Utilizing GIS-Based Suitability Modeling to Assess the Physical Potential of Bioethanol Processing Plants in Western Kenya

Joan Sein Koikai
Department of Resource Analysis, Saint Mary’s University of Minnesota, Minneapolis, MN 55404.

Keywords: GIS, Renewable Energy, Biofuel, Biomass, Bioenergy, Bioethanol, Suitability Model, Site Selection, Weighted Overlay

Abstract

Bioenergy has become an economically viable venture both on a subsistence level and on a vast commercial scale, allowing farmers, industries, and villages to attain energy independence. In Kenya, the government has formulated, published, and is now implementing a policy for wind, small hydro energy plants, and biofuels and biomass resource generated energy (MOE, 2008). This research project used siting analysis models to explore potential bioethanol processing plant locations that derive bioenergy from first-generation renewable energy sources from food crops in a province located in western Kenya. The potential economic viability of bioethanol production from crops in Nyanza province in western Kenya was assessed by identifying potential biofuel collection locations to explore future spatial distributions of biofuel sites along major road networks, major cities, and proximity of maize production areas and markets. The spatial distribution of economically viable biomass production was determined using a GIS-based sustainability management and site suitability model. The suitability model evaluated regions in Nyanza province with high maize productivity where potential bioethanol processing plants can be developed to improve economic sustainability of bioenergy.

Introduction

Bioenergy is defined as energy produced from organic matter or biofuels. Biofuels include all fuels produced directly or indirectly from biomass such as solid, liquid or gaseous fuel produced from biomass (FAO, 2008). Bioenergy includes agrofuels, which consist of biofuels obtained as a product of energy crops and/or agricultural residues, and wood fuels, which include all types of biofuels originating directly or indirectly from woody biomass (Milbrandt, 2005). Biomass consists of material of biological origin, however, excluding material embedded in geological formations and transformed to fossil (FAO, 2008). Bioenergy has become one of the most dynamic and rapidly changing sectors of the global energy economy. First-generation liquid biofuels are manufactured from a range of crops that are relatively specific to geographic locations. In temperate regions, rapeseed, maize and other cereals are used as biofuel feedstock, whereas in tropical regions, sugar cane, palm oil, and, to a lesser degree, soybeans and cassava are used (UN Energy, 2007). Energy conservation and efficiency in Kenya are vital aspects of
demand-side management of energy. The Kenyan government and other non-profit organizations are promoting energy conservation and efficiency improvement at the various consumer levels including industrial, institutional, and domestic. A number of energy crops are being promoted across sub-Saharan Africa. As Kenya explores new energy solutions to decrease energy dependence on imported fossil fuels, economical and renewable biomass sources are being considered necessary for domestically produced biofuels to make a significant contribution to the Kenyan strategic feed-in-tariffs policy (MOE, 2008).

Increasing energy prices and the search for sustained local energy supply have resulted in increased global support of bioenergy as an alternative. Biofuel energy systems are expected to result in the reduction of greenhouse gases, diversification of agriculture, and reduction of imported energy sources (Mangoyana, 2007). The Kenyan government plans to raise the quantity of renewable energy in its annual total energy consumption to reduce greenhouse gas emissions (MOE, 2008). Most studies project second-generation liquid biofuels from perennial crops and woody and agricultural residues dramatically reduce the life cycle of greenhouse gas emissions relative to petroleum fuels (FAO, 2008).

If technological developments make it more efficient and economical to produce liquid biofuels from cellulosic material rather than from food crops, the result would be reduced competition with food production, an increase in energy efficiency and improved overall energy balance (FAO, 2008). In addition, the current situation in Kenya shows that there is great potential in improving bioenergy efficiency even though access to bioenergy in Kenya is still very limited; significant potential and opportunities exist for improving all sectors of the economy (IEA, 2008). In order to understand the future of bioenergy, it is important to analyze the biomass resources that can be useful for energy conversion. Energy production from biomass represents an important element within an energy plan based on renewable resources (Frombo et al., 2008).

