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Doctoral Dissertation

A multidisciplinary assessment framework of biomass energy plantation to support regional planning: A case study of Napier grass plantation in Thailand

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List of Publications

Research Articles

1. Nantasaksiri, K., Charoen-amornkitt, P., and Machimura, T. "Land Potential Assessment of Napier Grass Plantation for Power Generation in Thailand Using SWAT Model. Model Validation and Parameter Calibration", Energies 14(5), 1326, 2021.

2. Nantasaksiri, K., Charoen-amornkitt, P., Machimura, T. "Integration of multi-criteria decision analysis and GIS for site suitability assessment of Napier grass-based biogas power plant in Southern Thailand", Renewable and Sustainable Energy Transition 1, 100011, 2021.

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3. Nantasaksiri, K., Charoen-amornkitt, P., Machimura, T., and Hayashi, K. “Modeling Watershed Scale Impacts of Napier Grass Bioenergy Crop Cultivation on Water Resources and Quality Using SWAT Model”, International Conference on Materials and Systems for Sustainability, Japan, 2021
   Date: 4-6 November 2021 Online conference

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CHAPTER 1

Introduction

1.1 Background

1.1.1 Decarbonizing the societies at regional scales

The growth of energy consumption directly reflects social, industrial and economic development as well as population growth. Because the world energy consumption increases continuously, it eventually leads to overconsumption of energy. Since the amount of conventional energy resources is limited, this overconsumption becomes the energy crisis. Moreover, due to the reason that conventional energy resources used by human beings are fossil fuels and socio-economic development by the human activities is inevitable, the increase of fossil fuel consumption has caused CO_2 emission increase resulting in the problems associated with global warming and climate change at global scale. The challenge of the world set by the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) is to keep a global temperature rise in this century well below 2°C, preferably to 1.5°C [1]. Not only that, the United Nations Development Program (UNDP) also initiated the sustainable development goals (SDGs) showing the direct concern over energy crisis and CO_2 emission as well as the indirect concern over a wide range of social issues [2].

To achieve the goals of climate and sustainability issues, it is not possible to force slowing down the economic activity and thus decarbonizing the economy is a path forward that requires urgent action. In this regard, at the 26th Conference of the Parties (COP26) of the UNFCCC in 2021, countries vowed to secure global net zero carbon emissions by 2050 [3]. Approaches to achieve the goal are to accelerate the phase-out of coal, to curtail deforestation, to speed up the switch to electric vehicles, to encourage investment in renewables, etc. However, this is only a broad guideline to achieve the goals combating with climate changes. In order to reach the goals, it is important for every country to take an action through effective national energy policies.

1.1.2 Building regional policy and planning introduction of renewable energy

A transition of energy resources is underway across the world as they begin to shift the reliance on fossil fuels to cleaner, renewable energy sources. The harmful effects of fossil fuels on ecology and health are well recognized which provide sufficient reasons for governments to accelerate the transition to alternative sources of energy. Regardless of the urgent needs for action, the energy transition pace varies from country to country. It depends on factors such as resource endowment, political and social circumstances. To build national energy policies, it is very important to consider from multiple aspects, e.g. security of energy, competitiveness of the energy industry and environmental protection.

Energy security generally refers to ensure capable and reliable energy supplies at reasonable prices. Thus, an efficient renewable energy system can enhance the net energy of a country towards a sustainable development. All citizens in the country should be able to access affordable, reliable, sustainable and modern energy which are a part of the primary needs for living. A successful overall strategy for the security of energy would aim at reducing the gap between energy demand and supply, diversifying sources of energy supply, shifting to alternative and renewable sources of energy and reducing vulnerability to energy price fluctuations [4].

To mitigate global warming, reducing the emission of CO_2 and other greenhouse gases is the most priority. Thus, the development of carbon neutral society by utilizing renewable energy sources is important. To promote the use of renewable energy, the cost of renewable energy resources must be able to compete with that of the fossil fuels. However, with the present technology, it can be clearly seen that the cost of renewable energy resources is significantly higher. To help promote the use of renewable energy, the cost of renewable energy resources must be reduced. This could be achieved by either the improvement of renewable energy technology or the financial support at the initiation so that the renewable technology would finally experience economies of scale and be able to compete with fossil fuels. Since the climate situation requires urgent actions, the financial support is a promising approach to help facilitate the use of renewable energy. Since the role of the policy makers is to promote the use of renewable energy, the policy makers need to provide policies that help ensure the benefits of people in the country. An important support mechanism for enhancing renewable energy development is the Feed-in tariff (FIT) which is a policy to ensure sufficient earning for renewable energy investors by a long-term fixed price. This is to encourage the development of renewable energy and decreasing uncertainty for potential investors. However, the renewable energy price policy can be beneficial only for the energy suppliers. Although the goal is to ensure the benefits of people in the country, there are various aspects involving benefits of people. For example, the benefits of land use should be shared among stakeholders because the total land is limited. Furthermore, the renewable energy system introduced must be sustainable environmentally and economically. Therefore, multi-disciplinary assessment is very important in building a policy to help facilitate the use of renewable energy.

1.1.3 Biomass energy plantation as a renewable energy resource

Biomass is one of the most promising renewable energy sources and it is considered as carbon neutral. As of 2019, bioenergy is a significant part of the energy economy which accounts for approximately 9.5% of total primary energy supply [5]. More than the half of this energy is used in households as direct combustion for cooking and heating. For the other purposes, biomass also can be converted into liquid and gaseous fuels for transportation and for electricity generation. This approach is gaining attention from many developed countries as it helps avoid additional CO_2 emissions from fossil fuel use.

Energy can be produced from a variety of biomass sources such as wood and wood processing wastes, biogenic materials in municipal solid waste, animal manure and agricultural crop. They can be classified into the two primary categories: residues and wastes, and dedicated energy crops. Dedicated energy crops are specifically planted for utilizing in energy conversion processes and do not displace food production. The crops yield utilized as bioenergy resources need to be obtained with minimal energy inputs for crop production including cultivation, planting, harvesting and transport. This requirement is to avoid the impacts on environment. According to general criteria proposed by Henry [6] for selecting bioenergy crop species, they should be high biomass yield, high water-use efficiency and harvest index, high N use efficiency and low cost of harvest. Energy grasses gain interest as energy resource since they are fast-growing crops and produce a large amount of biomass per unit land area. Not only that, another advantage is that it can spread quickly and generate new shoots easily.

1.1.4 Needs of multidisciplinary assessment for planning biomass energy plantation

As mentioned earlier that multi-disciplinary assessment is very important in building a policy to help facilitate the use of renewable energy, this is also supported by the Agenda for Sustainable Development in 2030, which is a global call for action in sustainable development covering the areas from poverty eradication and the supply basic services in order to combating climate change and reducing inequalities [2]. The 17 goals stated in the agenda, the SDGs and their targets are integrated and indivisible. Therefore, to implement the agenda and goals in the related national policies, the interlink between socio-economic and nature must be considered.

Utilizing bioenergy can directly promote achievements to some SDGs, for instance, SDG 7 which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Increasing the proportion of renewable energy use in a country can help climate change mitigation as shown in SDG 13 (climate action) which is to take urgent action to combat climate change and its impacts and promoting developments in renewable energy. Introducing the new energy systems also leads to create job opportunities in regions (SDG 8) in the sectors of both direct and indirect which would help promote circular economy. On the other hand, since planting new dedicated energy crops would potentially affect water and land, there are several SDGs that are indirectly related to the use of bioenergy. For example, SDG 6 ensures safe and affordable drinking water and freshwater supplies, while SDG 15 conserves and restores terrestrial and freshwater ecosystems. It is clearly seen that introducing new bioenergy system involving many aspects related to human lives, economic and environment. This highlights the importance of a multidisciplinary assessment for the safe introduction of bioenergy as a renewable energy source.

1.2 Possibility of a large-scale introduction of Napier grass plantation in Thailand

1.2.1 Power generation situation in Thailand

The energy consumption in Thailand tends to increase annually due to the growth of population and economic activities. Figure 1.1 shows Thailand's power statistics from 1986 to 2020 in which power generation and peak demand have been gradually increasing [7]. It is worth mentioning that the power consumption in 2020 slightly decreased due to the COVID-19 pandemic which slowed down the economic activities in the country. Although the power consumption tended to be flattened since the 2014 Thai coup d'état, the power consumption in Thailand was expected to rise by 2.8-3.8% per year [7].

In 2021, Thailand Prime Minister Prayut Chan-o-cha stated in the COP26 that Thailand is determined to reach a net-zero emissions target by 2065, which is 15 years later than the 2050 deadline adopted by most countries [3]. There were also key agreements at the COP26 that Thailand did not sign, i.e., to end deforestation by 2030, to cut methane emissions by 30 percent before 2030 and to end coal use. Besides Thailand's lack of ambition and concrete commitments on those issues, Thailand agreed on speeding up the use of electric vehicles. The government plans to promote the use of electric vehicles and expects to have 30 percent of the all-automotive production to be battery electric vehicles by 2030. With the plan on banning the sale of conventional internal combustion engine vehicles on 2035, the government targets to have 30 percent of all cars used in Thailand to be EVs by 2025 [8].

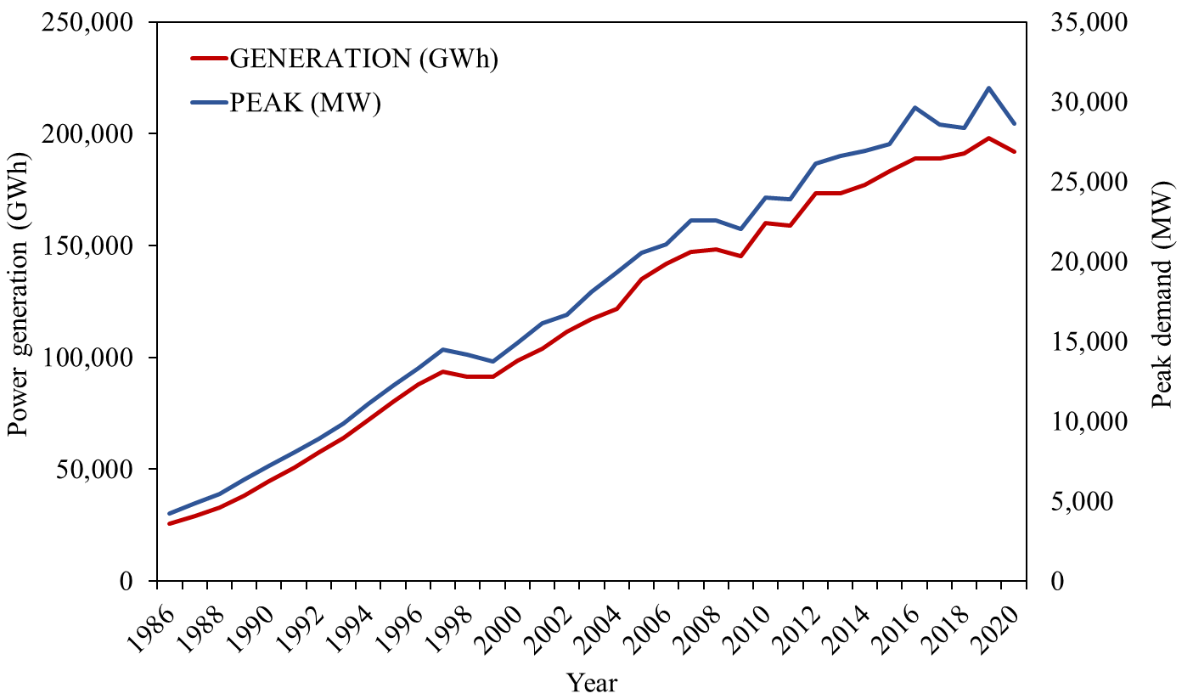

Figure 1.1 Annual power generation (red solid line) and annual peak demand (blue solid line) during 1986-2020

However, this could possibly cause the energy crisis considering the power generation capacity in Thailand and become a serious challenge on power generation in the country. Thailand has approximately 20 million units of registered cars, excluding motorcycles. Therefore, 30 percent of all cars used in Thailand is equivalent to 6 million units. Every household that owns a battery electric vehicle is expected to have a home charger so that they can charge their cars at home every night. A typical home charger has a capacity of approximately 7-8 kW which can fully charge a car from the state of charge of 0% to 100% within 6-10 hours depending on the size of the battery. If all households charge their cars at the same time, the power requirement will be around 42,000-48,000 MW, which far exceeds the present peak power demand. Together with the peak power demand, power generation of the country needs to be capable of providing approximately 80,000 MW. However, the installed generating capacity is only 50,000 MW [9]. Therefore, in order to achieve the target, increasing the power generation capability is a very important issue to be addressed at this moment. Switching the conventional internal combustion engine cars to battery electric vehicles with power generation mainly based on fossil fuels can increase carbon emission. To make the transition to battery electric vehicles green, cutting down the use of fossil fuel-based power generation and promoting the use of renewable energy is necessary.

1.2.2 Energy and climate change policies of Thailand

Renewable energies are required to sustain the environment and reduce the impacts of fossil fuel usage on the earth. Renewable and clean energies could also provide benefits to the energy security of the country. The energy resources that are categorized as clean energy are those which emit much less carbon as compared to the fossil fuels. Some of them are even carbon neutral. In Thailand, electricity was generated by Electricity Generating Authority of Thailand (EGAT) and private sectors. There are three main group of private sectors categorized by contracted power generation capacity which are independent power producers (IPPs), small power producers (SPPs) and very small power producers (VSPPs). The private-sector power generators accounts for over 53.4% of the total power generation while EGAT generated only 32.4% of the total national supply. EGAT and IPPs mainly use natural gas and coal as main sources of power generation, while SPPs and VSPPs typically generate power from renewable energy. Approximately 55.3% and 17.9% of power sources were obtained from natural gas and coal, respectively. This can be considered as a risk of energy-related situation since a huge proportion of energy sources is based on fossil fuels. A heavy reliance on one energy source, i.e., natural gas, could pose a problem on stability of power generation.

As of 2020, the alternative energy consumption in Thailand was approximately 15.51% of total energy consumption [9] which were utilized for electricity, heat energy and

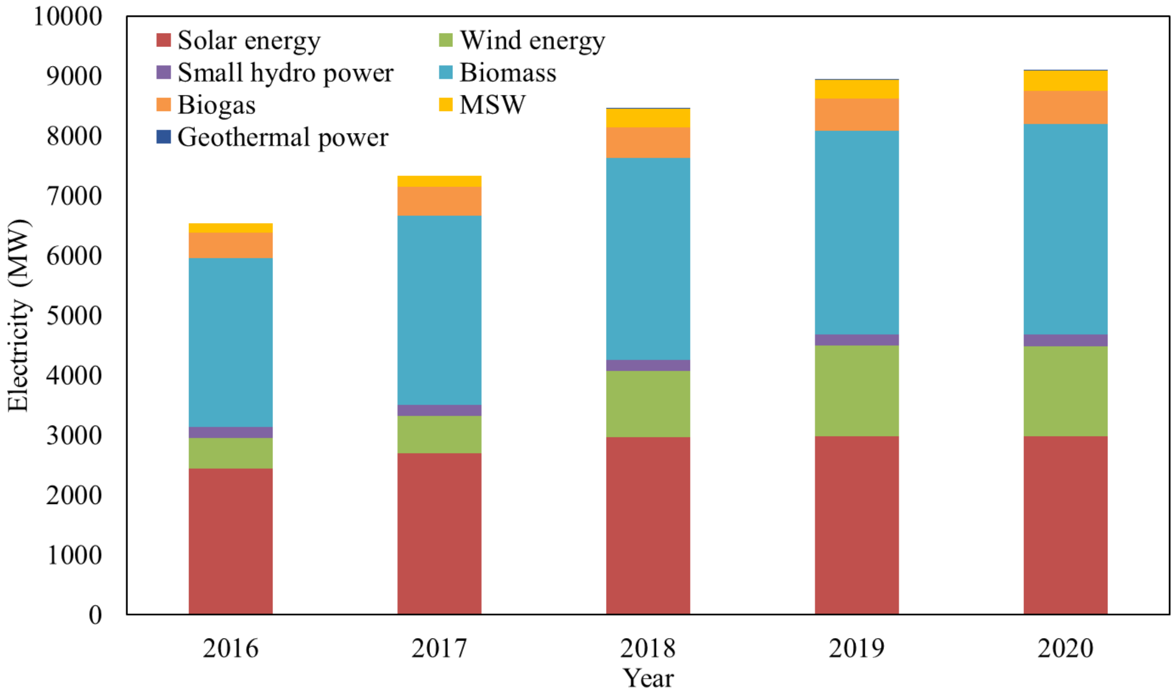

Figure 1.2 Installed capacity of electricity generated from renewable energy resources in Thailand during 2016-2020

biofuels. However, for electricity generation, renewable energy shared only 10% of the total energy production which is around 9,053 MW. Figure 1.2 shows the proportion of the installed capacity of renewable energy in Thailand. Biomass power plants were the largest which accounts for more than 29% of the total installed capacity. This follows by solar energy and large hydro power plants which are approximately 24% each. Biogas power plants show the good potential since the capacity was increased approximately 30% from 2016 (435 MW to 560 MW). However, the power generation from renewable energy at this moment is only 53% of the target set by Thailand's ministry of energy (MoE) which is producing 16,778 MW from renewable-based power supply by 2036 [9].

To reduce the share of fossil fuel consumption, the use of renewable energy such as wind, solar, biomass and biogas should be promoted. However, there are many factors need to be considered before implement such power generation. For instance, in the case of photovoltaics, cost, solar radiation, ecosystem impacts and policy enforcement should be assessed before implementing a solar farm. Even though solar energy is clean and renewable, photovoltaics may not suitable for all areas. Photovoltaics require a large area for power generation. Solar radiation provides power of around 1000 $W \cdot m^{-2}$. With an efficiency of around 20%, a 1 MW power plant requires an area of around 0.5 ha. Among the several candidates for such clean energy, biogas, which is a gaseous fuel obtained from the organic matter decomposition, has received widespread attention. Moreover, it is more suitable as compared to other renewable energy types because it is carbon neutral, promotes job creation, and do not need to concern about material recycling. Biogas feedstock can be found in various forms, such as agricultural residues, forestry products, animal wastes and dedicated energy crops. Biogas energy derived from dedicated energy crops can be considered as a carbon neutral resource because, although the carbon is released during the process of power generation, the same amount of carbon is absorbed by the crops as they grow. Their advantages were not only limited to carbon neutrality but also higher yield and shorter life cycle which are characters of a stable fuel supply. However, for the wide-scale use of these energy crops, there are several aspects to be considered prior to deciding land use change for energy plantations to avoid socioeconomic and environmental issues [10-13].

1.2.3 Napier grass plantation in Thailand

Dedicated energy crops are cultivated specifically for being converted into other forms of energy. There are many dedicated energy crops available in the market. For instance, palm oil, Jatropha, cassava, and sugar cane are those used in Thailand. However, one of the most promising energy crops gained attention from Thailand MoE is Napier grass. Napier grass (*Pennisetum purpureum Schum*) is originated in South Africa and was first imported to Thailand in 1929. The Napier grass is a tall perennial grass which is highly resistant, easily cultivated and fast growing. The three main species of Napier grass, which are usually planted in Thailand, are Napier grass, King grass (*Pennisetum purpureum CV. King grass*) and Mott dwarf elephant grass (*Pennisetum purpureum CV. Mott*). The Department of Livestock Development of Thailand has developed a new species, namely Napier grass CV. Pak Chong 1, which is a combination between pearl millet grass (*Pennisetum americanum*) and King grass. Napier grass CV. Pak Chong 1 has a high potential as it is relatively high in nutrients for animal and high dry matter yield (DMY) as compared to the others [14]. Biogas generated from Napier grass can be utilized in 2 applications which are electricity generation and compressed biogas production for transportation.

However, to plant dedicated energy crops, there are many aspects to be considered before deciding land use. Planting dedicated energy crops without considering related impacts can lead to the deterioration of land and possibly the ecosystem health. Thus, effects of Napier grass plantation and its impacts on socioeconomic and environmental issues need to be assessed prior to introducing it to a large-scale plantation.

1.3 Objectives and structure of the thesis

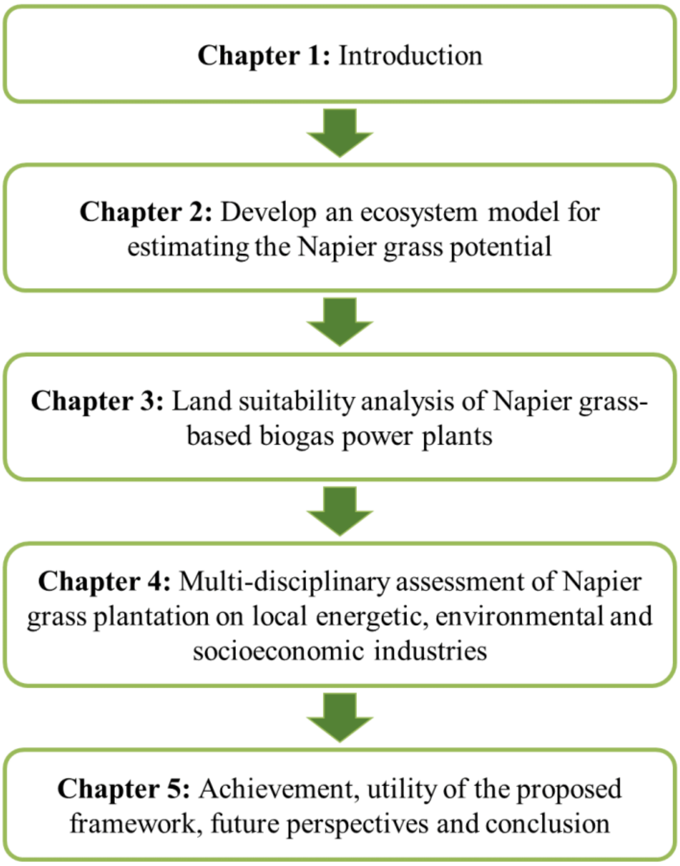

Figure 1.3 Thesis outline

The thesis consists of five chapters. Figure 1.3 reports the study structure and its links among the chapters. With this background, the objective of this work is to establish a logical framework to support decision-making for implementing new dedicated energy crops as a biogas feedstock, which is useful for the transition toward renewable and sustainable energy society. In order to do that, it is important to evaluate Napier grass DMY beforehand. However, as Napier grass is not yet widely planted in Thailand, it is not possible to estimate the land potential for biogas-based power plants. In chapter 2, the SWAT model for evaluating the land potential for Napier grass plantation in Thailand under different climatic and soil conditions across the country was developed. To apply the model, the parameters specific to Napier grass are required. However, these parameters have never been available in the study area. Sensitivity analysis, parameter calibration, and model validation were carried out and the model was later applied to develop the spatial distribution of the Napier grass when planted on abandoned croplands in Thailand. The results shown in this chapter are important for land suitability analysis to examine sites for Napier grass plantations and biogas power plants. In chapter 3, methodological framework for planning biogas power plant locations using energy crops along with the essential siting criteria to design the effective geographic allocation was developed. To locate the suitable sites for the bioenergy-based power plants, many aspects were considered such as distance from roads, distance from residential areas, supply of feedstock, etc. Land suitability analysis was conducted using AHP-MCDA analysis along with the spatial distribution of Napier grass DMY obtained in chapter 2. The results obtained from this chapter were further investigated the effects of Napier grass plantation with different management practices on hydrology and water quality in southern Thailand using SWAT model in chapter 4. The results of surface runoff, sediment yield and nitrate load which are considered as indicators of environmental burdens were determined. Based on the results on hydrology and water quality, multidisciplinary assessment was conducted for supporting decision-making for utilizing Napier grass as a feedstock for biogas-based power generation. By this analysis, the advantages and disadvantages among cultivation practice cases having different fertilizing levels would be assessed. Overall, a logical framework to support decision-making for implementing new dedicated energy crops as a biogas feedstock can be obtained considering socio-economic and environmental issues.

