incentivize indigenous communities. Moreover, high-calorie indigenous plants like *Gliricidia Sepium* (Gamal) naturally grow in several Bali regions. Thus, local wisdom deserves consideration in future discourse concerning social forestry's evolution towards bioenergy development.

Conclusion

This study focuses on opening a broader discussion on the role of social forestry in the development of bioenergy alongside degraded land. It addresses challenges in the sustainability of energy forests and biomass source instability, highlighting how the management of social forestry as community-based forestry serves as a solution to these challenges. By combining the analytical hierarchy process and fuzzy logic methods and applying them in a geospatial multicriteria environment, this study quantitatively assesses how social forestry significantly contributes to the theoretical biomass potential that has traditionally focused on degraded land.

Several limitations within the methodology and findings should be considered. Firstly, the availability of specific data related to biomass plantation cover is limited, which could impact the analytical comprehensiveness. Nevertheless, considering the limitations of previous studies in assessing the potential of integrating degraded land and social forestry, this study still provides a novel contribution. Secondly, the small-scale scope of the study focused on the subnational level may limit the generalizability of findings to a broader regional or national context. Therefore, this study recommends future research with extensive data sets and expanding the geographical scope of the study beyond the subnational level. We also acknowledge the use of the Analytic Hierarchy Process (AHP) and Fuzzy Logic methods, while robust and widely accepted, may have certain biases inherent to these techniques, potentially affecting the accuracy and objectivity. Furthermore, implementation complexity emerges as a significant limitation in the findings. A profound understanding of community perceptions and behaviors is essential. Conducting in-depth qualitative studies or social impact assessments can offer valuable insights into the motivations, challenges, and aspirations of local farmers, thereby promoting the adoption of sustainable practices.

The key findings identified 36,527 ha of potentially degraded land, 21,671 ha of social forestry, and 40 alternative optimal locations for bioenergy facilities, considering various spatial and temporal criteria.

The integration results in a significant increase of 60 % in land availability for Energy Forest development. This can be a significant consideration for further research by opening opportunities for social forestry to contribute to bioenergy development. Moreover, this study identified 120 social forestry sites in Bali, involving approximately 78,385 households. This could provide significant involvement of smallholder forest-dwelling communities as active local actors contributing to net-zero emissions. Among the identified social forestry sites, 16 sites actively engage in agroforestry partnerships that incentivize indigenous communities. Moreover, high-calorie indigenous plants like *Gliricidia Sepium* (Gamal) naturally grow in several Bali regions. Thus, local wisdom deserves consideration in future discourse concerning social forestry's evolution towards bioenergy development.

Practical and policy implications

Global bioenergy demand has increased in recent decades. Indonesia, as one of the major exporters, has the potential to strategically position itself in the bioenergy sector. However, bioenergy in Indonesia remains heavily reliant on oil palm, leading to various criticisms concerning deforestation, biodiversity loss, peatland drainage, and other socio-environmental issues (Abram et al., 2017; Gaveau et al., 2016; Sharma et al., 2018). Therefore, the formulation of a risk-based sustainability strategy is necessary for future bioenergy development. This study presents a proven management practice effective in minimizing environmental risks and enhancing socio-economic outcomes (Newton et al., 2015; Octavia et al., 2022), namely social forestry. Through the generated mapping, social forestry can significantly aid in meeting bioenergy demand alongside degraded land. Thus, it is recommended for policymakers at international, national, and subnational levels to integrate social forestry and degraded land into management guidelines and bioenergy strategies.

Previous studies have proven the effectiveness of social forestry, for instance, how social forestry transformed Vietnam into the largest wood pellet producer (Zhunusova et al., 2019). This positively impacted rapid afforestation (Van Hung et al., 2020). Nevertheless, rapid afforestation through monocultural fast-growing trees may not deliver the same environmental benefits as natural regenerating forests and may negatively affect biodiversity (IRENA, n.d.; Favero et al., 2020). The findings of this study offer perspectives on how Bali's indigenous communities possess local wisdom in managing their forests, such as the practice of agroforestry. Additionally, there are partnership practices among indigenous communities, government, and the private sector. These findings can assist developers in proposing sustainable business models for the diversification of plantation forests.

Finally, our findings successfully increased the potential land for bioenergy and mapped potential optimal facility locations based on sustainability criteria. This study discovered viable locations for biomass plant development in the Jembrana, Buleleng, Karangasem, and Nusa Penida districts. This can assist Bali's local government in achieving its renewable energy targets. Additionally, it provides information to a wide range of stakeholders with various interests and perspectives, such as customary governance, Independent Power Producer developers in their project planning, or the State Electricity Company (PLN), which is currently targeting a blending mandate for co-firing for the phaseout of coal plants.