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CHAPTER 2

Napier grass dry matter yield estimation using the SWAT model

2.1 Introduction

The average amount of atmospheric carbon dioxide (CO_2) increases every year due to the use of fossil fuels in energy production, resulting in the current problems associated with climate change. At present, the planet's temperature is higher than it has ever been over the past 12,000 years [1]. Moreover, the world's energy consumption is increasing annually, which, in the near future, will result in a severe energy crisis. Thailand is at risk in energy situation since approximately 55.3% of its energy resources used in power generation are derived from natural gas [2]. A heavy reliance on only one energy source may cause some problems. For example, if the system failed to transport natural gas through pipeline, electricity could not be generated. It impacts would be severe because of such a heavy reliance. Therefore, reducing the use of conventional energy would provide benefits in energy stability. As of 2020, the proportion of electricity produced from renewable energy is approximately 10% of the total electrical production capability of Thailand [2]. Therefore, the proportion of renewable energy resources should be promoted in order to satisfy SDGs

One of the most promising energy crops which gained attention from Thailand's Ministry of Energy due to its growth rate and high methane content is Napier grass. Napier grass was initially introduced to Thailand in 1929 as animal feed. With the tropical climate, Thailand is very suitable for Napier grass production since the grass would stop growing if the ambient temperature were lower than 15 °C [3]. To implement Napier grass as a new feedstock for electricity generation in Thailand, land suitability analysis should be carried out to minimize its impacts on land. However, to obtain effective results, the spatial distribution of the Napier grass DMY should be obtained. Therefore, assessing the land potential before planting takes place is necessary.

Although there were many approaches to develop the spatial distribution, such as obtaining the yield through field surveys or statistical data and utilizing them to create a spatial distribution map, these approaches are not suitable for the crop that has never been plant before like Napier grass. The suitable approach should be utilizing a model to estimate the yield that accounts for the change in soil, water, and weather conditions. There were many existing models to estimate the yield of crops, but a dynamic crop model is the most promising [4]. Over the past few decades, the dynamic crop models were widely used for estimating the interaction between environment and management practices to crop yield. The example of dynamic crop models are the environmental policy integrated climate (EPIC) model, the ALMANAC model, the Agro-BGC model, and the SWAT model. Besides the advantage that the SWAT model can assess the long-term impact of land use for various crops [5,6], it is an open-source tool, and thus it is more flexible as compared to the other models [7-9]. Also, it exhibits a user-friendly graphic user interface. For the SWAT model, to simulate crop growth, the model requires more than 30 specific parameters related to the plant of interest.

In the SWAT database, 120 crops are available with the relevant parameters. However, Napier grass parameters are not on the list. Therefore, performing land suitability analysis to find locations for Napier grass plantations, anaerobic digesters, and biogas power plants, all of which are important for Napier grass supply chains, is not possible. Although some of the parameters can be obtained from previous studies, some parameters are still missing. Therefore, sensitivity analysis as well as parameter calibration are necessary to obtain the set of parameters for the crop in question. Therefore, in this chapter, the main objective was to evaluate the Napier grass DMY in Thailand using the SWAT model. This model will account for different climatic and soil conditions across the country. To utilize the model, the parameters specific to Napier grass are required but these parameters have never been available in the study area. Sensitivity analysis and parameter calibration were carried out using the root mean square error (RMSE) of yield as a criterion to obtain the set of parameters. A range of parameters obtained from previous studies was utilized in the calibration process to ensure that the parameters are realistic. The time-series DMY calculated using the calibrated parameters was validated with the biomass yield obtained from experimental surveys over 10 years. The model was further applied to estimate the overall energy supply potential of Napier grass when planted on abandoned areas in Thailand. Only abandoned areas were considered to promote the utilization of abandoned areas as well as to avoid conflicts with existing industrial, urban, economical, and agricultural lands. The obtained results can be further utilized in land suitability analysis to examine sites for Napier grass plantations and biogas power plants.

2.2 Materials and Methods

2.2.1 The Soil and Water Assessment Tool and the Procedure for Parameter Selection

The SWAT model was developed by the Agricultural Research Service and Texas A&M University [10]. The model was run in ArcMAP 10.1 via the SWAT model user interface called ArcSWAT. Soil, land use, and elevation data were integrated into a homogeneous physical property to create hydrological response units (HRUs). This creates unique load combinations within sub-basin boundaries. After the HRUs were obtained, specific inputs such as crop parameters and management practices were combined with each HRU to examine the land load conditions. This model operates on a daily timestep. There are many components in the model, such as weather simulation, hydrology, nutrient cycling, and plant growth. However, since the main concern is to create the spatial distribution of Napier grass DMY in Thailand, only parameters related to biomass growth were considered. The crop growth calculation in the SWAT model [10] is based on the EPIC plant growth model developed by Monteith [11]. The model is capable of simulating several crops such as legumes, perennials, and trees. Each crop requires unique model parameter values. The model simulates the leaf area development of crops and the total solar radiation and using light interception, the intercepted photosynthetically active radiation can be obtained. These outputs were later converted into the total dry biomass growth based on species-specific radiation-use efficiency. The daily solar radiation intercepted by the crop leaves was estimated using Beer's law [10] which can be expressed in Eq. (2.1) as

$$H_{phosyn} = 0.5 \cdot H_{day} \cdot (1 - exp(-k_t \cdot LAI)) \tag{2.1}$$

where H_{phosyn} is the intercepted photosynthetically active radiation (MJ·m^2), H_{day} is the total solar radiation (MJ·m^2), k_t is the light extinction coefficient, and LAI is the leaf area index.

The product of intercepted photosynthetically active radiation and radiation-use efficiency of the crop of interest provides the daily total dry biomass growth as shown in Eq. (2.2) [10].

$$\Delta bio = BIO\_E \cdot H_{phosyn} \tag{2.2}$$

where Δbio is the total biomass growth on a given day (kg·ha^{-1}) and BIO_E is the radiation-use efficiency (kg·ha^{-1})/(MJ·m^2).

Table 2.1 List of parameters setting for Napier grass in the SWAT2012 crop database [12-16]

Parameter	Range	Initial value	Definition (unit)
BIO_E	35-53	47	Radiation use efficiency in ambient CO_2 (kg/ha)·(MJ/m^2)$^{-1}$
HVSTI	0.8-1.0	0.9	Potential harvested index for the plant at maturity
BLAI	6.0-8.0	6.2	Potential maximum leaf area index of the plant (m^2·m^{-2})
FRGRW1	0.1-0.15	0.15	Fraction of the growing season related to the 1st point on leaf development curve
FRGRW2	0.2-0.6	0.5	Fraction of the growing season related to the 2nd point on leaf development curve
LAIMX1	0.01-0.2	0.01	Fraction of maximum LAI related to the 1st point on leaf area development curve
LAIMX2	0.6-0.95	0.9	Fraction of maximum LAI related to the 2nd point on leaf area development curve
DLAI	0.45-1.0	0.95	Fraction of growing season at which growth process become dominant

In Eqs. (2.1) and (2.2), the parameters specific to a crop are LAI and BIO_E. LAI exhibits subsequent effects on the total amount of $\mathrm{H}_{\mathrm{phosyn}}$ and Δbio estimation. However, calculating the LAI curve is complicated as many parameters are involved. These parameters are not only used for LAI calculation, but are also closely tied to the other equations. Moreover, they can also be used to evaluate the potential harvest index, which directly affects the final biomass yields. After carefully investigating the set of equations related to crop growth, there are eight unique parameters. Although these parameters were provided by Gil et al. [12], after the preliminary attempt to apply this set of parameters, including the potential heat unit (PHU), to estimate the Napier grass DMY in Thailand was conducted, the model overpredicted the biomass growth and failed to predict harvesting schedules, as shown in Fig. 2.1. This is likely because on different weather conditions of each country, which affected the

PHU for crop growth. PHU is defined as the accumulated heat unit required for plant maturity. It is one of the major indicators defining when to harvest biomass. However, even when the harvesting schedule was used as in the experimental conditions (e.g., the biomass was harvested around every 70 days), the cutting schedule was approximately two times longer than that of the experimental conditions, resulting in two times higher simulated yield as compared to the observed yield. The aforementioned parameters were calibrated to accurately predict Napier grass DMY. However, to ensure that the obtained parameters were realistic, a range of parameters used in the calibration was obtained from various studies [12-16]. Table 2.1 provides the parameters (and their ranges) calibrated in this study.

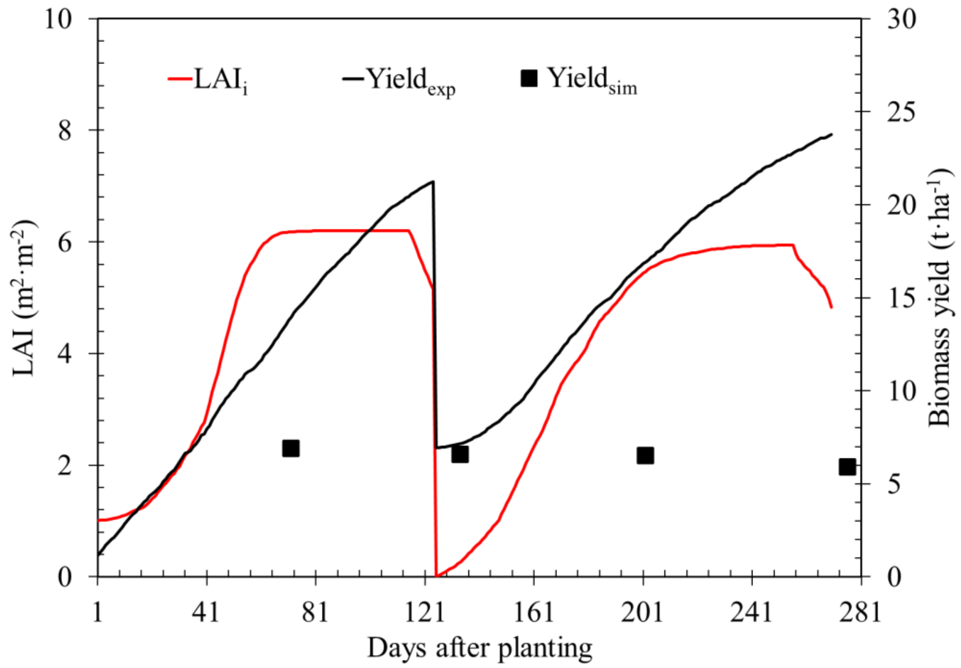

Figure 2.1 Simulation results for the development of LAI (red line) of Napier grass with the set of parameters (initial parameters) obtained from Gil et al. [11] and comparison of experimental yield at harvest (black squares) and simulated yield (black line) at Sukhothai plantation from May 2001 to April 2002 [17].

2.2.2 Data Sources and Model Setup

The input data are provided in Table 2.2. To utilize the SWAT model in yield prediction, the setup procedures consisted of 3 steps. First, DEM data obtained from CGIAR CSI [18] with the resolution of 90 m was used to determine slope, slope length and the stream network of each basin. This results in the topography map. Second, the topography map was combined with the data of soil, slope, and land cover to obtain HRU. The land cover data were obtained from GlobCover 2009 [19] provided by European Space Agency (ESA) and the land cover map developed by the Land Development Department (LDD) of Thailand. The GlobCover2009 contained only forest and agricultural data. However, it lacks local land use data. Therefore, data from the LDD were integrated with the data from ESA to locate abandoned and urban area in Thailand. Soil data used in this work were obtained from FAO-UNESCO harmonized world soil database [20]. The soil map contained the data of soil components, soil hydrologic groups, and acidity and alkalinity level in soil. Finally, after obtained the HRU map, it was integrated with weather data to create a ready-to-use map. Historical weather data, including the daily data of maximum and minimum temperature, precipitation, solar radiation, and wind speed, were obtained from the Thai Meteorological Department (TMD). However, it was found that, in some areas in Thailand, the data were not available. Therefore, the weather data from the National Centers for Environmental Prediction (NCEP) [21] as suggested by SWAT model were used in those areas instead. The reason for combining the data from those two sources was because the data from TMD provide a better resolution. Future weather data were generated by weather generator algorithm (dGEN) provided by the SWAT model.

The experimental data of Napier grass plantation used in the calibration and validation processes were obtained from the published reports by Animal Nutrition Division (AND), Department of Livestock Development, Ministry of Agriculture and Cooperatives of Thailand, during 1993–2005 [17,22-29]. In these works, the effects of management practice on the growth of Napier grass were carefully studies. The studies were conducted all over Thailand except the southern area. In total, 93 samples were obtained from nine reports in eight provincial pilot plants.

Table 2.2 List of data used in this work for SWAT2012 simulation

Data	Resolution/Type of data	Year	Source
Digital Elevation Model (DEM), (STRM 90 m)	90 m	-	United States Geological Surveys (USGS)
Land Use/Land Cover, (GlobCover 2009)	300 m	2009	European Space Agency (ESA)
Land cover	Polygons	2009-2014	Land Development Department of Thailand (LDD)
Soil data, (Harmonized World Soil Database v 1.2)	30 arc-second rasters	-	FAO-UNESCO harmonized world soil database
Weather data	Weather observing station	1993-2005	Thai Meteorological Department (TMD)
Weather data	2.5º x 3.75º	1979-2014	The National Centers for Environmental Prediction (NCEP)

As mentioned earlier, the PHU was crucial for the harvesting schedule. This parameter is unique for the growth of Napier grass in a country. Thus, it is important to calculate the PHU specifically for a country. To estimate for the PHU, the heating unit (HU) is required. The HU is basically defined as the difference of the average temperature for a day and the base temperature. In this work, the base temperature was assumed to be equal to the critical temperature below which Napier grass would not fully grow. The critical temperature for Napier grass is 15 °C based on the suggestion of Kiyothong [3]. The calculated HU was summed from the first to the last days of a harvesting cycle to obtain the PHU of each pilot plant. Assume the temperature was not much different throughout Thailand, the PHUs of eight pilot plants were later averaged resulting in 1300 °C as an input of the model. This value was set to be constant for all simulations. From the studies of AND, the level of N-fertilizer application was categorized into four groups which are 0 kg-N·ha^{-1} (Con), 125 kg-N·ha^{-1} (T1), 250 kg-N·ha^{-1} (T2), and 500 kg-N·ha^{-1} (T3).

2.2.3 Sensitivity Analysis, Parameter Calibration and Model Validation

As mentioned above, the SWAT model provides many components for simulation resulting in numerous parameter input. However, if all parameters are treated equally, calibration process will consist of an unrealistically high number of simulations. It would lead to impractical computational loads [30,31], which is time-consuming. Accordingly, the number of parameters was limited to those used in predicting crop growth, resulting in only the eight crop growth parameters, as listed in Table 2.1. Prior to conducting the parameter calibration, sensitivity analysis was performed to assess the sensitivity level of each parameter with respect to predicting biomass yield. To do so, the relative sensitivity index (S_r) defined in Eq. (2.3) was used [32,33]:

$$S_r = \frac{I_{in}}{O_{in}} \cdot \frac{O - O_{in}}{I - I_{in}} \tag{2.3}$$

where I is the model input parameter, O is the model output, and the subscript in refers the initial value of the parameters. A high index value means that the model outputs are sensitive to the input parameters. Lenhart et al. [34] suggested that indexes of 0.0–0.05, 0.05–0.20, 0.20–1.00, and >1.00 demonstrate negligible, medium, high, and very high sensitivity, respectively.

To investigate the parameter sensitivity, only one parameter was changed at a time to estimate the model response while the other parameters were kept constant. By modifying the parameters within the range listed in Table 2.1, the parameter sensitivity could be obtained. The initial values were obtained from Gil et al. [12]. Considering the parameter sensitivity, the number of parameters requiring calibration can be reduced. The RMSE of yield was set as the objective function in the parameter calibration process. In total, all 93 datasets were used for parameter calibration. The model performance was later evaluated using statistical analysis which are the RMSE, mean error (ME), and coefficient of determination (R^2).

2.2.4 Land potential Evaluation and Estimation of Energy Supply Potential by Napier Grass Biomass in Thailand

Only abandoned areas were selected for plantation sites to examine the primary potential of Napier grass in Thailand. The location of abandoned areas in Thailand was obtained from LDD for 2009–2014. The simulated Napier grass DMY from the SWAT model was integrated with GIS via ArcMap 10.1, resulting in the spatial distribution of biomass yield. The results will be further utilized in estimating the Napier grass-derived energy supply potential by assuming that all yields obtained from abandoned croplands can be utilized as feedstock in power generation. Thailand was categorized into six geographical regions, as suggested by the National Geographical Committee: central, eastern, northeastern, northern, western, and southern regions. The derived energy supply potential was compared with the statistical data of electric consumption provided by EGAT [2].

2.3 Results and Discussion

2.3.1 Sensitivity Analysis and Parameter Calibration

As presented in Section 2.2, eight parameters were unique to Napier grass growth, whereas the others were obtained from previous studies [12-16]. The most sensitive parameter was the first to be adjusted to minimize the RMSE value, whereas the others were kept constant. Next, the second most sensitive was adjusted, and the process was repeated accordingly for the remaining parameters. The sensitivity index of each parameter is depicted in Fig. 2.2. The analysis was performed by considering the upper and lower limits of the range shown in Table 2.1. These limits were obtained from previous studies to ensure that the parameters used in the present study are realistic. All parameters displayed the same direction of the sensitivity index, except FRGRW2. In FRGRW2, the lower limit value provided a positive index, whereas the upper gave a negative value. By increasing FRGRW2,

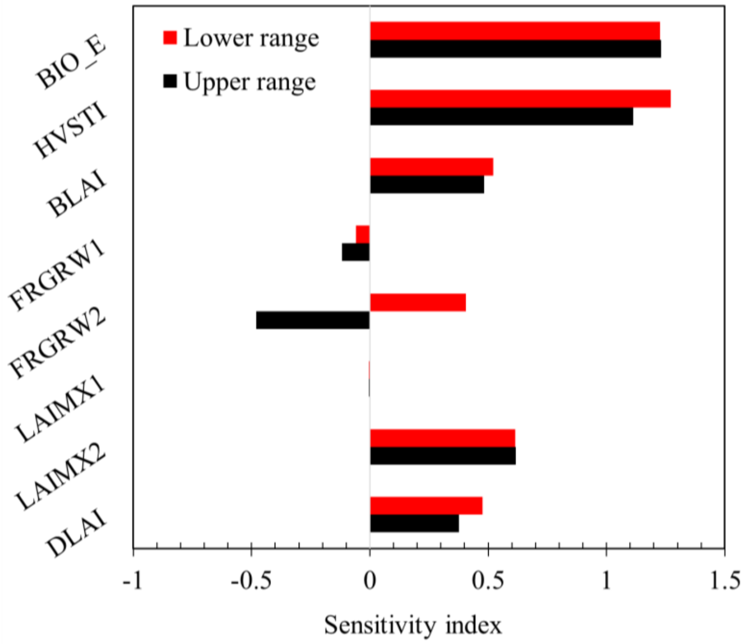

Figure 2.2 Comparison of the evaluations of sensitivity indices for the 8 parameters within their upper (■) and lower (■) range shown in Table 2.1.

which is the fraction of the growing season, to the second point on the optimal leaf area development curve, the leaf area development curve can be extended and the slope of the curve reduced. This means that a plant will take longer to grow, resulting in a negative sensitivity index. According to Beer's law expressed by Eq. (2.1), the amount of daily solar radiation intercepted by the leaf area of the plant H_{phosyn} is maximized only when the LAI is large. Since the rate of biomass growth Δbio is directly proportional to H_{phosyn} (see Eq. (2.2)), the biomass yield will be small if the process of developing leaf area is relatively slow.

The results of this analysis suggest that the sensitivity index of the studied parameters varies between negligible (–0.004 for LAIMX1) and very high (1.273 for HVSTI). Only two parameters, FRGRW1 and LAIMX1, demonstrated a negligible influence on simulated yield, although, according to their definition, they are directly related to the leaf area development

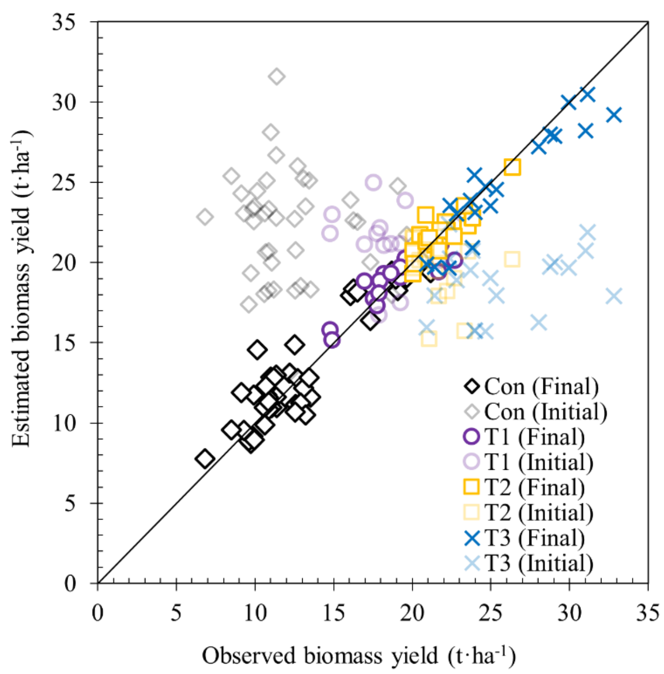

Figure 2.3 The goodness-of-fit plots with 1:1 line comparing the estimated and simulated dry matter yield of Napier grass with the 2 different sets of parameters which are the parameters before and after calibration under different N-fertilizer levels where C, T1, T2, and T3 represent N-fertilizer level of 0, 125, 250 and 500 kg·ha^{-1}, respectively

curve. This is unsurprising because FRGRW1 and LAIMX1 indicate the first point on the leaf area development curve. The other parameters were classified as demonstrating medium to very high sensitivity. The most sensitive parameters are BIO_E and HVSTI with sensitivity indexes of 1.230 and 1.273, respectively. These results are consistent with existing research [34], which analyzed the sensitivity of parameters to the yield of Switchgrass and Miscanthus. DLAI, BLAI, FRGRW2, and LAIMX2 exhibit medium sensitivity. As FRGRW1 and LAIMX1 were the least sensitive parameters, they were not adjusted in the optimization process. The calibration results in the reduction of the RMSE from 10.77 to 1.38 $t \cdot ha^{-1}$. The goodness-of-fit plot for simulated yield with the initial and final parameter sets is shown in Figure 2.3. The final parameters for Napier grass are displayed in Table 2.3.

Table 2.3 Parameter setting for Napier grass in SWAT model crop file and the RMSE of yield by initial and final values after calibration process

Parameters	Initial value	Final value
BIO_E $(kg/ha) \cdot (MJ/m^2)^{-1}$	47	38
HVSTI	0.9	0.8
BLAI $(m^2 \cdot m^{-2})$	6.2	6
FRGRW1	0.15	0.15
FRGRW2	0.5	0.2
LAIMX1	0.01	0.01
LAIMX1	0.9	0.7
DLAI	0.95	0.55
RMSE of yield $(t \cdot ha^{-1})$	10.77	1.49

Table 2.4 Mean simulated and observed Napier grass dry matter yield (DMY) in t·ha^{-1} depending on different treatments and statistical analysis results (RMSE, ME and R^2)

Treatment	Mean DMY (t·ha^{-1})		RMSE (t·ha^{-1})	ME (t·ha^{-1})	R^2
	Measured	Simulated			
Con (n=42)	12.58	12.83	1.491	0.249	0.81
T_1 (n=15)	18.60	18.68	1.163	0.083	0.74
T_2 (n=17)	21.94	21.87	0.866	-0.076	0.72
T_3 (n=19)	25.85	24.90	1.634	-0.949	0.64
All (n=93)	17.97	17.89	1.380	-0.082	0.95

2.3.2 Model and Parameter Validation

The parameters obtained from the calibration process were used to confirm the model validity. The sample temporal change plot of LAI curve development, the growth of simulated biomass yield, and the Napier grass DMY obtained experimentally during yearly cultivation are depicted in Fig. 2.4. The data shown in Fig. 2.4 was the data from Sukhothai plantation from May 2001 to April 2002 [29]. Day one of simulation was set to be the day after planting. According to the reports of AND, the first harvest was made on the 75th day, and the following harvests were performed every 60 days. The parameters obtained after calibration provide results (the solid lines) that are consistent with the harvesting schedule. Since the experimental LAI data were not available, the biomass growth was used for validation instead. The black line represents the predicted biomass growth, whereas the squares represent the yield obtained experimentally. The simulation results agreed well with the experimental data. The obtained yield outputs were statically analyzed to examine the model validity, as shown in Table 2.4. The average simulated Napier grass DMY is consistent with the average value for all N-fertilizer levels. In summary, the average measured and simulated DMY values are 17.97 and 17.89 $t{\cdot}ha^{-1}$, respectively. It is worth mentioning that, when the N-fertilizer level increases, R^2 decreases. This possibly can be attributed to the fact that planting conditions are highly manipulated when too much N-fertilizer is applied. Indeed, more information would help in making better predictions for cases with high N-fertilizer levels. Regardless, it is clear that the model can successfully and accurately estimate Napier grass DMY (R^2 = 0.95, ME = −0.082 $t{\cdot}ha^{-1}$, and RMSE = 1.380 $t{\cdot}ha^{-1}$). Although the experimental data were collected from eight provincial pilot plants over Thailand, the proposed model exhibits no apparent biases. In other words, the model is appropriate for investigating the land potential of Napier grass plantations under different land conditions in Thailand.

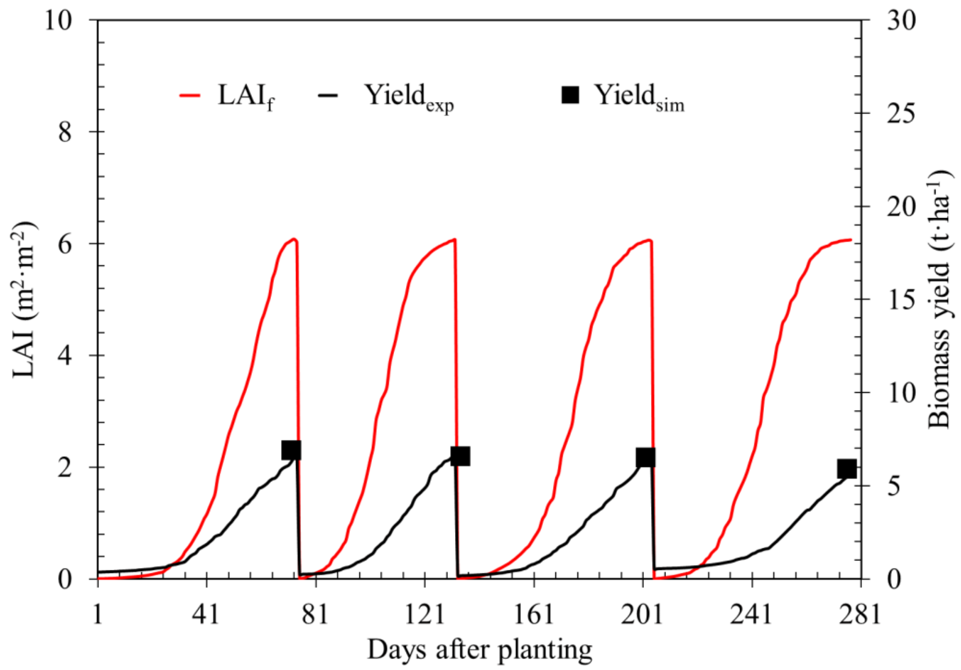

Figure 2.4 Simulation results for the development of LAI (red line) of Napier grass with the set of parameters (final parameters) obtained after parameter calibration and comparison of experimental yield at harvest (black squares) and simulated yield (black line) at Sukhothai plantation from May 2001 to April 2002 [17]

2.3.3 Application of Soil and Water Assessment Tool in the land Potential Evaluation of Napier Grass Plantations in Thailand

To obtain the spatial distribution for Napier grass DMY in Thailand, the model was applied to abandoned areas all over the country. This was conducted to avoid conflicts with industrial, urban, economical, and agricultural land; moreover, abandoned areas can be found all over Thailand, and we believe they should be effectively utilized. In total, the abandoned area of Thailand is approximately 2,200,000 ha, which is roughly 4.2% of the country. Simulations were carried out for a 20-year timespan with two warm-up years [36]. For management practices, as suggested by Kiyothong [3], 250 kg-N·ha^{-1} was used for the N-fertilizer level and irrigation was applied.

The spatial distribution of Napier grass DMY is displayed in Figure 2.5. This spatial distribution was the average simulated Napier grass DMY over 20 years in Thailand. Note that, for a better depiction of simulation results, all areas were included in the figure, except urban areas and the national forest reserves. Most of the abandoned areas can provide Napier grass DMY values in the range of 15–25 t·ha^{-1}·year^{-1}, which is a high output [3]. Low outputs are associated with areas dominated by clay soil, represented by the red area in Figure 2.5. These results reasonably agreed with the experimental results of Wijitphan and Lowilai [37], which suggest that grass prefers soil with good drainage ability.

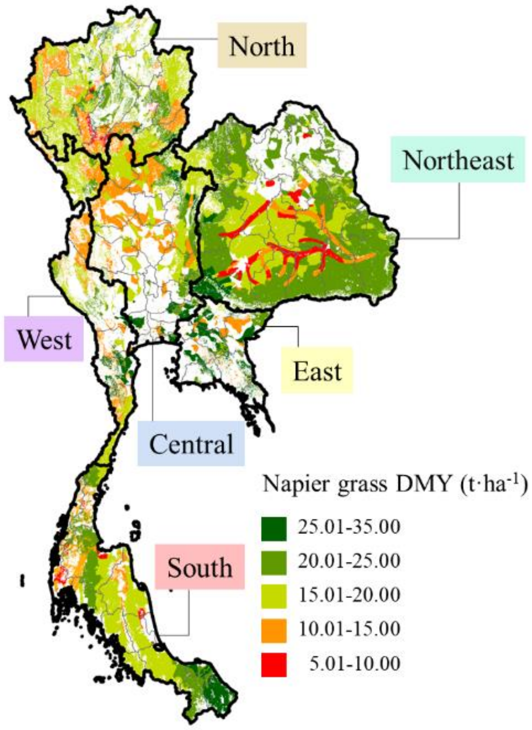

Figure 2.5 Spatial distribution of simulated mean yield per hectare of Napier grass in Thailand.

2.3.4 Potential of Power Supply Generated by Napier Grass in Thailand

Since the SWAT model, together with ArcMAP 10.1, provides the spatial distribution of Napier grass potential, it allows researchers and energy-related policymakers to assess the potential of power supply generated by Napier grass. Considering only abandoned areas, the results suggest that Thailand demonstrates good potential with respect to providing sufficient amounts of Napier grass DMY (approximately 42 megatons per year). Several approaches exist to utilize the DMY for electric production, one of which is anaerobic digestion, which converts the DMY into methane. According to Janejadkarn and Chavalparit [38], this approach could provide methane yields as high as 242 m^3 per ton of Napier grass DMY. Assuming the energy density of methane is 40 $MJ \cdot m^{-3}$ [39] and that thermal power plants based on combustion boilers and stream turbines with an efficiency of approximately 30–

40% are used to generate electricity, Napier grass DMY from abandoned areas can generate roughly 33,600–44,900 GWh of electricity every year, which is equivalent to 20–26% of Thailand's total energy demand.

Although this is a rough estimation, it is clear that Napier grass can help Thailand move toward renewable energy generation. By substituting conventional fossil fuels with Napier grass-derived natural gas for electric generation, CO_2 emissions can be also be reduced from 1080 to 450 kg-CO_2·MWh^{-1} [40]. Moreover, if all abandoned areas are utilized, the CO_2 emissions from power plants could be reduced by approximately 21.2–28.3 Mt-CO_2. It is worth noting that, although the combustion of Napier grass-derived natural gas also produces CO_2, the process is carbon neutral and does not require additional CO_2 to be added to the system.

Table 2.5 summarizes the regional data used in the potential assessment, e.g., electric consumption, estimated DMY, and Napier grass-derived electric supply potential. Average DMY obtained from southern Thailand was found to be the highest. The southern region can provide an average yield of 22.3 t·ha^{-1}, whereas the western region provides the lowest average yield (16.0 t·ha^{-1}). Considering the supply–demand ratio of each region, Napier grass could supply roughly 39.9% of the total energy demand for the northeastern region and approximately 28.0% for the northern and southern regions. However, a low ratio was found in the eastern and central regions, as these are mostly industrial and urban areas, and thus demand large amount of electricity.

Figure 2.6 depicts the provincial distribution of Napier grass-derived electric supply potential, total electric consumption per capita, and the supply–demand ratio. Although the spatial distribution in Figure 2.5 reveals that the south-northeastern region shows potential for Napier grass plantation, low electricity generation can be observed for this area in Figure

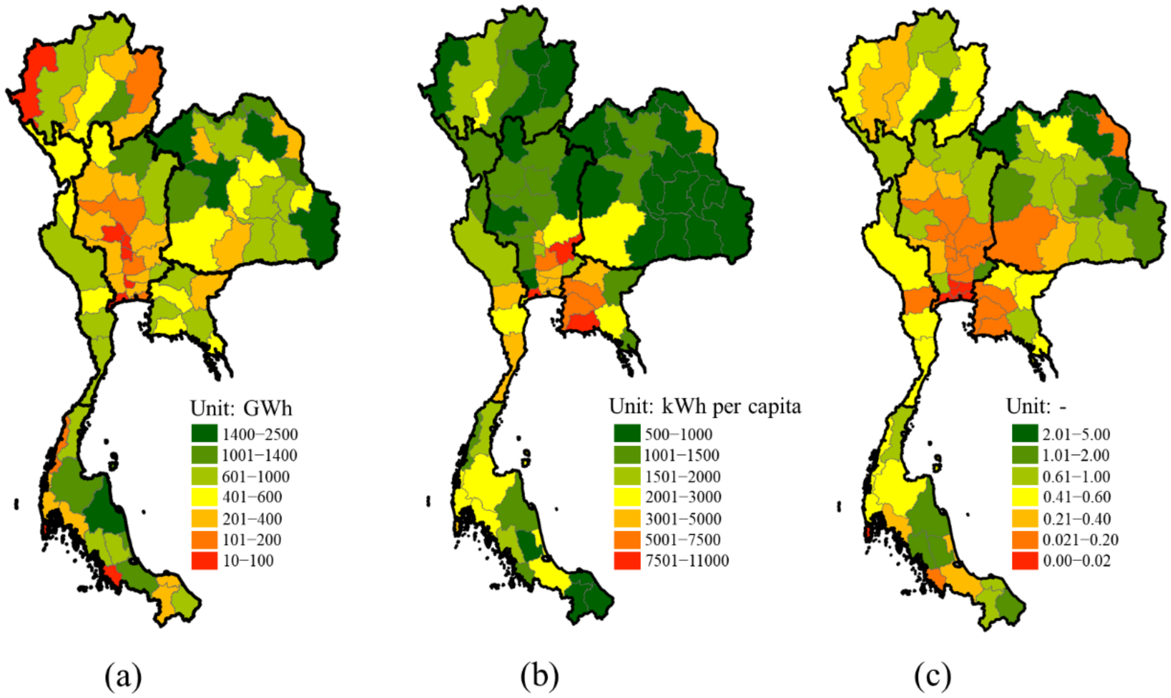

Figure 2.6 Provincial distribution of (a) Napier grass-derived electric supply potential, (b) total electric consumption per capita, and (c) the supply-to-demand ratio

2.6a. This can be attributed to the availability of land. In Figure 2.6b, in addition to the central and east regions, which possess a high electric consumption per capita due to industry, it is evident that southern Thailand also demands a lot of electricity.

Note that, for the southern region, the number of power plants is smaller by a factor of six compared with the central region, however, the power demand per person is smaller by a factor of two. Southern Thailand is the only region that exhibits a consumption demand that is higher than its production capability in Thailand. Since the region consumes more electricity than it can produce, electricity transmission from the central region or foreign countries is necessary. When the central region or Malaysia fail to contribute sufficient electricity, blackouts occur for all 14 provinces of the southern region. This last occurred on 22 May 2013 [41], and it took more than 9 h to restore everything. Since the electric situation in southern Thailand is unstable, the government was working on an appropriate energy plan based on a coal-fired power plant. However, it was forced to withdraw because the local people were concerned about the environmental impacts [42]. As the average yield was found to be highest in the southern region, planting Napier grass in this area would be an attractive option for power generation. This will not only provide clean energy generation but will also help in creating jobs for local people. Figure 2.6c reveals that Napier grass can provide a satisfactorily supply of electricity to provinces in the region.

This study considered an ideal situation, where all abandoned areas could be utilized. However, in reality, not all abandoned areas can be utilized, and, as such, a number of factors must be considered, such as biogas plant locations, the capacity levels of biogas plants, the amount of biomass to be transported from the feedstock region to the biogas plants, and the biogas production volume of each plant. To consider such effects, land suitability analysis should be carried out. Indeed, the results of this research could serve as the primary estimation method for Napier grass plantation in the country, and, in particular, the estimated DMY can be utilized as one of the criteria for evaluating land suitability. Without this work, performing land suitability analysis for Napier grass supply chains would be similar to locating photovoltaic sites without considering solar radiation. Regardless, this study is valuable for energy-related policymakers, and further studies should be conducted concerning the land suitability of biogas plants based on Napier grass supply chains in Thailand.

2.4 Conclusion

In this chapter, the spatial distribution of Napier grass DMY was successfully developed using the SWAT model. To simulate the Napier grass crop growth and consequently obtain the DMY spatial distribution, Napier grass crop growth parameters, including BIO_E, HVSTI, BLAI, FRGRW1, FRGRW2, LAIMX1, LAIMX2, and DLAI, were calibrated for different management conditions and analyzed using a sensitivity index to identify their sensitivity with respect to DMY. FRGRW1 and LAIMX1 are the least sensitive, whereas BIO_E and HVSTI are the most sensitive parameters. In the calibration process, the parameters were ranked according to their sensitivity levels and the most sensitive was the first to be adjusted. The parameters were calibrated one at a time by considering the RMSE of yield. To ensure that the calibrated values were realistic, the parameters were not adjusted beyond the range limits collected from previous studies. Model validation was successfully performed using the obtained parameters, and good agreement was found between the estimated yields and the experimental data. In addition, the model was used to predict Napier grass DMY and further estimate for power generation potential. The model confirmed that, even only abandoned areas were utilized, utilizing Napier grass as a new feedstock for power generation in Thailand can significantly decrease the dependency of imported electricity. The results also suggest that the southern region of Thailand is the most promising, as it demonstrates the highest average DMY. The results of this work can be further utilized as criteria for obtaining suitable areas for Napier grass plantations, anaerobic digesters, and biogas power plants in Thailand.

Table 2.5 The regional electric consumption, population, and electric consumption per capita collected from EGAT (2020). The estimated Napier grass yield, abandoned area, Napier grass-derived electric supply potential and supply/demand were calculated and summarized in this work

Region	Electric consumption (GWh)	Population (×1000)	Electric consumption per capita (kWh·person^{-1})	Estimated yield (kt)	Average yield (t·ha^{-1})	Abandoned area (ha)	Napier grass-derived electric supply potential (GWh)	Supply/ demand
North	7,786	5,954	1,308	4,099	17.4	235,470	2,182	28.0%
East	29,280	5,219	5,611	4,273	21.5	198,659	2,275	7.8%
West	7,438	3,059	2,432	2,949	16.0	184,458	1,570	21.1%
South	15,043	9,101	1,653	7,904	22.3	354,553	4,208	28.0%
Northeast	22,190	18,872	1,176	16,642	19.2	866,371	8,860	39.9%
Central	88,222	24,569	3,591	5,842	18.6	314,898	3,110	3.5%
Total	169,960	66,774	2,545	41,709	19.4	2,154,409	22,206	13.1%

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CHAPTER 3

Land suitability analysis of Napier grass-based biogas power plants in southern Thailand

3.1 Introduction

The industrial revolution was energized by the use of fossil fuels. Fossil fuel consumption has drastically changed over the past few centuries. Prior to 1900, coal is almost only the type of fossil fuels people use. From 1950 onward, fossil fuel consumption has increased of around seven-fold. The reliance was also shifted from solely coal towards a combination with oil and gas. According to COP26, countries are encouraging to phase out coal and this coincides with the trend of coal consumption that is falling in many parts of the world. Using fossil fuels create at least two global challenges: the energy crisis from the sole reliance of fossil fuels and CO_2 emission from burning hydrocarbons. It is undeniable that the biggest driver behind excessive fuel consumption has been economic activity all along [1].

In 2015, the United Nations General Assembly initiated the SDGs which are designed to be a blueprint to achieve a better and more sustainable future for everyone [2]. There are 17 interlinked SDGs in total which are intended to be achieved by 2030. The two global challenges mentioned earlier are among the matters under concern as reflected in several SDGs. For example, Goal 7 is to ensure access to affordable, reliable, and sustainable energy for everyone. Goal 8 is to promote sustainable economic growth and decent work for all, and Goal 13 is to take urgent action to combat climate change and its impacts. Although decreasing economic activity results in the reduction of CO_2 emission, as seen in 2020 during the pandemic, this is not the sustainable solution for people. Decreasing economic activity also results in poverty increment, which does not concur with SDG 1. Therefore, decarbonizing the economy is a path ensuring that all human beings can achieve prosperity while protecting the planet and living in harmony with nature.

Instead of using coal-fired power plants, biogas-based power generation, which can be considered as a net zero CO_2 emission approach, possesses a massive potential and has received a wide attention [3]. Typically, biogas feedstocks for power generation are agricultural residues, forestry products, and animal waste. Feedstocks in these forms cannot satisfy energy demand as they are highly fluctuated. Dedicated energy crops with low life cycles as feedstocks provide higher yield, resulting in more efficient land use. Moreover, introducing dedicated energy crops with short life cycles help encourage the utilization of abandoned areas and provide job opportunities for local populations. Therefore, supporting biogas-based power generations can serve the SDGs and benefit society in several aspects.

One of the most promising energy crops is Napier grass. It possesses advantages of being an energy crop with a short life cycle and providing relatively high methane content [4,5]. MoE interests in Napier grass as they plan to widely implement it in Thailand as a dedicated energy crop for biogas-based power generation [5]. Napier grass is viable of being utilized as both biomass and biogas. In the plan of MoE named Alternative Energy Development Plan (AEDP), Napier grass was proposed to be utilized as a feedstock of biogas. To convert Napier grass into biogas, anaerobic digestion is typically used. In anaerobic digestion, organic matters are decomposed by bacteria under the condition of limited oxygen. The methane yield as high as 0.242 $m^3 \cdot kg^{-1}$ has ever been reported [6]. Byproducts obtained from such a process are liquid and solid digestates [7]. Both of them are capable of being used as biofertilizers [8,9].

Based on the results in Chapter 2, it is clear that southern Thailand possesses high potential in planting Napier grass because the abandoned areas in the region provides the highest average DMY as compared to that of the other regions. Southern Thailand is the only region in the country where the electricity consumption exceeds its production capability [10]. Two main power plants in the region have a total capacity of 2,024 MW total generation capacity which is approximately 76% of peak electric consumption in the region. Thus, electricity has to be transmitted from the central region of Thailand (460 MW) and Malaysia (330 MW) everyday [10,11]. This results in an unstable electricity situation. As the electric consumption in southern Thailand increases approximately 3.4% per year, power plants to cover the electricity demand are urgently required. Since the region possesses high potential in obtaining Napier grass DMY, introducing Napier grass-based biogas power plants into this region would provide a good opportunity to promote the region's self-sufficiency in power generation, increase employment, and utilize abandoned areas.

In Thailand, there are many kinds of financial support mechanisms promoting electric supply from renewable sources, including feed-in tariff and adder schemes. EGAT will buy electricity from private sectors which have a contract with the government. Private electricity producers can be categorized into 3 types which are, IPPs, SPPs, and VSPPs. IPPs are those who possess a contracted capacity of higher than 90 MW. However, IPPs mainly use fossil fuels to fuel their power stations. For SPPs, the contracted capacity is usually 90 MW, which is the maximum capacity EGAT can purchase from private firms with such a contract. This type of producers must utilize alternative energy resources or cogeneration system in their power plants. VSPPs are those producers supplying electricity generated by renewable energy resources that have a contracted capacity no more than 1 MW. Mostly, the renewable energy resources used by VSPPs are solar and wind energy. The government utilize the financial support mechanisms through buying electricity from these producers to push AEDP forward to transition Thailand into a low carbon society. For biogas- and energy crop-based power generation, the goal of the plan is to increase the installed capacity from 311.5 MW in 2014 to 1280 MW in 2036 [12].

Although Napier grass was very promising for power generation in southern Thailand, there are many aspects that must be considered before deciding land use, e.g., the location of biogas power plants, distance from roads, distance from residential areas, access to the electricity grid, supply of feedstock, etc. Utilizing land to obtain dedicated energy crops without considering related impacts can lead to severe socioeconomic and environmental consequences. Therefore, it is necessary to assess land suitability prior to introducing crops or bioenergy-based power plants to minimize these impacts. Based on these backgrounds, the purpose of this chapter is to perform land suitability analysis for Napier grass-based biogas power plants considering environmental and socioeconomic criteria and the spatial distribution of Napier grass DMY obtained from chapter 2. The results of this chapter would provide a methodological framework for planning biogas power plant locations using energy crops for countries working towards a transition to renewable energy.

3.2 Recent research on multi-disciplinary assessment

To minimize effects of Napier grass plantation and its impacts on socioeconomic and environmental issues, land suitability analysis is a useful tool. In utilizing the analysis, various factors can be considered ranging from environmental to socioeconomic factors, and thus, it is extremely helpful to maximize the crop production per unit of land, labor, etc. [13]. To utilize land suitability analysis, the importance level of the considered factors must be known. This could be achieved through several approaches. One of the most popular approaches is multicriteria decision analysis (MCDA). Together with the geographic information system (GIS) application, MCDA has been employed widely to evaluate the land suitability level for various applications, including to identify the suitable areas for wind turbines [14-17], photovoltaic systems [18-22], and crops [23-35]. To utilize MCDA, an algorithm to determine factor weights that reflect their relative importance is required. One of the most used algorithms of MCDA in the studies that identified suitable areas for crops was the analytic hierarchy process (AHP) method.