Submission declaration and verification

This article has not been published previously and it is not under consideration for publication elsewhere. If accepted, we will not publish the paper elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

CRediT authorship contribution statement

Harkunti Pertiwi Rahayu: Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Al Hilal Firdaus S. Alim:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Kornelis Blok:** Supervision, Project administration, Funding acquisition, Conceptualization. **Seigo Nasu:** Writing – review & editing, Conceptualization. **Ganesha Mangkoesoebroto:** Writing – review & editing, Data curation.

Declaration of competing interest

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

Data availability

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Abram, N. K., Meijaard, E., Wilson, K. A., Davis, J. T., Wells, J. A., Ancrenaz, M., et al. (2017). Oil palm–community conflict mapping in Indonesia: A case for better community liaison in planning for development initiatives. *Applied Geography, 78*, 33–44. https://doi.org/10.1016/j.apgeog.2016.10.005

Artati, Y., Jaung, W., Juniwaty, K., Andini, S., Lee, S., Segah, H., et al. (2019). Bioenergy Production on Degraded Land: Landowner Perceptions in Central Kalimantan, Indonesia. *Forests, 10*, 99. https://doi.org/10.3390/f10020099

Baral, H., Leksono, B., & Seol, M. (2022). *Pongamia: A possible option for degraded land restoration and bioenergy production in Indonesia*. Center for International Forestry Research (CIFOR).

Beccali, M., Cellura, M., & Ardente, D. (1998). Decision making in energy planning: The ELECTRE multicriteria analysis approach compared to a FUZZY-SETS methodology. *Energy Conversion and Management, 39*, 1869–1881. https://doi.org/10.1016/s0196-8904(98)00053-3

Belton, V., & Stewart, T. (2012). *Multiple Criteria Decision Analysis: An Integrated Approach*. Springer Science & Business Media.

Bentsen, N. S. (2017). Carbon debt and payback time – Lost in the forest? *Renewable and Sustainable Energy Reviews, 73*, 1211–1217. https://doi.org/10.1016/j.rser.2017.02.004

Blomley, T., Pfliegner, K., Isango, J., Zahabu, E., Ahrends, A., & Burgess, N. (2008). Seeing the wood for the trees: An assessment of the impact of participatory forest management on forest condition in Tanzania. *Oryx*, 42. https://doi.org/10.1017/s0030605308071433

Campbell, J. E., Lobell, D. B., Genova, R. C., & Field, C. B. (2008). The Global potential of Bioenergy on Abandoned Agriculture Lands. *Environmental Science & Technology, 42*, 5791–5794. https://doi.org/10.1021/es800052w

Cebi, S., Ilbahar, E., & Atasoy, A. (2016). A fuzzy information axiom based method to determine the optimal location for a biomass power plant: A case study in Aegean Region of Turkey. *Energy, 116*, 894–907. https://doi.org/10.1016/j.energy.2016.10.024

Chung, J. N. (2013). Grand challenges in bioenergy and biofuel research: Engineering and technology development, environmental impact, and sustainability. *Frontiers in Energy Research*, 1. https://doi.org/10.3389/fenrg.2013.00004

Cuong, T., Chinh, T. T. Q., Zhang, Y., & Xie, Y. (2020). Economic Performance of Forest Plantations in Vietnam: Eucalyptus, Acacia mangium, and Manglietia conifera. *Forests, 11*, 284. https://doi.org/10.3390/f11030284

Delivand, M. K., Cammerino, A. R. B., Garofalo, P., & Monteleone, M. (2015). Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: A case study on electricity productions in South Italy. *Journal of Cleaner Production, 99*, 129–139. https://doi.org/10.1016/j.jclepro.2015.03.018

Favero, A., Daigneault, A., & Sohngen, B. (2020). Forests: Carbon sequestration, biomass energy, or both? *Science Advances*, 6. https://doi.org/10.1126/sciadv.aay6792

Gautam, A. P., Webb, E. L., & Eiumnoh, A. (2002). GIS Assessment of Land Use/Land Cover changes Associated with Community Forestry Implementation in the Middle Hills of Nepal. *Mountain Research and Development, 22*, 63–69. https://doi.org/10.1659/0276-4741(2002)022[0063:gaolul]2.0.co;2

Gaveau, D. L. A., Sheil, D., Husnayaen, Salim M. A., Arjasakusuma, S., Ancrenaz, M., et al. (2016). Rapid conversions and avoided deforestation: Examining four decades of industrial plantation expansion in Borneo. *Scientific Reports, 6*, 1–13. https://doi.org/10.1038/srep32017

Gingold B, Stolle F, Douard P, Rosenbarger A, Muliastra YIKD. How to Identify Degraded Land for Sustainable Palm Oil in Indonesia. World Resources Institute n.d. https://www.wri.org/research/how-identify-degraded-land-sustainable-palm-oil-indonesia.