Ramamurthy et al. [26] utilized the AHP method with GIS in land suitability analysis for maize plantation in southern India. Various factors, such as soil depth, length of growing period, soil surface texture, soil drainage, organic carbon, soil pH, slope, and elevation, were considered in their assessment. Özkan et al. [27] employed a similar set of criteria to identify suitable areas for agricultural activities in the semiarid terrestrial ecosystem in the Central Anatolia Region. Land suitability analysis was also conducted for rice cultivation by Maddahi et al. [28]. In addition to the criteria used in the work of Ramamurthy et al. [26] and Özkan et al. [25], the climate condition and accessibility, such as distance from main roads and water wells, were also considered. AHP-MCDA was also conducted to evaluate the suitability level of agricultural land for several crops in a hilly region of central Vietnam by Herzberg et al. [29]. In addition to those of Maddahi et al. [28], social criteria, such as poverty rate and farming skills, were also considered in their assessment. These studies employed MCDA to assess the land suitability level, which highlighted that MCDA is a useful approach to identify suitable areas for agriculture. Nonetheless, the results of these works present only suitable areas, but agricultural yield cannot be estimated quantitatively. This estimated yield is very important in some applications, particularly bioenergy-based power plants.

On assessing the optimal sites for bioenergy-based power plants, it is necessary to determine the number of materials utilized as the feedstock of such power plants [31-35]. Since there are many aspects to be considered, typically, criteria for site suitability assessment of bioenergy power plants were distance from residential areas, distance from water bodies, distance from roads, distance from transmission line, and land surface gradient. Besides the criteria mentioned earlier, because the feedstock supply for bioenergy-based power plants is geographically dependent and often dispersed, it is important to consider the feedstock quantity to identify suitable locations for bioenergy-based power plants [31]. There are so many approaches in estimating feedstock quantity. Höhn et al. [32] develop the spatial distribution of biomass sources by storing statistical data in a georeferenced database with attribute data. The kernel density map was developed with a search radius of three kilometers. Their work is to locate suitable sites for biogas plants in southern Finland, considering biowaste, sludge, agricultural residue, and energy crops as feedstock. The location of biogas plants must minimize CO_2 emissions, cost, and time due to feedstock transportation. Sultana and Kumar [31] used the statistical data of biomass availability obtained from annual reports of a local organization to generate spatial distribution by integrating them with the land cover map. Instead of using statistical data, Chukwuma et al. [33] collected biowaste data from field surveys. These data were stored as point data in geographical coordinates determined using a global positioning system (GPS) receiver. The spatial distribution map of biowaste was generated using the point-density tool in the spatial density toolbox in ArcGIS. Waewsak et al. [34] utilized landsat-8 satellite images together with sampling points for old Pará rubber trees obtained by ground surveys to generate a spatial distribution map of rubber trees. Trees' ages were obtained from the surveys and converted into biomass capacity using a simple function of the age.

Although the spatial distribution of the materials used in bioenergy-based power plants can be obtained in previous studies [31-35], it was obtained using rough estimation from the point data with geographical coordinates obtained through surveys and statistical data. This created two important issues. First, the yield was set as a constant, although it is known that the crop yield varies with soil, water, and weather conditions. Utilizing such treatments in land suitability analysis for bioenergy-based power plants can result in over/underprediction of feedstocks. Second, those studies considered only crops or materials that were already present in the area of study because all the data were obtained though field surveys and statistical data. Therefore, it is not possible to apply the procedures presented in previous studies to generate a distribution map for crops that are not yet widely planted.

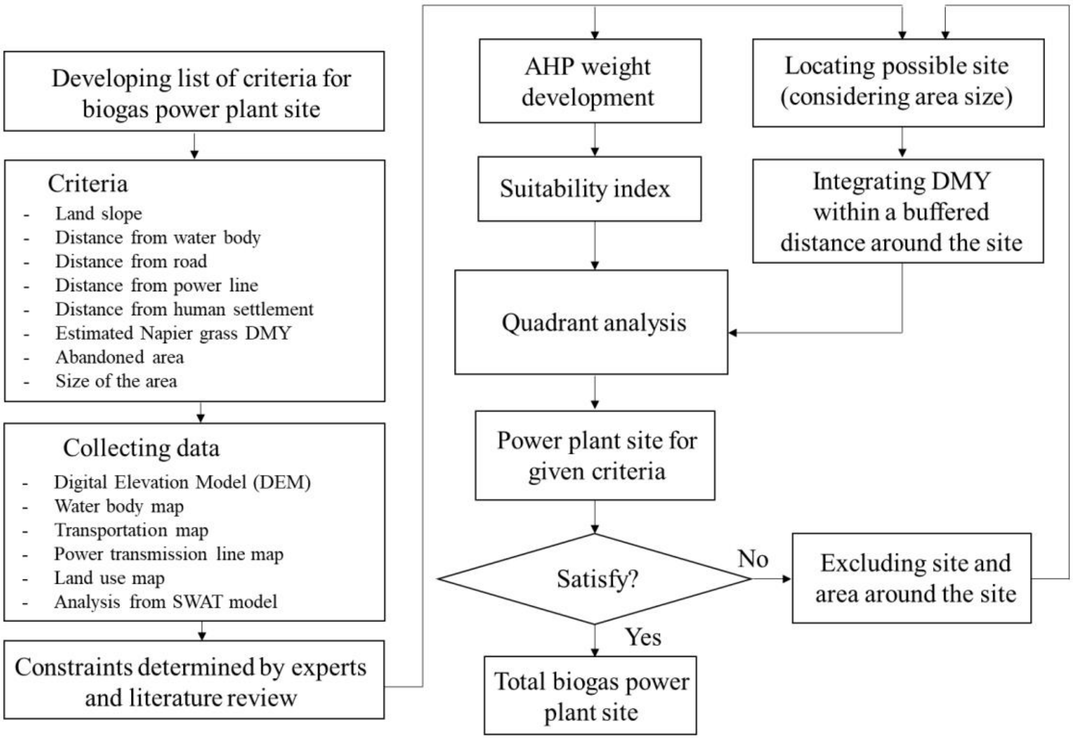

Figure 3.1 Schematic for locating suitable biogas power plant sites

3.3 Data and methods

To perform land suitability analysis, the SWAT model [36], ArcMap 10.1, and geospatial information were integrated. The SWAT model is employed to generate the spatial distribution of Napier grass DMY considering the soil conditions, elevation, slope, weather, irrigation, and crop-management practices. The procedures and data used to evaluate the Napier grass yield using the SWAT model was described in detail in chapter 2. To promote the utilization of abandoned areas, only abandoned areas are considered for Napier grass plantations in the preliminary consideration. Suitability analysis was carried out for candidate power plants. However, the Napier grass DMY should not be the only criterion to decide suitable locations for biogas power plants because without considering other socioeconomic and environmental impacts, a candidate power plant can negatively affect the environment in the long term and results in a huge hidden cost. Therefore, AHP-MCDA is carried out to identify the weights for socioeconomic and environmental factors. The suitability index (SI) for siting Napier grass-based biogas power plants is evaluated using the calculated weights. Subsequently, the SI was considered together with the nearby available Napier grass yield via quadrant analysis to locate sites for biogas power plants. This is because the biogas power plants require a sufficient Napier grass yield within a given range in order to minimize energy use and transportation time. To maximize the benefits of land use, abandoned areas should be utilized as much as possible. To do such that, the procedures were repeated to determine if there were any other candidate sites for biogas power plants when some criteria were less restricted. The methodology developed for siting biogas power plant using new dedicated energy crops is summarized and depicted in Fig. 3.1.

3.3.1 Data used in this study

The map of southern Thailand, which consists of 14 provinces is depicted in Fig. 3.2. Only the mainland is considered for land suitability analysis. Therefore, Phuket, an island province, was excluded. Maps of data used are presented in Fig. 3.3a-d. Land use data provided by the Department of Land Development (DLD) is shown in Fig. 3.3a. The data showed that the land use of this region is mostly agricultural (57.21%) and forest (29.63%). This region is renowned of being an area for planting Pará rubber tree. With almost 60% of agricultural area utilized for Pará rubber trees, this region makes Thailand one of the largest countries in terms of latex production [37]. Figure 3.3b shows the electric consumption distribution in this region. The highest power-consuming provinces were Songkhla (4.4 TWh/year), Phuket (3.6 TWh/year), Suratthani (3.3 TWh/year), and Nakhonsithammarat (2.6 TWh/year) [16]. In total, the consumption of these four provinces makes up more than 60% of the power consumption of the entire region. Although electricity is mainly consumed by residential users (36.0%), the hospitality (21.7%) and industrial (20.0%) sectors also share a large portion of the electricity use in the region [10]. In Fig. 3.3c, the elevation distribution in southern Thailand obtained from CGIAR CSI is shown. From the contour, the elevation in the study area ranged from 0 to 1,729 m [38]. The map of the main road network and power transmission lines, provided by the DLD and Provincial Electricity Authority (PEA),

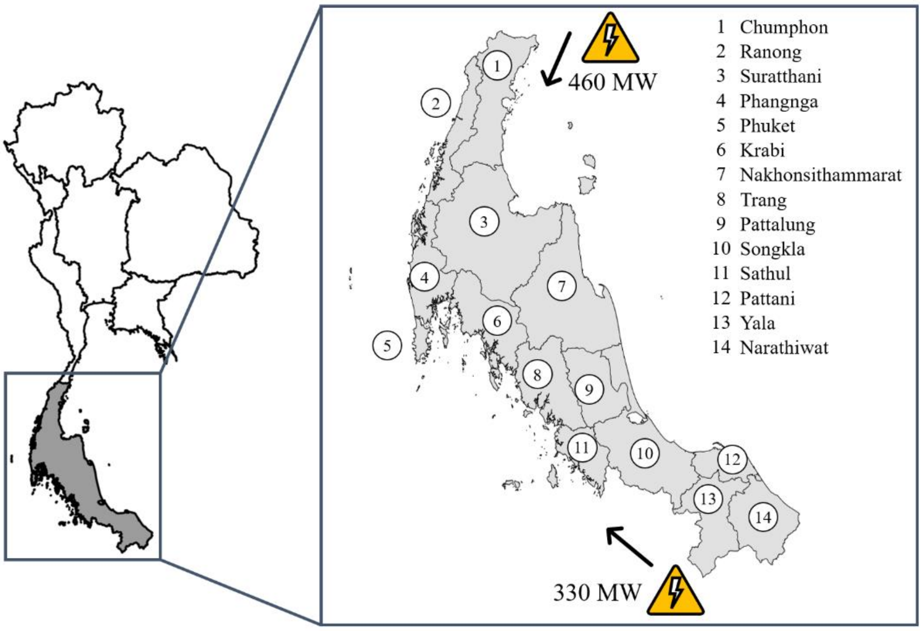

Figure 3.2 Map of the study area (southern Thailand)—the arrow indicates power transmission from other regions

respectively, is shown in Fig. 3.3d. It can be seen that the main roads and power transmission lines had similar network systems of the power consumption of the entire region.

For further analysis, the digital elevation model (DEM) was used to generate the slope data with a resolution of 30 m from the elevation distribution [38]. As these data, including the land use, water body, road network, and power transmission-line data, were in different feature classes (points, lines and polygons), they were converted to a raster dataset with a resolution of 50 m to perform suitability analysis.

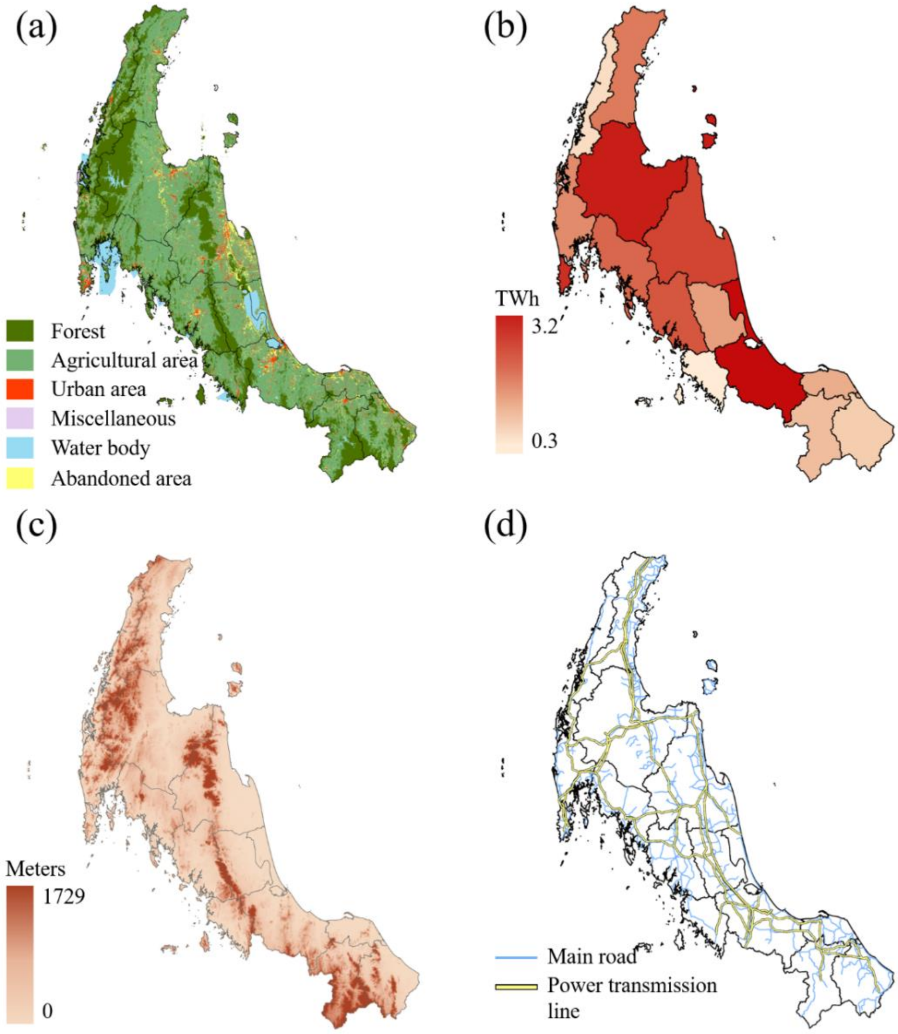

Figure 3.3 Maps of (a) land use, (b) energy consumption, (c) elevation, and (d) main roads and power transmission-line networks in southern Thailand

3.3.2 Criteria used in the study

3.3.2.1 Environmental criteria

Although renewable energy resources are a better choice as compared to conventional energy resources for power generation, they could provide some negative consequences on environment [39]. If the development of biogas power plants with renewable energy resources are not planned carefully, significant impacts on ecosystems and communities may arise. Hence, the environmental impacts of introducing biogas power plants should be considered for environmental protection, e.g., for air- and water-quality preservation.

The environmental criteria in this work were classified into two main categories which are impacts on water and air. In order to avoid water contamination which may occur during the power-generation process, biogas power plants should be located far from bodies of water [40]. Therefore, the spatial distribution of bodies of water was considered in this analysis. Even though biogas power plants produce lower air pollution than coal-fired power plants [41], their byproducts (e.g., noise and air pollution) can still impact people's health [42]. The location of power plants should be sufficiently far from residential areas to avoid impacts on public lives, which will also reduce opposition to the development of the power plants. Thus, residential areas were extracted from the DLD's land cover map and were considered in this study.

3.3.2.2 Socioeconomic criteria

In the energy-planning phase, it is essential to address social and economic impacts. The socioeconomic sub-criteria were the distance from residential areas, land slope, distance from main roads, and distance from power transmission lines. As mentioned, power facilities can produce air pollution in the nearby area. Thus, it is very common to avoid placing facilities near residential areas. Because the distance from residential areas depends on both environmental and socioeconomic criteria, it can be implied that this criterion is among the most important criteria to assess land suitability for power plants.

For the land slope criterion, it is apparent that the steeper slopes result in the higher costs because land grading is required. Furthermore, land use on steep slopes is limited by law. Therefore, steep slopes negatively impact land suitability. Biogas power plants are expected to operate all year, which means that the feedstocks are required to feed the plant daily. Thus, the transportation cost is a factor that significantly affects the operating cost of the system. Reducing the transportation distance directly results in a lower transportation cost. The last sub-criterion considered in this section is the distance to power transmission lines. Increasing the proximity to transmission lines can significantly decrease power losses.

3.3.2.3 Spatial distribution of biomass

To determine sites for biogas power plants, it is important to know the amount of feedstock required to serve the plant. Hence, the spatial distribution of feedstock is necessary to assess how the feedstock supply is distributed. Previous studies [31-35] developed the spatial distribution based on statistical and land cover data. However, the crop yield varies with soil, water, and weather conditions. Utilizing such an approach can provide only a rough estimate over a large area. Moreover, this approach can only be utilized with crops that are widely planted. Therefore, it is not possible to obtain the spatial distribution of Napier grass yield. In this work, instead of roughly estimating Napier grass yield over an area, the Napier grass DMY was calculated using the SWAT model by considering the soil, water, and weather conditions. As it is important to use accurate and reliable parameters for simulation, the Napier grass parameters were obtained from results of chapter 2. To apply the SWAT model, the geospatial information of the soil, elevation, weather, irrigation, and crop-management practices were used. As a preliminary consideration, only abandoned areas were considered for Napier grass plantations, based on an assumption that people should be encouraged to utilize abandoned areas to help promote sustainable employment and economic growth.

3.3.2.4 Multicriteria decision making, suitability analysis, and GIS application

To serve a 90-MW power plant, based on the results from chapter 2, a Napier grass biomass of approximately 730–970 kt·year^{-1} is required. The following assumptions have been made; including the methane yield of 0.242 m^3·kg^{-1} obtained from an anaerobic digestion process [7]; the energy density of methane of 40 MJ·m^{-3} [43]; and the energy conversion efficiency of approximately 30–40% by a thermal power plant with a combustion boiler and a steam turbine. However, as mentioned earlier, the amount of biomass alone is not sufficient to locate the optimal site for biogas plants. Environmental and socioeconomic criteria must also be considered. This makes locating biogas power plants a difficult task, as it involves multiple factors. A logical and systematic decision-making process would help determine appropriate sites. In energy applications, the MCDA is a well-known method [14-35]. The AHP algorithm was employed to carry out the MCDA as a decision-supported method. In the algorithm, the criteria weights of importance were calculated by using the normalization and eigenvector of pairwise criteria factors. Note that the relative importance of each pair is very specific to the objective of the study and the study area. For example, Ruiz et al. [44] performed land suitability analysis for siting solar energy plants. They admitted that the slope was an important factor that helped minimize the construction cost. However, the study area was mostly flat, and thus, the relative importance of this criterion was small. In this work, 11 experts from EGAT played a critical role in deriving the relative importance scores in the pairwise comparison matrix.

In the pairwise comparison, the relative importance score between two factors is assigned on a scale from 0 to 9 [45] (see Appendix A1). The assigned scores were then applied to the pairwise matrix displayed in Eq. (3.1).

$$M = \begin{bmatrix} 1 & c_{12} & . & c_{1n} \\ c_{21} & 1 & . & c_{2n} \\ . & . & 1 & . \\ c_{n1} & c_{n2} & . & 1 \end{bmatrix}, \qquad (3.1)$$

where the subscript n indicates the number of criteria, c_{ij} represents the importance of criterion i over j, and the inverse value of input c_{ji} is $1/c_{ij}$. The elements c_{ij} were determined as the mean of the paired importance ratios judged by the 11 experts (see Appendix A2) and rounded to integer numbers. The weights of the criteria $\{w_i\}$ were then calculated as the eigenvector of matrix *M*.

To ensure that the output weights are reliable, the consistency ratio (CR) is used as an indicator of the degree of consistency. The matrix is considered consistent when the CR is less than 10% [45]. However, if the CR exceeds 10%, the relative importance is considered to be inconsistent and the corresponding relative importance scores are required to be revised. The CR is the ration of the consistency index (CI) and random index (RI), expressed as

$$CI = \frac{(\lambda_{max}) - n}{n - 1}, \qquad (3.2)$$

where n is the matrix size $[n \times n]$ and λ_{max} is the maximum eigenvalue. The CR can be written as

$$CR = \frac{CI}{RI}, \qquad (3.3)$$

where the *RI* is that developed by Saaty [45], which is 1.12 for a matrix of size $[5 \times 5]$.

After the weights of each criterion were calculated, the suitability map was obtained by the calculating *SI*, as expressed in Eq. (4).

$$SI = \sum_{i=1}^{n} w_i a_i, \tag{3.4}$$

where w_i and a_i are the weight and the classification level of criterion i, respectively, and n is the total number of subcriteria used in this study.

For the land suitability analysis, five thematic layers of subcriteria were created. The distance from the subcriteria of interest at every local point needs to be known. The Euclidean distance technique was utilized to evaluate the distance. However, the distance obtained from the technique is continuous. For the sake of convenience in land suitability analysis, the processed maps were reclassified into 7 classes with class 1 being the least suitable and class 7 being the most suitable. The constraint of each criterion was obtained from the experts' suggestion, regulations in Thailand, and the literature to avoid conflict with people's health, the environment, and the economy. The final land suitability is obtained using the weighted sum function in ArcMap 10.1, in which all five maps are overlaid and, according to Eq. (4), the field values for each input raster are multiplied by the specified weight. The land suitability map contains the SI for the environmental, social, and economic criteria.

To locate possible sites for biogas power plants, some constraints were considered. The first constraint was land use and only abandoned areas were assumed to be available for power plant construction. Thus, industrial, urban, agriculture, forest, and water areas were excluded. The second constraint was the size of area for power plants because a large plant cannot be located in a small area. Hence, abandoned areas smaller than 20 ha were filtered out. The third constraint was the sufficient feedstock supply to power plants from the surrounding areas enough close to the plants, because the farther transportation must bring the more energy loss and cost. Circular buffers with a radius of 50 km were created around the possible sites, where the radius is a distance that a cargo truck can travel within 1 h to minimize the feedstock transportation cost. As a 90-MW plant requires the feedstock of 730–970 kt·year^{-1}, the possible sites of which total feedstock amount from abandoned areas within the buffer did not satisfy the required amount were excluded. These constraints could help filtering out the possible power plant sites that stand on unrealistic locations.

After considering the constraints, the locations of possible sites that have sufficient area and feedstock within a reasonable distance, was combined with the suitability map for further examination through quadrant analysis. A scatter plot of the SI and feedstock quantity was divided into four quadrants. Each possible site, along with its corresponding amount of feedstock and SI, was categorized into quadrants. This analysis is a great visualization tool to aid in decision-making. In this study, the SI is deemed slightly more important than the amount of feedstock within the area. This is due to the background of southern Thailand. It should be noted that the buffered area should not intersect within the consideration cycle to prevent two power plants from using feedstock from the same area. However, when the sites were selected, the sites and the amount of feedstock in the buffered areas were excluded from the consideration, and the procedure was repeated until the total power of the power plants satisfied the plan.

3.4 Results and discussion

3.4.1 Land suitability assessment

To locate a suitable site for Napier grass-based biogas power plants, the land suitability was analyzed by integrating the GIS and AHP. The raster dataset of the five subcriteria, including the land slope and distance from water bodies, residential areas, power transmission lines, and roads, was developed using the Euclidean distance technique. Figure 3.4a–e displays the reclassification map of the sub-criteria and the constraints for each parameter are summarized in Table 3.1.

The land slope of the area under study, as shown in Fig. 3.4a, ranges from approximately 0°–43°. Although most areas are flat, there are some highly sloped areas. Those areas are a part of Tenasserim hills (also called Thio khao tanaosi in Thai) which is a roughly 1,700-km-long mountain chain in Southeast Asia. It is known that areas with lower slopes are better for positioning buildings. Slopes of 2° or less were considered in the best rank, whereas higher slopes had lower suitability scores according to their order. Slopes of 15° or greater were excluded because of ministerial regulations from the Ministry of Interior on issuing the title deed. This is consistent with the classification from previous studies [31,33,46] that also exclude slopes exceeding 15° from analysis.

Table 3.1 Suitability classification of favorable criteria used in this study

No.	Criteria (Unit)	Suitability classification							Constraints	References
		7	6	5	4	3	2	1		
		Very high			Medium			Very low		
1	Slope (Degree, ◦)	0-2	2-5	5-8	8-10	10-15	-	-	>15	[31,33,46], the ministerial regulations, and experts from EGAT
2	Distance from water body (m)	1000-5000	-	5000-10000	-	10000-20000	-	500-1000, >20000	0-500	Experts from EGAT
3	Distance from residential area (m)	3000-5000	-	5000-10000	-	10000-20000	-	1000-3000, >20000	0-1000	[31,33,47] and experts from EGAT
4	Distance from power line (m)	100-5000	5000-8000	8000-11000	11000-20000	20000-30000	30000-40000	>40000	0-100	[31,33] and experts from EGAT
5	Distance from road (m)	100-5000	5000-8000	8000-11000	11000-20000	20000-30000	30000-40000	>40000	0-100	[48] and experts from EGAT

In Fig. 3.4b, the reclassification of the distance from bodies of water is displayed. Although locating power plants close to water is a great option from an engineering perspective, owing to the convenience of utilizing the available water in a cooling system [31,33], there are always concerns about used water impacts on ecosystems, as this process can impact water in terms of both temperature increase [49] and contamination [50]. Based on the experts' suggestions, a minimum distance of 500 m from any body of water was required for resting used cooling water. Therefore, areas around 1,000–5,000 m from water were preferred to reduce the risk of water pollution. In contrast, areas within 500 m of the water were excluded, and those within 500–1,000 m were ranked as the least suitable.

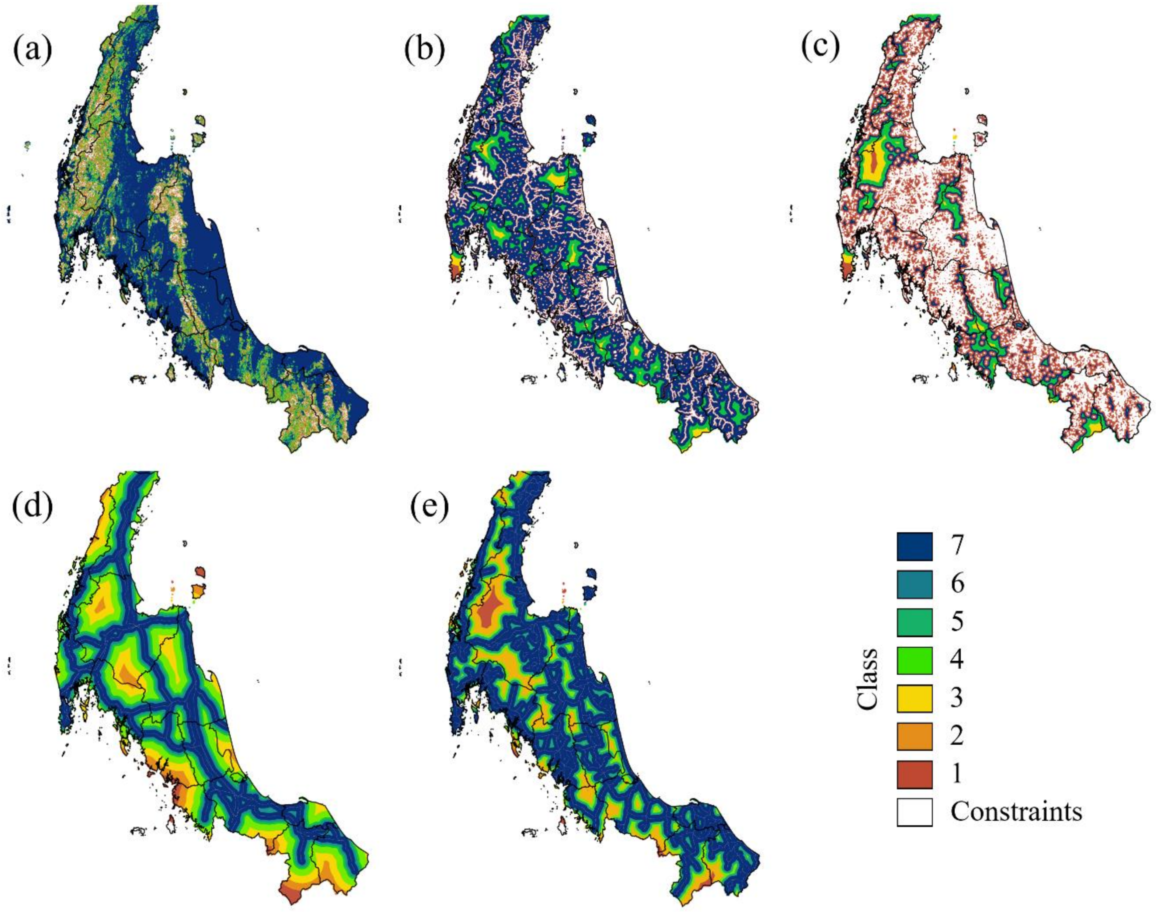

Figure 3.4 Reclassification map of (a) land slope, (b) water bodies, (c) residential areas, (d) transmission lines, and (e) roads

Figure 3.4c depicts the reclassification of the distance from residential areas. From previous studies [31,33,51-53], distances within 300–2,000 m from residential areas were avoided to prevent impacts on human health. Several studies linked residential proximity to power plants to cardiovascular and respiratory disease [54] and adverse birth outcomes [47,55]. To avoid such impacts, areas within 1,000 m of residential areas were constrained. Tsai et al. [47] reported that women who lived within 3,000 m from power plants had higher risks in preterm birth delivery than those who lived farther away. However, not only the health issues, but also the distance between power plants and living areas, must be considered to decrease transportation time. Thus, the most suitable areas were within the range of 3,000–5,000 m, and the least suitable distance was set to be within 1,000–3,000 m.

The reclassification of the distance buffered from the power transmission line and road is shown in Fig. 3.4d and 3.4e, respectively. For safety, the areas within 100 m of buffer were avoided for both criteria [31,33,48]. These criteria were considered solely because of their economic impacts. If power plants were positioned close to power transmission lines and roads, the transportation cost for feedstocks and electricity could be avoided.

Table 3.2 Pairwise comparison matrix and weights of sub-criteria with AHP

Item Number	1	2	3	4	5	Weight
Item Description	Slope	Water body	Residential area	Power transmission line	Road	
Slope	1	1/5	1/4	1/2	1/3	0.065
Water body	5	1	1	3	2	0.333
Residential area	4	1	1	2	2	0.296
Power transmission line	2	1/3	1/2	1	1/2	0.120
Road	3	1/2	1/2	2	1	0.185

Before evaluating the distribution of SI for siting biogas power plants, the importance weight of each criterion must be evaluated. In this work, the weight of selected criteria was determined using the AHP method, in which the relative importance score of each criterion pair, according to the Likert scale (see Appendix A1), was assigned in the pairwise comparison matrix, as enumerated in Table 3.2. The paired importance ratios judged by the 11 experts are listed in Appendix A2. Using the given weights resulted in CR of 1.0% which indicates that the assigned weight values are consistent and acceptable. The obtained importance weights were 0.065, 0.333, 0.296, 0.120, and 0.185 for the land slope and distances from bodies of water, residential area, power transmission lines, and roads, respectively. These weight values concur with our assumption that the water bodies and residential areas were the most important parameters, as they are very difficult to modify. However, if needed, the slope, power transmission lines, and roads can be modified through some investments. Afterwards, the weights were inserted into the GIS model builder in ArcMap 10.1 to assess the land suitability for constructing biogas power plants.

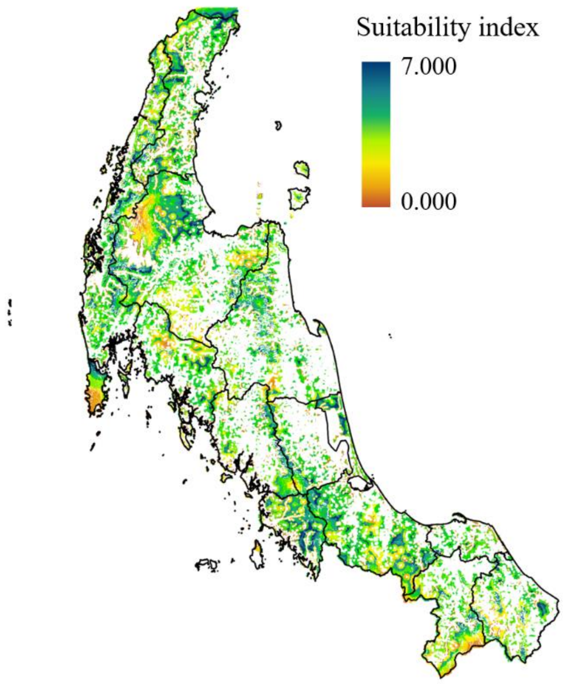

Figure 3.5 Spatial distribution of SI for constructing biogas power plants in southern Thailand

The spatial distribution of SI for siting biogas power plants was obtained from the geospatial overlay of the reclassification map of the five sub-criteria, considering the importance weights obtained from the AHP method. The suitability map, as depicted in Fig. 3.5, was useful for suggesting suitable areas for power plant sites. From the selected parameters, the areas with $SI \geq 6$ corresponded to 8.2% of the total territory. Around 30.1% of the total territory had $5 \leq SI < 6$, whereas the area of $1 \leq SI < 3$ made up 23.4%.

3.4.2 Finding suitable candidate sites for biogas power plants

Although the high SI sites as possible power plant locations distributed widely in the study area, they needed to be further screened considering the constraints of sufficient feedstock supply from nearby abandoned area. Utilizing the distribution without considering the nearby feedstock supply would result in insufficient feedstock supply. Only abandoned areas were considered for Napier grass plantations for two main reasons. The first is to encourage people to use abandoned areas, which could provide several benefits to the local communities. The other is to avoid conflicts with existing industrial, urban, economical, and agricultural lands. Thus, introducing Napier grass as a feedstock would disturb ecosystems as little as possible. To assess the optimal sites for biogas power plants while considering amount of feedstock supply within plant proximity, the distribution of the feedstock supply is required. Figure 3.6 displays the distribution of the DMY of Napier grass in abandoned areas, which was calculated using the parameters and procedures described in chapter 2. The average DMY from the abandoned areas in this region were approximately 22.3 $t \cdot ha^{-1}$. This DMY was obtained by considering soil conditions, elevation, slope, weather, irrigation, and crop-management practices in the SWAT model.

The Napier grass DMY from abandoned areas (Fig. 3.6) within a buffered distance of 50 km around possible sites was summed up and the SI was plotted against the amount of Napier grass DMY within the buffered distance, as displayed in Fig. 3.7. The scatter plot was divided into four quadrants for quadrant analysis. To do so, the threshold limit for the x and y axes was set as 6.00 and 1,000 kt, respectively. The results revealed that there were totals of 55 and 421 sites categorized into quadrants 1 and 4, respectively. It is worth noting that the DMY of 1,000 kt was selected because it is sufficient for 90-MW biogas power plants with a certain margin. Although this insufficient feedstock supply could be solved through agricultural zoning and encouraging the local people to plant Napier grass, this must be done carefully because introducing a new crop could result in severe consequences on the ecosystem and economy. Thus, the life-cycle assessment and cost–benefit analysis should be performed if agricultural zoning is utilized. The Napier grass DMY of 1,000 kt was based on

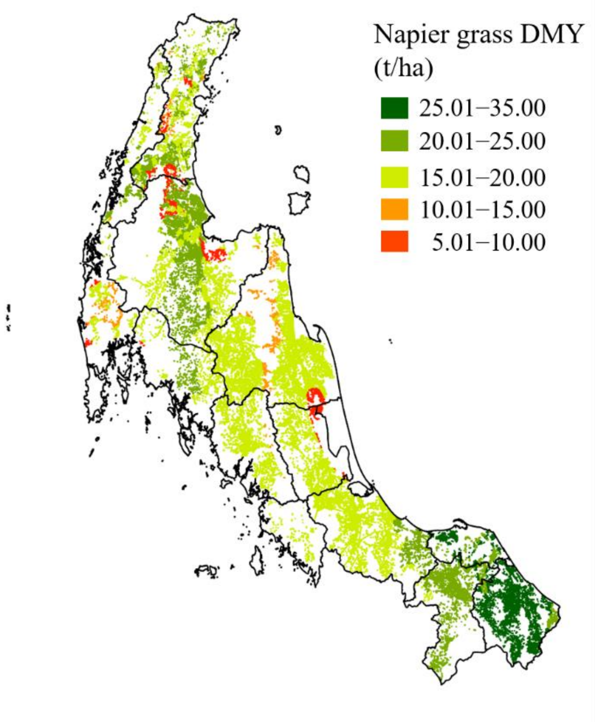

Figure 3.6 Spatial distribution of Napier grass DMY from abandoned areas in southern Thailand

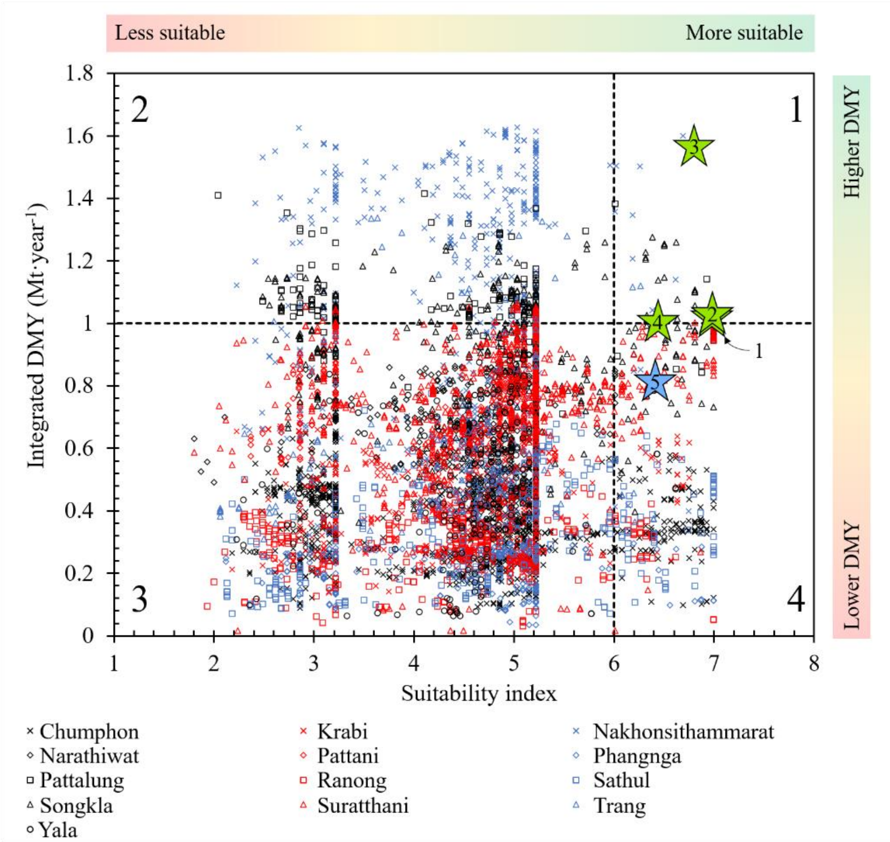

Figure 3.7 Scatter plot of the SI and DMY integrated within a buffered distance of 50 km, where the green and blue stars represent the selected initial candidate sites for 90- and 60-MW power plants, respectively

an assumed 30% energy-conversion efficiency for 90-MW power plants. With a constant improvement in energy-conversion efficiency of power plants, 1,000 kt would be an overestimation (11.1 kt·MW^{-1}). This number was reasonable since MoE estimated the amount of Napier grass DMY required for power plants to be around 5.6–8 kt·MW^{-1} [56].

From the total of 55 sites in quadrant 1, most of the sites were located in Songkhla and Suratthani. However, the buffered distance of those available sites in these provinces overlapped each other and, hence, only one site from each province could be selected as a suitable candidate site for biogas power plants. Both selected sites possessed the SI of 6.993. Within a buffered distance of 50 km, the amount of Napier grass DMY of those two sites located in Songkhla and Suratthani was 1,036 and 1,052 kt, respectively. Besides these sites, a site in Nakhonsithammarat was selected. The SI was found to be 6.808 and the DMY of 1,562 kt, which was 50% higher than the requirement, was observed. Considering the SI and DMY, only three sites were qualified as a suitable candidate site for 90 MW biogas power plants. However, there are still many abandoned areas left in southern Thailand. Hence, the procedures were repeated again.

After careful investigation of the data, it was observed that there were some possible sites, but their buffered distance intersected with that of the selected sites. One such site possessed the highest potential because of its SI and integrated DMY. A site in Trang had a DMY of 554 kt within the 50-km buffered distance after the exclusion of the buffered areas of the site in Nakhonsithammarat and Songkla. In the overlapping area between this site and the site in Nakhonsithammarat, the integrated DMY was 426 kt. Assuming that the DMY in the overlapping area was utilized in the site in Trang instead of the site in Nakhonsithammarat, the Napier grass supply was still sufficient for the 90-MW power plant in Nakhonsithammarat. The integrated DMY would be 980 and 1,136 kt for the sites in Trang and Nakhonsithammarat, respectively. Please note that, for safety, 1,000 kt was assumed to be the DMY required for 90-MW power plants, even though our calculation suggested that 970 kt was sufficient for a power plant with an energy-conversion efficiency of 30%.

Because there were no other candidates that came close to 900 kt of DMY around the site, power plants with a smaller capacity were considered. Typically, the contracted capacity of natural gas power plants from private firms is 90 MW, and the next largest capacity is usually 60 MW [57]. Hence, the next capacity to be considered was 60 MW. For 60-MW power plants, the amount of the DMY around the site was required to be at least 650 kt. After having gone through the procedures, a site in Pattani with the amount of the DMY around the site of 833 kt was found to be the most suitable candidate as its SI was 6.428 (see Fig. 3.8).

Table 3.3 Summary of proposed sites for constructing Napier grass-based power plants in southern Thailand

Plant size	No. of site	Locations	Total DMY (Yield in overlapping area) (Unit: kt·year^{-1})	Suitability index
90 MW	1	Suratthani	1,036	6.993
	2	Songkla	1,052 (30)	6.993
	3	Nakhonsithammarat	1,562 (426)	6.808
	4	Trang	1,010 (456)	6.448
60 MW	5	Pattani	833	6.428

In total, with a buffered distance of 50 km, the location of the five selected sites for biogas power plants accounted for 63% of the total Napier grass DMY from abandoned areas in southern Thailand. The remaining possible sites had DMYs below 600 kt, which suggested that the capacity of biogas power plants needed to be smaller. As our primary focus is to suggest the locations of biogas power plants for SPP, which mainly produce 60 and 90 MW, smaller power plants are out of our research scope. However, the results of this chapter provided the spatial distribution of the SI for locating new biogas power plants, which could be useful for future studies, regardless of size. Therefore, the selected sites are summarized in Table 3.3. Altogether there are five power plants with a contracted capacity of 420 MW to sell electricity to EGAT, which could significantly decrease the amount of electricity imported from other regions (790 MW from central Thailand and Malaysia). Please note that, based on the DMY in the buffers, the power plants can generate 460 MW or 620 MW in total assuming the energy-conversion efficiency of 30% or 40%, respectively. Because the generated power exceeding the contracted capacity to EGAT can be supplied to local users, all of the generatable power of 460–620 MW by these five Napier grass-based biogas power plants is a possible contribution to the country’s power supply.

Figure 3.8 presents the location of the proposed sites for constructing biogas power plants along with the power transmission-line map and Napier grass yield density map. Because the roads and power transmission lines had similar networks, as shown in Fig. 3.2d, it is obvious that all the proposed sites were located next to the transmission line and road. This is great for both private firms and the government, as they do not need to worry about the costs of power transmission and transportation. All the sites were located in the middle of the region because abandoned areas were rare on the coast. This is a good sign for introducing Napier grass as a feedstock for power generation, because both of the coal-fired power plants opposed by local residents were planned to be located on the coast for the convenience of coal transportation. However, southern Thailand is famous for beautiful beaches. The local population was concerned that locating coal-fired power plants on the

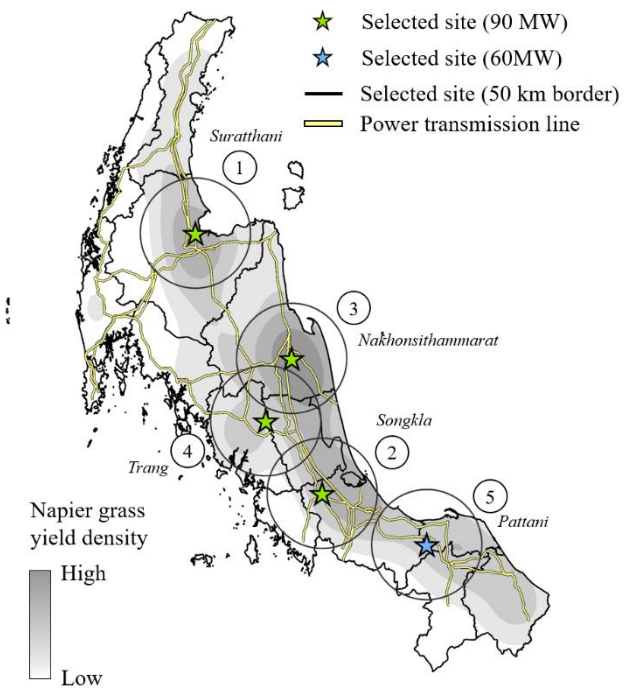

Figure 3.8 Location of the proposed sites for constructing power plants, overlaid on power transmission-line map

coast would impact the environment and local economy in the region. Instead of risking the local economy by introducing coal-fired power plants, biogas power plants would help provide job opportunities for local people. Therefore, introducing Napier grass-based biogas power plants would not only serve SDGs 7 and 13, i.e., promoting sustainable energy and combating the climate change, but also Goal 8, promoting economic growth and providing work for all.

This study considered only small biogas power plants, which typically have capacity of 60 and 90 MW. To maximize the land potential of this area, biogas power plants of smaller sizes, such as 10 and 1 MW, should be considered. Moreover, an ideal situation, wherein all abandoned areas could be utilized, was assumed. However, in practice, not all abandoned areas can be utilized, and some existing agricultural areas are needed for Napier grass. In this case, the effects of introducing Napier grass on the land, water, air, as well as the economy, must be investigated before agricultural zoning is applied. Regardless, this study is valuable for energy-related policymakers to plan the locations of biogas power plants using a dedicated energy crop that has never been widely planted before.