Giuntoli, J., Barredo, J. I., Avitabile, V., Camia, A., Cazzaniga, N. E., Grassi, G., et al. (2022). The quest for sustainable forest bioenergy: Win-win solutions for climate and biodiversity. *Renewable and Sustainable Energy Reviews, 159*, Article 112180. https://doi.org/10.1016/j.rser.2022.112180

Greening, L. A., & Bernow, S. (2004). Design of coordinated energy and environmental policies: Use of multi-criteria decision-making. *Energy Policy, 32*, 721–735. https://doi.org/10.1016/j.enpol.2003.08.017

Hess, J. R., Lamers, P., Stichnothe, H., Beermann, M., & Jungmeier, G. (2016). Bioeconomy strategies. In *Developing the Global Bioeconomy* (pp. 1–9). Elsevier.

Höhn, J., Lehtonen, E., Rasi, S., & Rintala, J. (2014). A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland. *Applied Energy, 113*, 1–10. https://doi.org/10.1016/j.apenergy.2013.07.005

IRENA. Bioenergy for the Transition: Ensuring Sustainability and Overcoming Barriers n.d. https://www.irena.org/Publications/2022/Aug/Bioenergy-for-the-Transition.

Jaung, W., Wiraguna, E., Okarda, B., Artati, Y., Goh, C., Syahru, R., et al. (2018). Spatial assessment of degraded lands for biofuel production in Indonesia. *Sustainability, 10*, 4595. https://doi.org/10.3390/su10124595

Jayarathna, L., Kent, G., O'Hara, I., & Hobson, P. (2022). Geographical information system based fuzzy multi criteria analysis for sustainability assessment of biomass energy plant siting: A case study in Queensland, Australia. *Land Use Policy, 114*, Article 105986. https://doi.org/10.1016/j.landusepol.2022.105986

Kordi, M., & Brandt, S. A. (2012). Effects of increasing fuzziness on analytic hierarchy process for spatial multicriteria decision analysis. *Computers, Environment and Urban Systems, 36*, 43–53. https://doi.org/10.1016/j.compenvurbsys.2011.07.004

Lewandowski, I. (2015). Securing a sustainable biomass supply in a growing bioeconomy. *Global Food Security, 6*, 34–42. https://doi.org/10.1016/j.gfs.2015.10.001

Loken, E. (2007). Use of multicriteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews, 11*, 1584–1595. https://doi.org/10.1016/j.rser.2005.11.005

Marland, G., & Schlamadinger, B. (1995). Biomass fuels and forest-management strategies: How do we calculate the greenhouse-gas emissions benefits? *Energy, 20*, 1131–1140. https://doi.org/10.1016/0360-5442(95)00061-k

Menéndez, J., Loredo, J., Galdo, M., & Fernández-Oro, J. M. (2019). Energy storage in underground coal mines in NW Spain: Assessment of an underground lower water reservoir and preliminary energy balance. *Renewable Energy, 134*, 1381–1391. https://doi.org/10.1016/j.renene.2018.09.042

Milbrandt A, Overend RP. Assessment of Biomass Resources from Marginal Lands in APEC Economies n.d. https://www.nrel.gov/docs/fy10osti/46209.pdf.

Mitchell, S. R., Harmon, M. E., & O'Connell, K. E. B. (2012). Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy, 4*, 818–827. https://doi.org/10.1111/j.1757-1707.2012.01173.x

Moeliono, M., Sahide, M. A. K., Bong, I. W., & Dwisatrio, B. (2023). *Social Forestry in Indonesia: Fragmented Values, Progress, Contradictions, and Opportunities. Social Value, climate Change and Environmental Stewardship: Insights from Theory and Practice* (pp. 117–138). Cham: Springer International Publishing.