3.5 Conclusion

In this chapter, the methodology for locating biogas power plants was successfully developed by integrating AHP-MCDA and GIS. Several criteria, including environmental impacts, socioeconomic factors, Napier grass yield distribution, and land availability, were considered to find optimal sites for the biogas power plant. To perform land suitability analysis, the AHP-MCDA method was utilized to evaluate the weight of each criterion. A map of five sub-criteria was reclassified and assigned suitability scores. The obtained maps were overlaid in ArcMAP 10.1 considering their importance weight to obtain the spatial distribution of SI. However, the SI alone was insufficient to locate power plants in this case, as not all areas can be utilized for biogas power plants due to biomass availability. Furthermore, locating biogas power plants using new energy crops as a feedstock is unlike that for power plants using biowaste or agricultural residue, as biomass availability cannot be obtained through surveys or statistical data. The DMY of Napier grass was estimated through the SWAT model considering the soil, water, and weather conditions. The spatial distribution of DMY was integrated with the land suitability map to indicate suitable locations to construct biogas power plants. Because the decarbonized economy is gaining more attention, the approach presented in this study would be a logical framework for siting potential biogas power plants using new dedicated energy crops, which are important for green-energy development. The proposed approach was then applied to suggest biogas power plant locations for SPP (60- and 90-MW power plants) in southern Thailand. The results revealed that there are five suitable sites for biogas power plants with a total contracted capacity of 420 MW by utilizing only abandoned areas for Napier grass plantations. Based on the Napier grass DMY in the buffers of 50 km radius, the power plants can contribute 460-620 MW to the country's power supply. The total capacity of the proposed power plants could significantly decrease the transmission of electricity from other regions. This would stabilize the power-generation situation for local communities.

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CHAPTER 4

Multi-disciplinary assessment of Napier grass energy plantation on local energy, environmental and socioeconomic benefits: A watershed scale study in Southern Thailand

4.1 Introduction

The increase in fossil fuel-based energy consumption resulted in an energy crisis and a critical state of global warming in the 21st century. A new energy source that is renewable, clean, and sustainable is necessary for achieving net zero carbon emission. Among the candidates suitable for renewable energy, biogas, which is a gaseous fuel obtained from the decomposition of organic matter, has received widespread attention [1-3]. Biogas can be can be derived from various types of feedstocks, such as agricultural residues, forestry byproducts, animal waste, and dedicated energy crops. Biogas energy derived from dedicated energy crops can be considered net zero. This is because although carbon is released during the process of power generation, the same amount of carbon is absorbed by the crops during their growth. However, for the widescale commercialization of these renewable energy crops prior to making decisions regarding land use change for energy plantations, there are several aspects to be considered to avoid unforeseen socioeconomic and environmental issues [4-7].

As mentioned earlier, Napier grass is one of the popular perennial grasses used in biogas-based power generation [8-13] as it possesses many desirable characteristics for energy crops, such as a short life cycle, relatively high methane content, and high water use efficiency [14-16]. Not only that, but it has also been widely reported that perennial grasses help reduce a waterborne pollutant such as nitrate transport into the soil. Additionally, Napier grass can grow well under flooded soil conditions, making it suitable for use in water pollution treatment [17]. Although Napier grass can serve as an alternative fuel source and reduce carbon emissions, there are concerns over the impacts of such a crop on the local soil and water, due to changes in land use and intensive agricultural practices [18-20].

To investigate the impacts of land use changes on the local soil and water, SWAT model is one of the most promising models. Dos Santos et al. [21] utilized the SWAT model to investigate the impacts of land use changes on streamflow and sediment yield and discuss ways to consider future land use conditions in Atibiai river basin, Brazil. The results provided useful information for proposing improvements in the basin's environmental quality and management. The SWAT model was also applied to assess the impact of changes in agricultural management practices on nitrate loads by Epelde et al. [22]. They found that trends of nitrogen surplus in the system generally increased as the fertilization input increased. Effects of replacing conventional crops by Miscanthus on riverine nitrate load were investigated by Ng et al [23] using the SWAT model. The results revealed that the nitrate load tended to decrease when replacing conventional crops by Miscanthus. Similarly, using the SWAT model, Cibin et al. [24] investigated the impacts of bioenergy crops on hydrology and water quality. The study also found that perennial grass reduced pollutant load at the watershed outlet. This suggested that the study on the im-pacts of land use changes on the local soil and water is currently of interest.

In chapter 2, the land potential for Napier grass cultivation or the dry matter yield (DMY) was estimated using the soil and water assessment tool (SWAT) model [25]. The SWAT model successfully estimated the Napier grass DMY in Thailand, with a coefficient of determination of 0.951; results also show that southern Thailand had the highest average DMY. In chapter 3, we integrated the land suitability map, obtained from a multicriteria decision analysis and the spatial distribution of DMY obtained from chapter 2, to assess the suitability of a site for Napier grass-based biogas power plants in southern Thailand. The location of biogas power plants and their distance from roads, residential areas, waterbodies, their access to the electricity grid, and their supply of feedstock were all considered during the site suitability analysis. Results revealed that, using only Napier grass from abandoned areas, five biogas power plants could be built with a total contracted capacity of 420 MW. This highlights that Napier grass can significantly reduce Thailand's dependency on imported electricity.

Although it was found that Napier grass possesses massive potential in biogas-based power generation in southern Thailand, with a few socioeconomic and environmental criteria considered, a study on the impacts of Napier grass on hydrology and water quality is yet to be performed. To cover more aspects in SDGs, effects of Napier grass on hydrology and water quality needed to be investigated. However, the factors to be considered should not be limited to hydrology and water quality, because there are several varied parties involved; the government will likely focus on energy supply, CO_2 reduction, and sustainability, while the local community and farmers are likely most interested in job creation and income. Hence, the broad objective of this study was to investigate the effects of different management practices for Napier grass plantations on surface runoff, sediment yield, and nitrate load in southern Thailand, using the SWAT model and carry out a multidisciplinary assessment for supporting adequate decision-making to utilize Napier grass as a feedstock for biogas-based power generation. This is to comparatively assess the advantages and disadvantages of various cases of cultivation practices with different fertilizing levels. The results from this study provide a logical framework to support decision-making for implementing new dedicated energy crops as a biogas feedstock, which is useful for the transition toward a renewable and sustainable energy society.

4.2 Material and methods

4.2.1 Study site

The Songkhla Lake Basin (SLB), shown in Fig. 4.1, was selected as the study site since the results from chapter 3 showed that there are three potential sites suitable for biogas-based power plants here. This basin is located in southern Thailand and lies within three provinces, namely Phattalung, Songkhla, and Nakhonsithammarat, and has an area of approximately 8,157 km^2. The elevation of the watershed ranges from 0 to 1,334 m above sea level, and the average annual precipitation is 1992 mm. In this watershed, the annual average temperature is 27.4 °C; the highest average temperature (33.9 °C) was observed in April, and in October, the average temperature was found to be lowest (23.0 °C). The average relative humidity for the SLB was 81.0%. The major land uses in the basin are agricultural (60.46%), forest (13.79%), and water bodies (13.54%). Southern Thailand is famous for latex

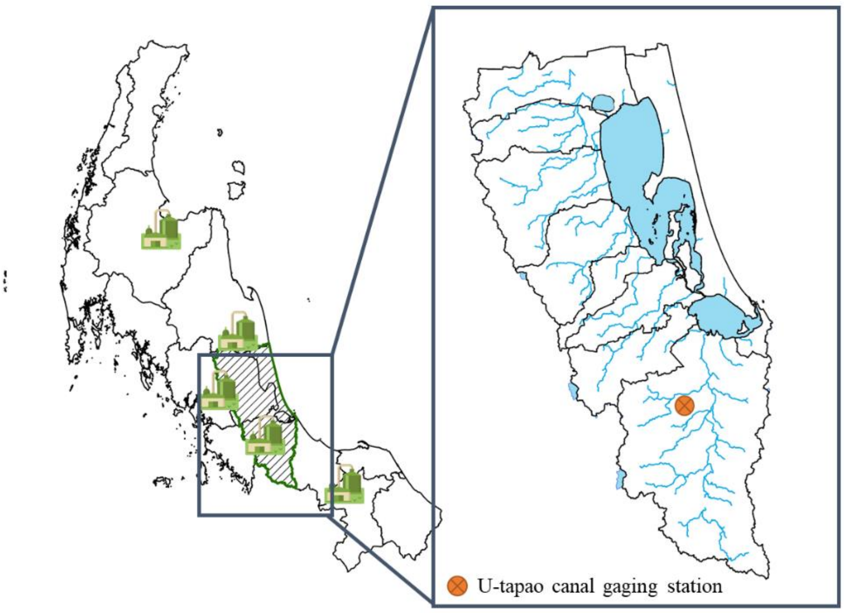

Figure 4.1 Map of the study area (Songkhla Lake Basin) and the location of U-tapao canal gaging station.

production, and 41.33% of the total area in this basin is utilized for the Pará rubber tree plantation. The largest natural lake in Thailand, i.e., Songkhla Lake, is located in the SLB. Among the chain of lagoons that form Songkhla Lake, the northernmost lagoon, i.e., Thale Noi, was declared a protected freshwater wetland in 1975. In addition, the Kuan Ki Sian knoll in the non-hunting area was declared a wetland of international importance in 1998 by the Ramsar Convention. Approximately 1.5 million people live in the basin, resulting in the rapid degradation of natural resources in the area because of economic activities. Because many parts of the SLB are wetlands, the area is highly susceptible to flooding and landslides, and several studies have focused on combating these issues [26,27].

4.2.2 Model description

The SWAT model, a continuous time- and process-based watershed model, was used to examine the impacts of Napier grass plantations on the hydrology and water quality within SLB. A detailed description of the SWAT model used for calculating Napier grass DMY was described in chapter 2. Based on the SWAT theoretical documentation [25], surface runoff, sediment yield, and nitrate load, which are considered indicators of environmental burdens corresponding to flood, erosion, and water pollution, respectively, were calculated. The schematic of SWAT model depicted in Fig. 4.2 shows the cycle of hydrology and nitrogen occurring in the watershed. Both of hydrology and nitrogen cycle can be transported in both vertical and horizontal directions. The water on the ground surface can be flown through the runoff mechanism while the water in the soil profile is transported to streams by lateral flow and percolated into groundwater. The SWAT model simulates both inorganic and organic forms of nitrogen cycle. The additional nitrate in the system is calculated through mineralization, and fertilization. Denitrification and plant uptake were considered as the loss

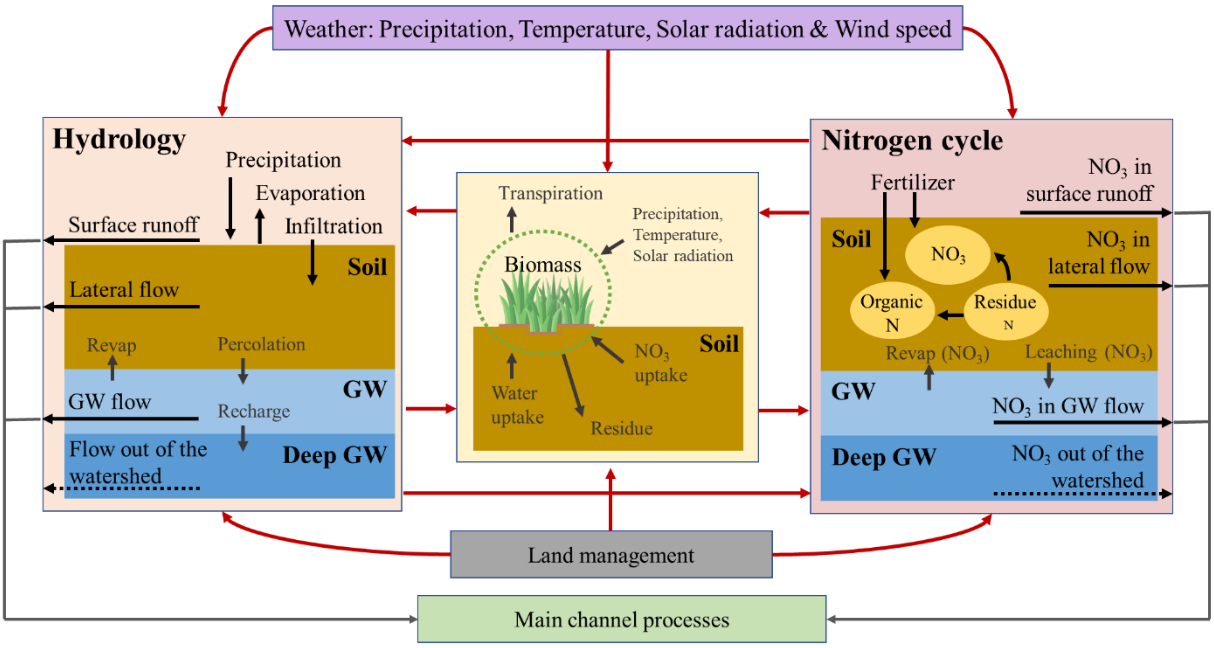

Figure 4.2 Schematic of SWAT model components

of nitrate in the system. The transportation of nitrate is similar to hydrology system which can be moved by surface runoff, lateral flow, and groundwater flow. The surface runoff Q_{surf} (mm-H_2O) is described using the following equation:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{R_{day} + 0.8S} \tag{1}$$

where R_{day} is the rainfall depth for the day (mm-H_2O) and S is the retention parameter (mm-H_2O), which is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2}$$

where CN is the curve number for the day. The curve number CN is an important parameter for calculating surface runoff, depending on the hydrologic soil group and land use. In the

SWAT model, a higher curve number indicates a higher runoff potential, and a lower number indicates greater retention.

To calculate sediment yield sed (metric tons), The modified Universal Soil Loss Equation (MUSLE) equation was used to calculate the sediment yield (metric tons). In this approach, the sediment yield is a function of the surface runoff Q_{surf}. The MUSLE equation can be expressed as:

$$sed = 11.8\left(Q_{surf} q_{peak} A_{hru}\right)^{0.56} K \cdot C \cdot P \cdot LS \cdot CFRG \tag{3}$$

where q_{peak} is the peak runoff rate ($m^3 \cdot s^{-1}$), A_{hru} is the area of the hydrological response unit (HRU) (ha), K is the USLE soil erodibility factor, C is the USLE cover and management factor, P is the USLE support practice factor, LS is the USLE topographic factor, and $CFRG$ is the coarse fragment factor.

The total nitrate content assessed in the SWAT model is an integrated contribution of fertilizer, manure application, bacterial attachment, mineralization, atmospheric deposition, plant uptake, leaching, volatilization, denitrification, and erosion. Because there are several equations involving calculations of the nitrate cycle, the SWAT model’s description was carefully summarized by Hass et al. [28], which will not be repeat here. The total nitrate balance, ΔN can was calculated using Eq. (4), i.e., the difference between nitrate input into the nitrate pool and the nitrate used by agricultural activities.

$$\Delta N = \left(N_{fert} + N_{hum} + N_{min} + N_{atm}\right) - \left(N_{denit} + N_{up} + N_{leach} + N_{surf} + N_{latf}\right) \tag{4}$$

where N_{fert} is the amount of nitrate in fertilizers, N_{hum} is the nitrogen mineralization from the humus active organic nitrogen pool (the amount of nitrogen moving from the active organic to nitrate pool in the watershed), N_{min} is the nitrogen mineralization of the fresh organic nitrogen pool (the amount of nitrogen moving from fresh organic, i.e., residue to the nitrate pool in the watershed), N_{atm} is the nitrate from atmospheric deposition, N_{denit} is the nitrate from denitrification, N_{leach} is nitrate percolation through the bottom layer of the soil profile in the watershed, N_{surf} is the nitrate loading to stream in the surface runoff in the watershed, and N_{latf} is the nitrate loading to stream in the lateral flow in the watershed.

Hass et al. [28] found that the nitrogen uptake distribution, or β_n, was strongly correlated with the nitrate concentration in crops. In the periods of increased nitrate uptake by plants in the root zone, the dominant phases of the nitrogen uptake distribution β_n were observed, which indicated that the crops consumed nitrate. SWAT calculates the nitrogen removed from the soil by plants by taking nitrogen from the nitrate pool [25]. If the nitrates in the upper layers of the soil was insufficient, the nitrates in the root zone were allowed to fully compensate for it. The actual amount of nitrogen removed from the soil, $N_{actualup,ly}$ is calculated using Eq. (5):

$$N_{actualup,ly} = \min\left[N_{up,ly} + N_{demand}, NO3_{ly}\right] \tag{5}$$

with,

$$N_{up,ly} = N_{up,zl} - N_{up,zu}$$

where $N_{up,ly}$ is the potential nitrogen uptake for layer ly (kg N·ha^{-1}), N_{demand} is the nitrogen uptake demand not met by overlying soil layers (kg N·ha^{-1}), $NO3_{ly}$ is the nitrate content of the soil layer ly (kg N ·ha^{-1}), $N_{up,zl}$ is the potential nitrogen uptake from the soil surface to the lower boundary of the soil layer (kg N·ha^{-1}), and $N_{up,zu}$ is the potential nitrogen uptake from the soil surface to the upper boundary of the soil layer (kg N·ha^{-1}).

To calculate the potential nitrate uptake $N_{up,z}$, from the soil surface to the depth z, Eq. (6) is used.

$$N_{up,z} = \frac{N_{up}}{[1-\exp(-\beta_n)]}\left[1 - \exp\left(-\beta_n \cdot \frac{z}{z_{root}}\right)\right] \tag{6}$$

with

$$N_{up} = \min\left[bio_{N,opt} - bio_N,\ 4fr_{N,3}\Delta bio\right]$$

and

$$bio_{N,opt} = fr_N bio$$

where N_{up} is the potential nitrogen uptake (kg N·ha^{-1}), β_n is the nitrogen uptake distribution parameter, z is the depth from the soil surface (mm), z_{root} is the depth of root development into the soil (mm), $bio_{N,opt}$ is the optimal mass of nitrogen stored in plant material for the current growth stage (kg N·ha^{-1}), bio_N is the actual mass of nitrogen stored in plant material (kg N·ha^{-1}), fr_N is the normal fraction of nitrogen in the plant biomass, Δbio is the potential increase in total plant biomass on a given day (kg·ha^{-1}), bio is the total plant biomass on a particular day (kg·ha^{-1}), and subscript 3 indicates the maturity growth stage.

4.2.3 Data used

The SLB is located in the western gulf of southern Thailand, and covers an area of approximately 820,000 ha. For ease of calculation, the watershed was divided into small units called HRUs. An HRU unit is the smallest spatial unit that consists of a unique load combination of land use, soil type, and slope. Figures 4.3a and 4.3b display the geographical data used in this study, including land use and elevation. To determine the slope, slope length, and stream network of each basin, digital elevation model (DEM) data with a resolution of 30 m were extracted, obtained from CGIAR CSI [29] as shown in Fig. 4.3a. The topographical map thus obtained needed to be integrated with soil and land use maps to obtain HRUs in the area of interest. To integrate these data, all maps were converted to a raster dataset with a resolution of 50 m. The spatial distribution of soil types was provided by the FAO-UNESCO harmonized world soil database [30]. Figure 4.3b displays the land use map from the Land Development Department (LDD) of Thailand used in this study. To calculate plant growth and water and nitrate cycles occurring in a watershed, weather data from the National Centers for Environmental Prediction (NCEP) called Climate Forecast System Reanalysis (CFSR) [31] were used, which was recommended by SWAT developers and various studies utilized to predict crop production, streamflow, sediment yield, and nitrate load [32-34].

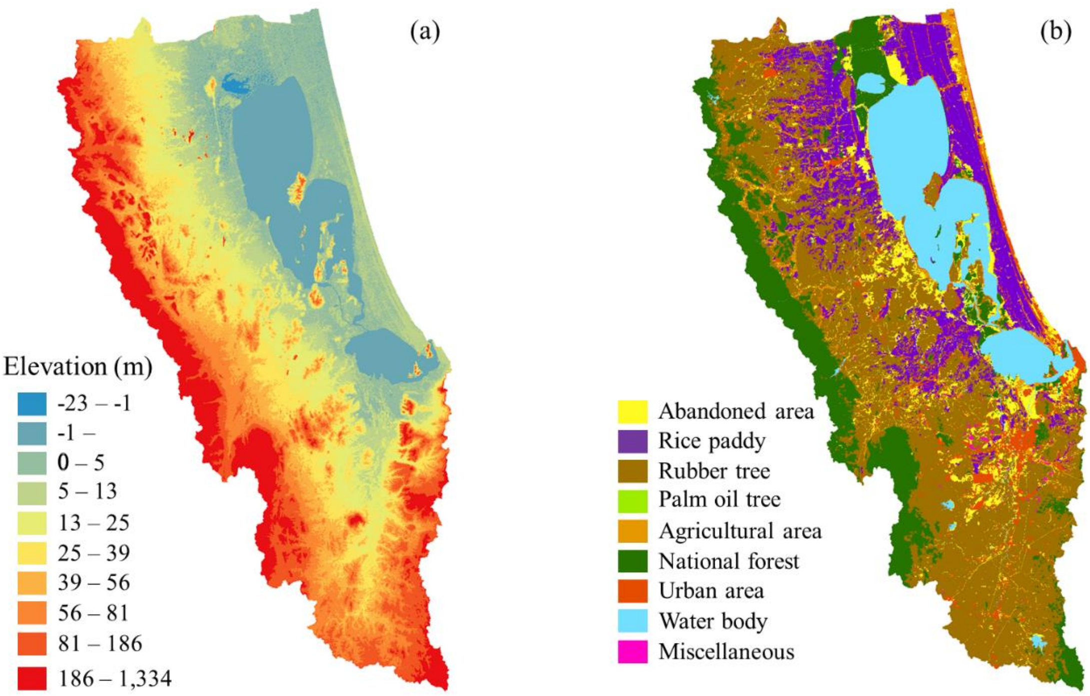

Figure 4.3 Maps of (a) elevation and (b) land use in Songkhla Lake Basin.

These data include the maximum and minimum temperatures, precipitation, solar radiation, and wind speed. Since the data from NCEP were available only from 1979 to 2014, a daily weather generator algorithm (dGEN) of the SWAT model was used to generate weather data during the rest of the calculation period. The CFSR data are provided on a Gaussian grid, defined by the NCEP, with a horizontal resolution of 38 km (0.3125°); the vertical resolution was not equally spaced. By combining the abovementioned data, we obtained ready-to-use data of the watershed of interest.

Table 4.1 Summary of calibrated SWAT parameters.

	Parameter	File	Description (unit)	Default range	Previous studies [21,22,35,36]	Default value	Calibrated value
Hydrology	CN2	.mgt	SCS runoff curve number	0-100	Default ×0.7	depends on soil and land use	55-69
	ESCO	.hru	Soil evaporation compensation factor	0-1	0.6-0.9	1	0.9
	CANMX	.hru	Maximum canopy storage (mm)	0-100	15-80	0	20
	ALPHA_BF	.gw	Baseflow recession constant	0.0071-0.0161	0.01-0.048	0.048	0.048
	GW_REVAP	.gw	Ground water revap coefficient	0-0.4	0.13-0.04	0.003	0.04
	GW_DELAY	.gw	Ground water delay (days)	0-500	14-500	31	14
	REVAPMN	.gw	Threshold depth of water in shallow aquifer for revap to occur	0-1000	250-500	750	500
	EVRCH	.bsn	Reach evaporation adjustment factor	0.5-1	0.5-0.9	1	0.9
	SURLAG	.bsn	Surface runoff lag coefficient	0.05-24	15	4	15
Sediment	SPCON	.bsn	Linear parameter for calculating the maximum amount of sediment that can reentrained during channel sediment routing	0.0001-0.01	0.001-0.008	0.0001	0.001
	LAT_SED	.hru	Sediment concentration in lateral flow and groundwater flow	0-5000	5.7-3000	0	3000
	CH_COV1	.rte	Channel erodibility factors	0-0.6	0.1-0.17	0	0.1
	CH_COV2	.rte	Channel cover factors	0-1	0.1-0.6	0	0.6
Precipitatio	rexp	-	The exponent of the exponential distribution	1.0-2.0	-	-	1.3

4.2.4 Model calibration and validation

To obtain a reliable prediction, the model must be carefully calibrated and validated. The main focus of this study was to investigate the effects of Napier grass plantations on hydrology and water quality; hence, streamflow and sediment yield observations were used for the calibration and validation. Since weather data greatly affected the simulation outputs, and since it is unclear if the weather data, including the maximum and minimum temperature, precipitation, solar radiation, and wind speed, generated by dGEN resembled the actual historical data, precipitation was also included in the calibration and validation processes. Only precipitation was selected for the process, because it significantly affected the simulation outputs of the hydrological model, and because precipitation data were available. Although there are several gauging stations in the Songkhla basin, data on hydrology, water quality, and precipitation of most stations are not publicly available. To the best of our knowledge, the only station that can be readily accessed for streamflow, sediment yield, and precipitation data is the U-tapao canal gaging station (6°55’52.32″ N, 100°26’24.72″ E). Therefore, the monthly streamflow, sediment yield, and precipitation data from the station during 2009-2018 were used for calibration and validation.

For simulation using the SWAT model, there were several parameters affecting hydrology, water quality, and precipitation, approximately 13 parameters exist that are related to the output of interest. With such a large number of parameters, it is difficult to perform manual calibration. Therefore, to perform the calibration, four steps were used to adjust the parameters. In the first step, previous studies [21,22,35,36] were reviewed to identify a range of parameters and sensitive parameters. Then, as a starting point, a simulation was performed using the default values suggested by the SWAT. Subsequently, the sensitive parameters were calibrated manually, similar to the manual calibration in Mengistu et. al. [37] and

Arnold et al. [38]; except for the curve number that Mendonça dos Santos et al. [21] suggested for multiplying the default numbers by 0.7. Finally, when needed, the input parameters were re-adjusted within reasonable parameter ranges obtained from the first step, and the process was repeated until satisfactory results were obtained. The coefficient of determination (R^2) of streamflow, sediment yield, and precipitation was used as an objective function, and the criterion for judging the quality of calibration was to identify the set of parameters that improved R^2 of all outputs to the desirable value of 0.70. The calibrated values are presented in Table 4.1. After a set of reliable parameters was obtained, the SWAT model was validated using three statistical parameters: the Nash–Sutcliffe model efficiency index (NSE), percent bias (PBIAS), and R^2.

4.2.5 Napier grass plantation cases and calculation setting

The land use in the SLB at present (i.e., the baseline) and in case of the sites of Napier grass plantation are shown in Table 4.2. The non-hunting area must be preserved, and thus cannot be used for planting Napier grass. To avoid conflicts with existing industrial, urban, economical, and agricultural lands, only abandoned areas were considered for Napier grass plantations. It should be noted that land used for agricultural purposes was found to decrease, because those areas were considered abandoned agricultural lands by the LDD.

Since the growth of Napier grass is highly dependent on management practices [39], particularly on the amount of nitrogen fertilizer applied, a total of four cases were formulated, in each of which the amount of the applied nitrogen fertilizer varied from 0 to 500 kg $N \cdot ha^{-1}$, at four levels. These values were obtained from studies by the Animal Nutrition Division, the Department of Livestock Development, and the Ministry of Agriculture and Cooperatives, and were published between 1993-2005 [40-48]. It was found that nitrogen fertilizer could increase Napier grass DMY by up to three times the DMY without the fertilizer [40-48].

However, it is unclear if such a large amount of fertilizer negatively impacts the environment in any way. The purpose of this variation was to investigate the impact of such an intensive fertilizer. These cases were applied to the ready-to-use data for the watershed of interest (as described above) to evaluate the impacts of different nitrogen fertilizer levels on Napier grass DMY, streamflow, sediment yield, and nitrate load.

Table 4.2 The differences of land use areas between the baseline case, which is current agricultural land use, and the cases where the abandoned areas were utilized to plant Napier grass in Songkhla Lake Basin

Land use type	Baseline scenario		Napier grass scenario		%Change
	Area (ha)	%	Area (ha)	%	
Rice	118769.9	14.6%	113769.9	13.9%	-4.2%
Rubber Trees	347112.5	42.6%	337112.5	41.3%	-2.9%
Oil Palm	5592.5	0.7%	5592.5	0.7%	0.0%
Agricultural Land	31624.8	3.9%	28624.8	3.5%	-9.5%
Forest-Mixed	112485.4	13.8%	112485.4	13.8%	0.0%
Residential-Med/Low Density	46483.2	5.7%	46483.2	5.7%	0.0%
Water	110469.8	13.5%	110469.8	13.5%	0.0%
Miscellaneous area	2394.9	0.3%	2394.9	0.3%	0.0%
Abandoned area	40800.5	5.0%	0	0.0%	-100.0%
Napier grass	0.0	0.0%	58800.5	7.2%	–
Total area	815733.5	100.0%	815733.5	100.0%	

In this study, the calibration period was from 2009 to 2013, while data from 2014 to 2018 were used for validation. Five warm-up years were used in the model initialization, as suggested by Tudose et al. [49], and the investigation was carried out over 10 years. Since the preset parameters for Napier grass plantation did not exist in the original SWAT model, a parameter set for predicting Napier grass crop yield must be developed. The simulation setup, model calibration, and validation were described in chapter 2, and will not be repeated here. Since the models for other land uses were well established, the default setups for each land use suggested by SWAT were applied, except for the abandoned and miscellaneous areas that were not defined in SWAT. These areas were assumed to have a low agricultural area based on but the fact that little agricultural activity has been observed in the area. Changes between the parameter set of abandoned land and Napier grass cultivation are listed in Table 4.3.

Table 4.3 SWAT model parameters for abandoned land and Napier grass cultivation

Category	Parameter	Definition	Abandoned land	Napier grass
Land cover/plant	IDC	Land cover/plant classification	6 (perennial)	6 (perennial)
	BIO_E	Radiation use efficiency	30	38
	CHTMX	Maximum canopy height (m)	0.9	2.5
	RDMX	Maximum root depth (m)	1.3	2.2
Runoff	CANMX	Maximum canopy storage (mm)	20 (calibrated)	20
	CN	Curve number	65 (calibrated)	55
Sediment	USLE_C	Minimum USLE crop factor	0.003	0.003
Fertilizer	FMINN	Fraction of mineral N (NO_3 and NH_4) in fertilizer (kg min-N·kg^{-1} fertilizer)	0	0.46
	FORGN	Fraction of organic N in fertilizer (kg org-N·kg^{-1} fertilizer)	0	0
	FNH3N	Fraction of mineral N in fertilizer applied as ammonia (kg NH_3 -N·kg^{-1} fertilizer)	0	0

4.2.6 Multidisciplinary assessment supporting decision-making for utilizing Napier grass

Since solely considering the impact of Napier grass plantations on land is insufficient for decision-making, this study considers impacts such as energy supply, carbon reduction, and benefits to farmers, aside from hydrological impacts, in order to provide a better overview for decision-making. From the simulation results obtained from the SWAT model, Napier grass DMY was utilized to evaluate energy supply, carbon reduction, and farmer benefits.

For energy supply, based on chapter 3, approximately 11.1 kt biomass was required for generating 1 MW of electricity. This is based on the assumption that a methane yield of 242 m^3 can be obtained from a ton of Napier grass DMY [9]. In addition, a methane energy density of 40 $MJ \cdot m^{-3}$ [50] and an energy conversion efficiency of 30% was assumed; the potential power generation could be conveniently evaluated using a factor of 11.1 $kt \cdot MW^{-1}$. Beyond the benefit of obtaining electricity, Napier grass-based power generation could serve as a substitute for conventional power generation derived from fossil fuels. In a previous study [51], by utilizing Napier grass-derived natural gas for electric generation instead of fossil fuels, approximately 60% of CO_2 emissions could be reduced (i.e., from 1080 to 450 kg-$CO_2 \cdot MWh^{-1}$).

Using Napier grass as a biogas feedstock not only helps reduce CO_2 emissions, but also provides benefits to farmers. Currently, the Napier grass purchase price in Thailand is approximately 300 $Baht \cdot t^{-1}$-fresh yield (equivalent to 1,500 $Baht \cdot t^{-1}$-DMY). Furthermore, the cost of nitrogen fertilizers was only approximately 30 $baht \cdot kg\text{-}N^{-1}$ at the time of this study. This is a relatively high purchase price with a relatively low additional cost and, thus, it was encouraging for farmers to aim to achieve more production per area. This could lead to environmental problems owing to the overutilization of nitrogen fertilizers. Therefore, the tradeoff between Napier grass production and nitrate loads should be carefully considered. The main purpose of this work is to investigate the impact of different applied fertilizer inputs on additional revenue. The money spent on fertilizers was deducted from the Napier grass selling price to evaluate the farmer’s operating income under different management practices.

After all impacts, including surface runoff, sediment yield, nitrate load, energy supply, carbon reduction, and benefits to farmers, were determined in each case, they were normalized using max-min normalization to make it convenient for comparison. The max and min values were set to 1.0 and 0.5, respectively. The comparison was performed using a radar chart to enhance visibility.

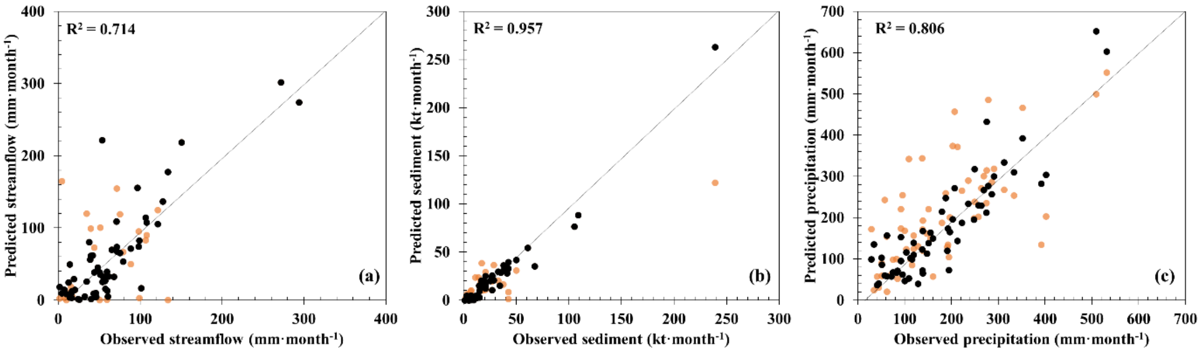

Figure 4.4 Goodness-of-fit plots with 1:1 line comparing the observed and simulated (a) streamflow, (b) sediment, and (c) precipitation with parameters before and after calibration during 2009-2013 at U-tapao canal gaging station. Presented R^2 is after calibration, where the orange (●) and black dots (●) indicate the predicted data before and after calibration, respectively.

4.3 Results and discussion

4.3.1 Model calibration and validation

Figures 4.4a-c show the goodness-of-fit plots for monthly streamflow, sediment yield, and precipitation, with the initial and final parameter sets in the calibration period from 2009 to 2013. Using the manual calibration process mentioned above, the R^2 of the streamflow increased from 0.476 to 0.714, as depicted in Fig. 3a. For the sediment yield, the R^2 of 0.828 from the default parameter set was improved to 0.957 (see Fig. 3b). The initial parameter set provided a reasonable prediction for precipitation, as an R^2 of 0.476 was initially achieved. However, the accuracy can be further improved after calibration, and an R^2 of 0.806 was

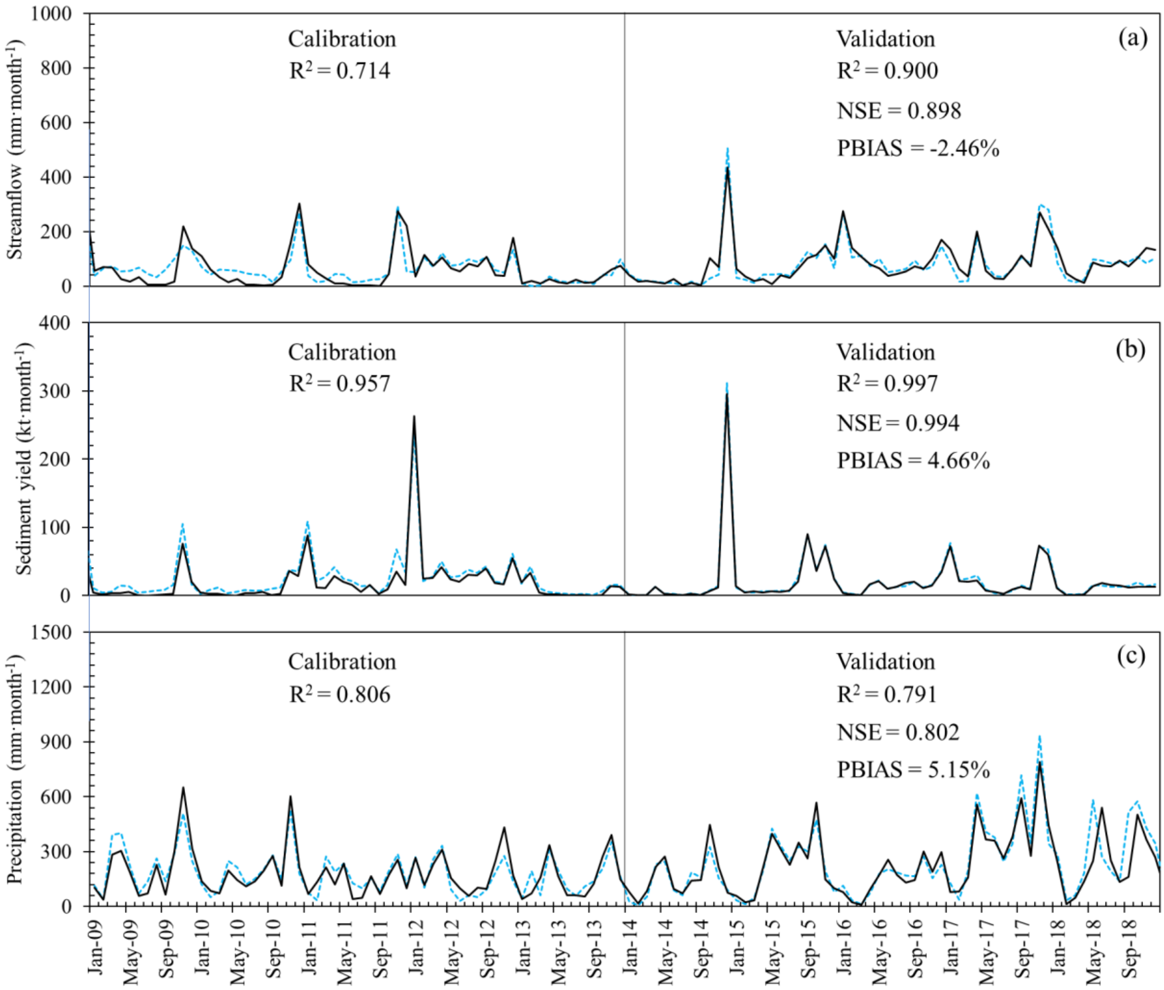

Figure 4.5 Model calibration and validation for Songkhla Lake Basin at U-tapao canal gaging station using (a) streamflow, (b) sediment, and (c) precipitation.

obtained. Overall, it is clear that predictions can be satisfactorily improved by using the manual calibration process; Table 1 displays the final parameter set.

To validate the generalization performance of the calibrated model, data from 2014 to 2018 were compared with the simulation data obtained from the parameter set obtained after the calibration. Figures 4.5a-c compare the temporal changes in the simulated and observed monthly streamflow, sediment yield, and precipitation obtained during calibration and validation. Results reveal that although some parts were over/underestimated, the model could reasonably predict the overall variation in streamflow, sediment yield, and precipitation. There was a slight concern regarding the accuracy of the weather data generated by the dGEN, because precipitation data are generally recognized as the most important data for hydrological analysis. To ensure that the data were of adequate quality, careful validation was performed. It is clear that the precipitation data generated by dGEN resembled the actual historical data as the dGEN could predict the precipitation data from to 2013-2018, with an R^2 of 0.791, NSE of 0.802, and PBIAS of 5.15%.

With accurate weather data, it was found that the SWAT model can successfully and accurately estimate the streamflow during 2014-2018, with an R^2 of 0.900, NSE of 0.898, and PBIAS of -2.46%. The negative value of PBAIS indicate that the model overestimated the streamflow by approximately 2.5% (on average). On the other hand, the sediment yield at the U-tapao canal gaging station during 2014-2018 can be estimated by the SWAT model with an R^2 of 0.997, NSE of 0.994, and PBIAS of 4.66%. The sediment yield was positive for the PBAIS, indicating that sediment yield was underestimated by approximately 4.7%. Considering all the statistical indicators, the model is deemed adequate for investigating the effects of Napier grass plantations on hydrology and water quality.

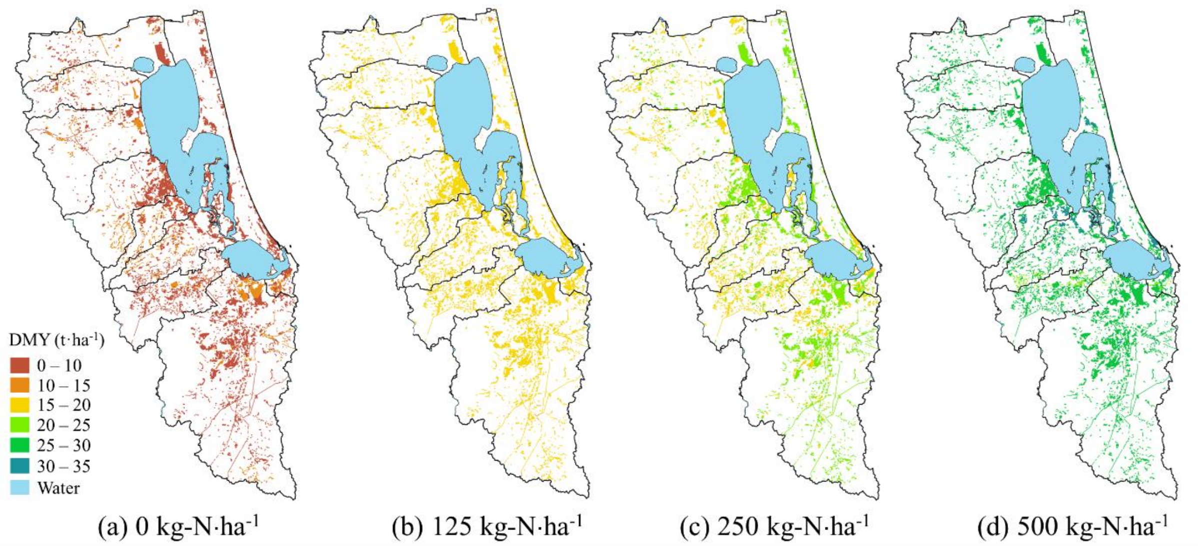

Figure 4.6 Spatial distribution of Napier grass DMY from abandoned areas in Songkhla Lake Basin under different nitrogen fertilizer of (a) 0, (b) 125, (c) 250, and (d) 500 kg-N·ha^{-1}

4.3.2 Impacts of Napier grass energy plantation cases

The impacts of different levels of applied nitrogen fertilizer on Napier grass production, streamflow, sediment yield, and nitrate load were investigated over a period of 10 years. Figures 4.6a-d depicts the spatial distribution of average Napier grass DMY planted with different nitrogen fertilizer levels in the abandoned area in SLB. The results, as shown in Fig. 4.7, revealed that without applying the nitrogen fertilizer, the average DMY in the basin was approximately 11.28 t·ha^{-1} (i.e., 663 kt in total); however, as the amount of applied nitrogen fertilizer increased, DMY increased. The Napier grass DMY can be increased to 18.19, 22.71, and 27.52 t·ha^{-1} after the application of nitrogen fertilizers of 125, 250, and 500 kg N·ha^{-1}, respectively. These results align with the hypothesis from Hazary et al. [39], that the fertilizer application rate positively affects the production of dedicated energy crops. The DMY increased by approximately 61% when nitrogen fertilizer of 125 N·ha^{-1} was applied; however, when the amount of fertilizer was doubled to 250 kg N·ha^{-1}, only a 25% increase in

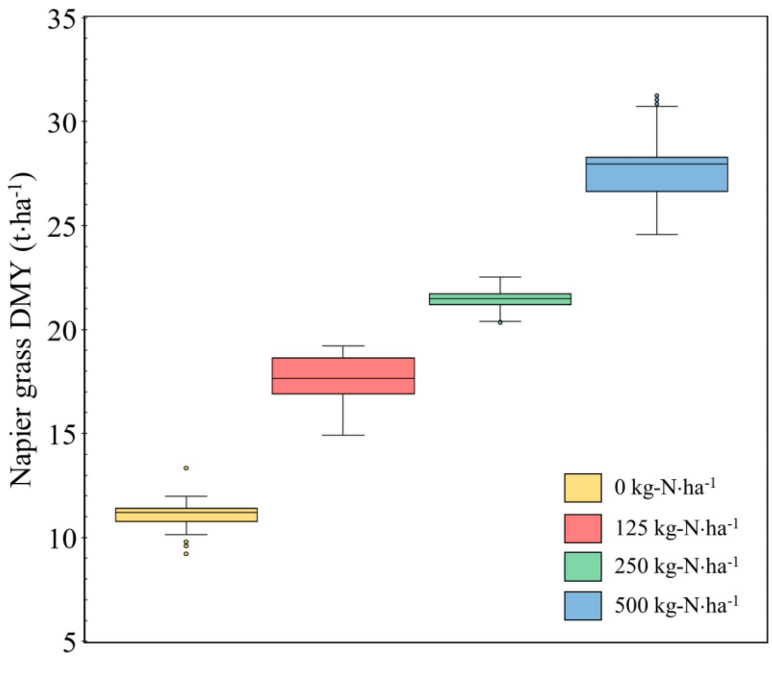

Figure 4.7 Box plots of Napier grass DMY from abandoned areas in Songkhla Lake Basin under different nitrogen fertilizer of 0, 125, 250, and 500 kgN ha^{-1}

DMY was observed. An increase in the DMY of only 22% was achieved when the nitrogen fertilizer level was further increased to 500 kg N·ha^{-1}. Considering the diminishing return, it is unsurprising that a fertilizer level of 250 kg N·ha^{-1} was recommended by the handbook from Nakhon Ratchasima Animal Nutrition Research and Development Center [52]. Although DMY was increased along with the amount of nitrogen fertilizer, it was not clear

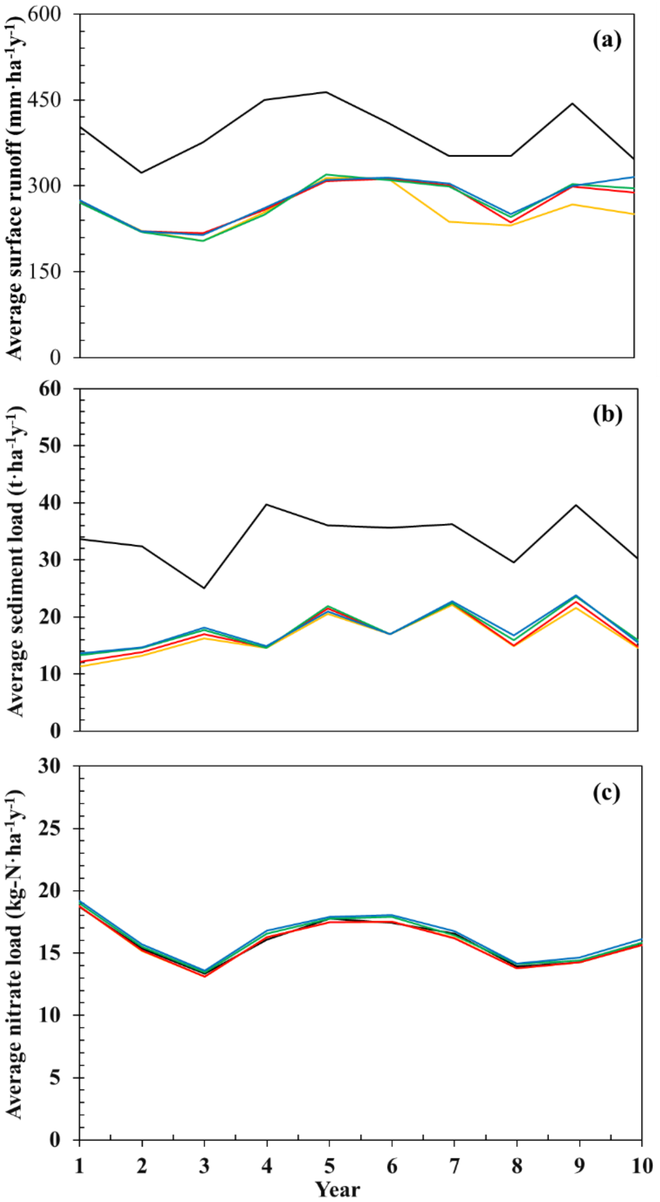

Figure 4.8 Average annual (a) surface runoff, (b) sediment load, and (c) nitrate load of Songkhla Lake Basin for 10 years timespan, where black, yellow, red, green, and blue solid lines indicate the baseline case and the Napier grass plantation cases with the nitrogen fertilizer application of 0, 125, 250, and 500 kgN ha^{-1}, respectively.

how it affected hydrology and water quality. Hence, it is important to investigate its effects on surface runoff, sediment yield, and nitrate load.