Nabuurs, G.-J., Arets, E. J. M. M., & Schelhaas, M.-J. (2017). European forests show no carbon debt, only a long parity effect. *Forest Policy and Economics, 75*, 120–125. https://doi.org/10.1016/j.forpol.2016.10.009

Newton, P., Schaap, B., Fournier, M., Cornwall, M., Rosenbach, D. W., DeBoer, J., et al. (2015). Community forest management and REDD+. *Forest Policy and Economics, 56*, 27–37. https://doi.org/10.1016/j.forpol.2015.03.008

Nijsen, M., Smeets, E., Stehfest, E., & van Vuuren, D. P. (2011). An evaluation of the global potential of bioenergy production on degraded lands. *GCB Bioenergy, 4*, 130–147. https://doi.org/10.1111/j.1757-1707.2011.01121.x

Octavia, D., Suharti, S., Murniati, Dharmawan I. W. S., Nugroho, H. Y. S. H., Supriyanto, B., et al. (2022). Mainstreaming smart agroforestry for social forestry implementation to support sustainable development goals in Indonesia: A review. *Sustainability, 14*, 9313. https://doi.org/10.3390/su14159313

Offermann, R., Seidenberger, T., Thrän, D., Kaltschmitt, M., Zinoviev, S., & Miertus, S. (2010). Assessment of global bioenergy potentials. *Mitigation and Adaptation Strategies for Global Change, 16*, 103–115. https://doi.org/10.1007/s11027-010-9247-9

Perpiña, C., Martínez-Llario, J. C., & Pérez-Navarro, Á. (2013). Multicriteria assessment in GIS environments for siting biomass plants. *Land Use Policy, 31*, 326–335. https://doi.org/10.1016/j.landusepol.2012.07.014

Provincial Government. Governor of Bali Province Regulation No. 45 of 2019 n.d. https://jdih.baliprov.go.id/produk-hukum/peraturan-perundang-undangan/pergub/24818 (accessed December 11, 2023).

Provincial Government. Regional Regulation (PERDA) of Bali Province Number 9 of 2020. General Regional Energy Plan for Bali Province Tahun 2020–2050. Database Peraturan | JDIH BPK n.d. https://peraturan.bpk.go.id/Details/148301/perda-prov-bali-no-9-tahun-2020 (accessed December 11, 2023).

Rakatama, A., & Pandit, R. (2020). Reviewing social forestry schemes in Indonesia: Opportunities and challenges. *Forest Policy and Economics, 111*, Article 102052. https://doi.org/10.1016/j.forpol.2019.102052

Rodríguez, R., Gauthier-Maradei, P., & Escalante, H. (2017). Fuzzy spatial decision tool to rank suitable sites for allocation of bioenergy plants based on crop residue. *Biomass and Bioenergy, 100*, 17–30. https://doi.org/10.1016/j.biombioe.2017.03.007

Saaty, T. L. (1990). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*.

Schlamadinger, B., & Marland, G. (1996). The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy, 10*, 275–300. https://doi.org/10.1016/0961-9534(95)00113-1

Sharma, B., Birrell, S., & Miguez, F. E. (2017). Spatial modeling framework for bioethanol plant siting and biofuel production potential in the U.S. *Applied Energy, 191*, 75–86. https://doi.org/10.1016/j.apenergy.2017.01.015

Sharma, R., Nehren, U., Rahman, S., Meyer, M., Rimal, B., Aria Seta, G., et al. (2018). Modeling Land Use and Land Cover changes and their Effects on Biodiversity in Central Kalimantan, Indonesia. *Land, 7*, 57. https://doi.org/10.3390/land7020057

State Electricity Company (PLN). (2021). Business plan for providing electricity. https://gatrik.esdm.go.id/frontend/download_index/?kode_category=ruptl_pln (accessed December 11, 2023).

Sultana, A., & Kumar, A. (2012). Optimal siting and size of bioenergy facilities using geographic information system. *Applied Energy, 94*, 192–201. https://doi.org/10.1016/j.apenergy.2012.01.052

Van Hung, T., Thuy, P., & L.Chi ĐT.. (2020). *Vietnam Forestry Development Strategy: Implementation results for 2006–2020 and recommendations for the 2021–2030 strategy*. Center for International Forestry Research (CIFOR).

Zhang, F., Johnson, D. M., & Sutherland, J. W. (2011). A GIS-based method for identifying the optimal location for a facility to convert forest biomass to biofuel. *Biomass and Bioenergy*. https://doi.org/10.1016/j.biombioe.2011.06.006

Zhunusova, E., Sen, L. T. H., Schröder, J.-M., Ziegler, S., Dieter, M., & Günter, S. (2019). Smallholder Decision-making on Sawlog Production: The Case of Acacia Plantation owners in Central Vietnam. *Forests, 10*, 969. https://doi.org/10.3390/f10110969