The surface runoff at the SLB for different cases was investigated, as shown in Fig. 4.8a. It is clear that planting Napier grass in abandoned areas has a positive impact on surface runoff prevention. While reducing surface runoff may be beneficial for flood control, it can be considered detrimental for water resources and lake ecosystem health. This is due to the fact that SLBs are extremely prone to flooding and landslides. Thus, the decrease in surface runoff was considered to have a positive effect on the area. Surface runoff can be reduced by approximately 30% by Napier grass plantations. These results concur with the results of previous studies, that show that perennials can help reduce surface runoff [23,53]. This is due to the fact that most studies replaced row crops with perennials, and the perennials have better soil cover. In this study, abandoned areas were used in Napier grass plantations; based on Eq. (1) and (2), the surface runoff Q_{surf} is a function of the curve number. The curve number directly reflects the characteristic land cover and hydrologic soil groups. When the abandoned areas were replaced by Napier grass, the curve number decreased from 65 to 55, resulting in better water retention. The lower curve number is likely due to the large transpiration rate of the Napier grass. While the surface runoff greatly decreased with the Napier grass plantation, no significant differences between the case of different applied nitrogen fertilizer levels were observed. This is because the increase in the vertical growth of Napier grass did not affect the lateral soil coverage, which is a key factor in reducing surface runoff [23].

Figure 4.8b displays the sediment yield for the different planting scenarios at the SLB. The sediment yield decreased when abandoned areas were used for Napier grass plantations. This has a positive impact, as the sediment yield is strongly related to soil erosion. The decrease in sediment yields implied that water bodies would be less polluted by soil erosion; sediment yield was significantly reduced, by approximately 50%. When different nitrogen fertilizer levels were applied, no significant differences were observed. These results were similar to those of the surface runoff presented above. It is unsurprising that the SWAT model utilizes the MUSLE equation (see Eq. (3)), where the surface runoff volume and peak flow rate were used while calculating sediment yield. Besides these two factors, the USLE cover and management factor C are the only parameters that change with land use, which involves only the impacts of crop type and tillage method. Since the applied fertilizer level did not affect the USLE cover and management factor C, it is unsurprising that the sediment yield was not affected by the different fertilizer levels. It is worth noting that the USLE_C, which is the minimum USLE crop factor, is the same for abandoned areas as well as Napier grass plantations, as shown in Table 3. This is because the crop types considered in the abandoned and Napier grass plantation areas were the same. A USLE_C of 0.003 was suggested as a default value for perennials; however, the USLE cover and management factor C could be different because it was calculated based on the USLE_C by considering the seasonal effects. Moreover, Singh et al. [54] suggested that the USLE cover and management factor C are the least influential parameters in sediment yield calculation.

For the nitrate loads calculated as the sum of leaching and loading to the water stream by surface runoff and lateral flow, the average nitrate loads over SLB with different planting cases are shown in Fig. 8c. The results revealed that the nitrate loads can be reduced slightly when fertilizer rates of 0 and 125 kg N·ha^{-1} were applied. The reduction in nitrate loads is in agreement with the results of previous studies, which indicated that dedicated energy crops consume much nitrogen for growth [39]. In addition, several studies have shown that perennials can help reduce nitrate loads [23,24,55,56]; however, the nitrate loads increased slightly when the amount of applied nitrogen fertilizer exceeded 250 kg N·ha^{-1}. Although a large amount of nitrogen fertilizer was applied in the cultivation, the nitrate loads, as compared to the baseline (see above), increased by approximately 1.13% and 2.32% for the applied fertilizer rates of 250 kg N·ha^{-1} and 500 kg N·ha^{-1}, respectively. This can be explained by the total nitrate balance summarized in Table 4.4. It is clear that nitrogen uptake by plants was the most influential nitrogen removal process. Because of diminishing returns, Napier grass cannot consume all the applied fertilizer for the case of 250 and 500 kg N·ha^{-1}, resulting in surplus nitrogen in the considered area.

Table 4.4 Soil system nitrate balance in SLB. Values are expressed per hectare of the whole basin (kg-N ha^{-1} y^{-1}) including all land uses.

Item	Baseline	Napier grass plantation			
		0	125	250	500
Inputs					
Fertilizer application	39.88	39.88	42.90	47.15	51.88
Humus mineralization	9.36	9.06	9.31	10.15	10.31
Residue mineralization	6.78	6.37	6.76	8.12	8.94
Atmospheric deposition	0.26	0.26	0.26	0.26	0.26
∑ Inputs	56.28	55.58	59.23	65.68	71.39
Outputs					
Denitrification	3.65	3.65	4.00	5.65	6.44
Nitrate uptake	37.64	37.84	40.37	43.64	47.51
Nitrate leached	13.86	13.34	13.86	14.53	14.58
Nitrate loading to stream in surface runoff	1.19	1.16	1.20	1.29	1.38
Nitrate loading to stream in lateral flow	0.04	0.04	0.04	0.04	0.04
∑ Outputs	56.39	56.03	59.47	65.15	69.95
∑ Inputs−∑ Outputs	-0.11	-0.45	-0.24	0.53	1.44

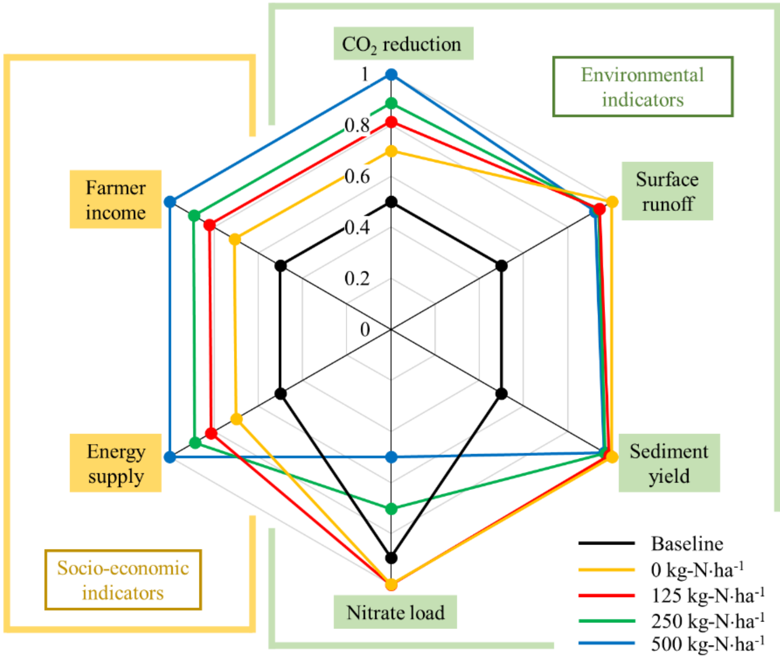

Figure 4.2 Comparison of the evaluation indicators of baseline and Napier grass plantation cases on surface runoff, sediment yield, nitrate load, energy supply, farmer income, and CO_2 reduction. The indicators were scaled by the max-min normalization of the values, where max and min values were set to be 1.0 and 0.5, respectively.

To obtain a better basis for decision-making, a multidisciplinary evaluation was carried out to compare the advantages and disadvantages of different planting cases. Figure 4.9 shows the radar chart of the evaluation indicators, including surface runoff, sediment yield, nitrate load, energy supply, farmer income, and CO_2 reduction, for different planting cases. The results revealed that although applying nitrogen fertilizers of 500 kg N·ha^{-1} provided the highest benefits in energy supply, farmer's incomes, and CO_2 reduction, it also performed the worst in hydrological indicators among the different planting cases considered in this study. Together with the case of 250 kg N·ha^{-1} nitrogen fertilization, these were the only two cases that performed worse than the baseline upon increasing the amount of nitrate load into the system. On the other hand, without the applied fertilizer, benefits from Napier grass were in contrast with that of the case when nitrogen fertilization of 500 kg N·ha^{-1} was applied. This suggests that there is a trade-off between hydrological indicators and other factors, including energy supply, farmer income, and CO_2 reduction. The case in which nitrogen fertilization of 125 kg N·ha^{-1} was applied would be a better choice as it was more balanced in all indicators.

Overall, from the simulated results of this study, Napier grass plantation in the abandoned land in SLB resulted in a decrease in surface runoff and sediment yield, which is beneficial to the water cycle control in SLB since the SLB is prone to flooding and landslides. In addition, nitrate loads were shown to be reduced in the Napier grass plantation cases with modest fertilizer applications. The socio-economic indicators supported utilizing abandoned areas in southern Thailand to plant Napier grass for biogas-based power generation, which can help reduce the dependency on imported electricity and provide additional income and/or job opportunities for local people. However, it should be noted that the decrease in surface runoff, sediment yield, and nitrate load does not always have a positive impact on ecosystem health in areas that are not susceptible to flooding and landslides. Therefore, prior to the introduction of new dedicated energy crops, it is important to assess the impacts on land, ecosystems, and other criteria unique to the area of interest. Although there are several potential benefits to be obtained from Napier grass plantations, it is unclear if the Napier grass-related businesses will be economically sustainable. In this study, analysis was not quantitative because the importance of all evaluation indicators could not be adequately compared. Therefore, a further study on the economic perspective of introducing Napier grass as a biogas feedstock for power generation should be carried out.

4.4 Conclusion

To introduce new crops for specific purposes, such as bio-energy resources, it is important to consider their impacts on environmental and socioeconomic benefits. In this study, a methodological framework for investigating the impacts of Napier grass plantations and a multidisciplinary assessment was successfully developed, based on the SWAT watershed model. To obtain a reliable parameter set for the simulation, this model was carefully calibrated and validated. Utilizing manual calibration, a set of parameters used to predict streamflow, sediment yield, and nitrate load were obtained by considering R^2. Results showed that by planting Napier grass, surface runoff, sediment yield, and nitrate load can all be greatly reduced. This is because of the increase in land cover and the nature of Napier grass, which consumes a large amount of nitrogen. The increase in nitrogen fertilizer was found to be relatively insignificant to overall surface runoff and sediment yield; however, the amount of N fertilizer significantly affected the nitrate load— as the nitrogen fertilizer level increased, the nitrate load increased. To have a clearer idea of how different cases impacted other perspectives, energy supply, farmer's incomes, and CO_2 reduction were included further considerations. The results of this consideration revealed that while no fertilizers were applied, the management practice performed best in reducing the negative impacts on hydrology and water quality. However, applying fertilizer as high as 500 kg $N \cdot ha^{-1}$ provided the highest energy supply, income to farmers, and CO_2 reduction. The results of this study provide information about the environmental impacts as well as crop production. This is supportive for both energy-related policymakers and farmers, since policymakers can utilize this information to consider a tradeoff between environmental impacts and crop production, and the farmers can learn how to achieve high comprehensive benefits from their crops.

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CHAPTER 5

Conclusion

5.1 Achievement of the thesis

Overall, a logical framework to support decision-making for implementing new dedicated energy crops as a feedstock was established considering socio-economic and environmental issues, which is beneficial for the transition toward renewable and sustainable energy society. Multi-disciplinary assessment considering environmental and socioeconomic impacts on land use changes is a huge issue in making bioenergy-related policy. A procedure for assessing impacts of land use changes was developed. Since the SWAT model possessed advantages, particularly DMY of bioenergy crops, hydrology and water quality can be assessed conveniently, the developed procedure was based on such a model. However, the SWAT model gives only one-dimensional result as there were many to be considered, including energy supply to power plant, CO_2 reduction, and farmers' benefits. The SWAT model was insufficient to provide a whole picture for bioenergy planning. This thesis evaluated and planned implementation of Napier grass plantation in Thailand considering those impacts.

In chapter 2, an assessment of land potential for Napier grass plantation using SWAT model was presented. Parameter calibration and model validation were carefully carried out to ensure the accuracy of the model performance. The results were further analyzed to evaluate regional potential for Napier grass-derived power generation. To introduce a new crop for power generation, the land potential and its impacts on land should be investigated prior to the plantation. To ensure that the simulations are realistic, preliminary, the parameters were collected from various studies and applied them to evaluate the land potential in Thailand. However, the model showed poor agreement between simulated outputs and experimental data. It was found that crop growth parameters were not universal. It was because of the difference of weather condition between countries. Therefore, parameter calibration needed to be carried out. Model validation was performed and the results showed excellent agreement with the experimental data. The model was then extended to estimate Napier grass yield and Napier grass-derived power generation. The approach would be a useful tool to help obtaining accurate parameters which consequently led to reliable simulated outputs.

Although, in chapter 2, it was found that abandoned area in Thailand possessed a high potential for introducing Napier grass as a feedstock for power generation. However, in fact, not all abandoned area can be utilized. There are plenty of factors to be considered in energy-related decision making, including biogas plant locations, the size of biogas plants, the distance of feedstock to be transported from the plantation to the biogas plants and impact on local people. To consider such effects, land suitability analysis should be carried out. Nonetheless, the results obtained from this chapter are very important in such analysis as the Napier grass has never been widely planted before.

The site suitability assessment of Napier grass-based biogas power plants using the combination of SWAT model, MCDA and GIS was presented in chapter 3. The procedure presented in this chapter was not only able to help energy-related policy makers locating suitable sites for the biogas power plants that satisfied environmental and socio-economic criteria, but also to ensure that those sites would have sufficient Napier grass supply. Before making any decision on land use, it is important to consider various aspects to avoid impacts on socio-economic and environment. MCDA was used to perform land suitability analysis for locating Napier grass-based biogas power plants. However, to locate biogas power plants, not only the pre-assessment of land is important, but the amount of feedstock supplied to plants is also necessary considering transportation cost. Therefore, Napier grass plantations should be in the area around biogas power plants to avoid these problems. To overcome the issue, the yield distribution obtained from chapter 2 was utilized. Combining suitability level and yield distribution together, the suitable candidate sites for Napier grass-based biogas power plants can be suggested. The proposed approach, which was a useful tool for implementing new dedicated energy crops to be used as a feedstock for power generation, was applied to suggest the suitable candidate site of Napier grass-based biogas power plants in southern Thailand. The results revealed that the total capacity of the power plants could promote the region to be self-sufficient in power generation.

Although the results obtained from chapter 3 provided candidate sites for Napier grass-based biogas power plants by considering both environmental and socio-economic criteria. However, to implement new feedstocks into the area in such a widescale manner proposed by MoE, the impacts of land use changes must be considered in order to avoid unforeseen socioeconomic and environmental issues. Due to the intensive agricultural practices typically utilized when planting fast-growing crop, the impacts of Napier grass plantation on hydrology and water quality have never been performed yet. Not only that, those are just one side of the picture. Other factors such as the concerns over CO_2 reduction and farmers' benefits should also be considered to achieve sustainability in implementing bioenergy crops.

In chapter 4, the multi-disciplinary assessment of Napier grass plantation was proposed by combining the SWAT model and GIS. The procedure presented in this chapter was able to help energy-related policy makers assess the advantages and disadvantages of various cases of cultivation practices with different fertilizing levels for new dedicated energy crops. Before making any decision on land use, it is important to consider various aspects to avoid impacts on socio-economic and environment. Although chapter 3 considered a few socioeconomic and environmental criteria, information about impacts of Napier grass on hydrology and water quality has never been obtained. In this chapter, the SWAT model was employed to investigate the impacts of land management practices on Napier grass dry matter yield, water sediment, and agricultural chemical loads over time in SLB. A multi-disciplinary assessment for evaluating socio-economic and environmental impacts of implementing Napier grass as a bioenergy crop for power generation by combining the SWAT model, GIS, and MCDA was successfully developed. Results from the SWAT model were utilized to carry out a multidisciplinary assessment considering surface runoff, sediment yield, nitrate load, energy supply, farmer income, and CO_2 reduction. The results revealed that implementing Napier grass could provide benefits on hydrology, water quality, power generation, job creation, and CO_2 reduction. However, the fertilization rate had to be taken with care because too much fertilizers could result in higher amount of nitrate loads.

5.2 Utility of the proposed framework in practical energy system planning

In order to introduce a new energy system utilizing new dedicated energy crops in the area, there are many parties involved, for example government, private sectors, farmers and local people or customers. The benefits of land use should be shared among stakeholders because the total land is limited. Furthermore, the renewable energy system introduced must be sustainable environmentally and economically. Therefore, multi-disciplinary assessment is very important in building a policy to help facilitate the use of renewable energy.

In this work, the framework for implementing new dedicated energy crops as a feedstock was proposed considering socio-economic and environmental issues. The proposed framework is not limited to Napier grass but it can be also applied to any energy crop that has never been widely planted before. The framework consists of 3 main steps; which are estimating feedstock potential; finding the location that is suitable for biogas power plant considering feedstock availability, environmental and socioeconomic criteria; and assessing impact of energy crop plantation on hydrology, water quality, power generation, job creation, and CO2 reduction.

Utilizing a new dedicate energy crop is unlike other biomass products. This is because the crop is not yet widely planted, making it difficult to estimate the amount of feedstock. Not only that since the condition of geographical and weather of each region is not the same, using the data from other region can lead to impractical estimation. In chapter 2, the SWAT model was proposed for assessing land potential. Before apply the model to estimate land potential, it is necessary to calibrate the set of parameters. This is because parameters can differ from area to area. Procedure provided in chapter 2 is very useful as a guideline to obtain the set of parameters that used for crop growth simulation. This could be very helpful for both farmers and private sector to assess the feedstock potential that could supply from that area.

To find the location for biogas power plants, not only the feedstock distribution is important, there are also plenty of factors to be considered in energy-related decision making in order to avoid the impact on environment, economic and local people. In chapter 3, feedstock distribution is integrated with AHP-MCDA and GIS to assess for site suitability of biogas power plants. An algorithm for locating suitable biogas power plant sites was proposed in chapter 3. This could be very helpful for both farmers and private sector to assess the suitable location for both power plant and energy crop plantation to locate within plant proximity.

After obtained suitable location for biogas power plant, the impact of energy crop plantation on land and water is needed to be assessed. The locations of biogas power plant help reduce the number of computational areas. In chapter 4, SWAT model was applied to investigate the impact on land use change.

By utilizing this proposed framework, the government does not only benefit in energy security and GHG emission reduction, but the output could help on suggesting energy policy for promoting renewable energy which is the cost that government should support each section for example FiT, feedstock price and special loan for private sectors and farmers. The framework could be able to suggest the plan that encourages both of private sectors and farmers to invest on new energy system utilizing new dedicated energy crop in the area.

5.3 Future perspectives

It should be noted that, in this study, the indicators of surface runoff, sediment yield, nitrate load, energy supply, farmer income, and CO_2 reduction were just a relative measure. Thus, the importance of all evaluation indicators is not quantitatively comparable as they are not in the same unit. Future works may be required for solving this issue. Furthermore, a study on the economic point of view for building energy policy for Napier grass-based biogas power plant is not yet performed. The energy policies for promoting renewable energy which is the cost that government should support parties needed to be carefully analysed. The results for such a study would provide an estimation of how much money should the government spend through FiT scheme, feedstock price support, and special loan for private sectors and farmers. Thus, trade-offs analysis is needed in order meet policy objectives and secure a platform for bioenergy investment.

5.4 Conclusion

In this study, the SWAT model was employed to investigate land potential for Napier grass plantation in Thailand. The spatial distribution of estimated yield in chapter 2 was further utilized to evaluate land suitability for biogas power plants based on environmental and socioeconomic criteria along with AHP-MCDA. A multidisciplinary assessment supporting future decision-making was conducted considering environmental and socioeconomic impact. The findings of this study would be beneficial for sustainable energy-related policy makers on decision-making for implementing new dedicated energy crops as a feedstock considering socio-economic and environmental issues. The thesis provides the logical framework for introducing an energy crop that has never been widely planted before. This framework is not limited to Napier grass and biogas-based power plant. It can be applied with another energy crop of interest, biomass and power plants under different geographical and weather conditions.

Appendix

Table A1 Scale of relative importance (Likert scale)

Definition	Intensity of relative importance
Equal importance of i and j	1
Moderate importance of i and j	3
Strong importance of i and j	5
Very strong importance of i and j	7
Extreme importance of i and j	9
Intermediate values	2,4,6,8

Table A2 Relative importance of the sub-criteria according to 11 experts

	Criteria *i*	Slope				Water body			Residential area		Power transmission line	CR
	Criteria *j*	Water body	Residential area	Power transmission line	Road	Residential area	Power transmission line	Road	Power transmission line	Road	Road	
Expert	1	1/7	1/3	1/2	1/2	1	3	1	2	5	1	8.2%
	2	1/3	1/5	1/2	1/2	1/2	3	3	2	3	1/3	7.1%
	3	1/3	1/3	1/2	1/2	2	2	3	3	3	1/2	5.3%
	4	1/7	1/3	1/3	1/3	1	2	2	2	2	1/2	2.9%
	5	1/5	1/3	1/2	1/5	1/2	3	2	1	3	1	9.4%
	6	1/3	1/2	1/2	1/3	1/2	3	3	3	1	1/2	8.0%
	7	1/7	1/3	1/3	1/3	1	2	1	3	2	1/3	5.2%
	8	1/7	1/5	1/3	1/5	1	5	1	2	2	1/3	4.1%
	9	1/5	1/5	1/3	1/3	2	3	2	3	3	1/5	9.5%
	10	1/7	1/5	1/2	1/2	3	2	3	3	1	1	5.0%
	11	1/5	1	1/2	1/3	1/2	3	2	2	10	1	4.8%