Background

Overview of Kenya

The Republic of Kenya is located astride the Equator on the East Coast of Africa. It covers an area of 583,000 sq km (225,000 sq miles). Kenya has a common border with Ethiopia, Sudan, Somalia, Uganda and Tanzania. Nairobi, the capital city of Kenya, is part of the Kenyan Highlands which consists of one of the most flourishing agricultural production regions in Africa (CIA, 2008). Strategically located, Kenya is an economic hub and a natural gateway to Africa’s major trading blocs including: the Common Market for East and Central Africa (COMESA), the East African Community (EAC), and export markets in the Middle East, Europe, and Asia (KNBS, 2008).

The current population of Kenya is approximately 34 million. The country consists of eight provinces, namely Nairobi, Rift Valley, Western, Coast, Nyanza, Eastern, Central and North-Eastern. All provinces in Kenya are subdivided into 69 districts which are subdivided into 497 divisions. The divisions are then subdivided into 2,427 locations and those locations are further subdivided into 6,612 sub-locations.
Natural resources and agriculture in particular is the cornerstone of Kenya’s economy employing over 80 percent of the population (MOA, 2008).

**Study Area: Nyanza Province**

Nyanza province is one of the eight provinces of Kenya. To the north, it is bordered by Western province, to the east, Rift Valley province and to the south and west are the Republics of Tanzania and Uganda as depicted in Figure 1. The total land area is approximately 15,482 km$^2$. Nyanza province also borders Lake Victoria, the largest fresh water lake in Africa; the area under water of Nyanza province is approximately 3,291 km$^2$ (MOA, 2008). Energy use in Nyanza province is reasonable and the potential for bioenergy production from maize and other food crops in this province has been estimated to be increasing steadily. This is largely due to the fact that Nyanza province is one of the highest producing maize regions in the country (MOA, 2008). The interest in bioenergy crops is increasing in Nyanza province and the desire to keep the agricultural sector for both food crops and biofuels raises motivation and possibilities (MOE, 2008). Most of the cities and villages, like many regions in Kenya, still use biomass from burning wood fuels as their primary source of energy (MOA, 2008). Nyanza province in western Kenya (Figure 1) was selected for this research project because it has districts covering a broader area of Kenya that represent the Kenyan highlands well, differing in demography, agroecology and access to markets.

This province also represents, to a large extent, the climatic variability found in western Kenya and has an annual rainfall of 1800 and 1400 mm following a bimodal distribution that allows two major maize growing seasons per year. About 78% to 86% of the Nyanza districts are agricultural lands. The abundant small farms in the province can be considered agro-forestry systems since they integrate crop-livestock activities and on-farm crop production (Henry et al., 2008).

![Figure 1. Location of study area showing Nyanza province in western Kenya.](image)
Maize as a Bioethanol Source

Agriculture is the leading component in Kenya’s growing economy, providing employment for more than two-thirds of the population. Maize continues to be the major staple food and Kenya has one of the highest rates of maize consumption and production per capita in Africa (Smale et al., 2006). Presently bioethanol is regarded as Kenya’s major source of biofuel. Bioethanol is fuel that has been produced through fermentation of sugars by microbes and these sugars are derived from starch found in feedstock such as maize and sugarcane (UN Energy, 2007).

Currently in Kenya, first-generation biofuels such as ethanol and butanol from sugar and grains, and diesel from oilseeds such as Jatropha Curcas, have become extremely popular. The availability of maize has also allowed these developing areas to produce maize economically. Subsidiary lands are now being used extensively for growing grains such as maize to produce bioethanol (Gressel, 2007). Nyanza province borders Lake Victoria; its tropical region is characterized by agro-forestry systems with dense human population, and where small subsistence agriculture predominates and the expansion and intensification of integrated agro-forestry systems may be an option to increase biodiversity (Henry et al., 2008).

Methods

Data Sources

The GIS dataset layers were obtained from the following data source networks and websites: International Livestock Research Institute (ILRI), Center for Disease Control Data Clearinghouse (CDC) and the Farming and Agriculture Organization (FAO). Geographically referenced data for Kenya was used from all these sources. All other non-spatial data was retrieved from publications from organizations such as: United Nations Environmental Programme (UNEP), United Nations Industrial Development Organization (UNIDO), Kenyan Ministries of Energy and Agriculture and Kenya National Bureau of Statistics (KNBS).

Software & Technology

The software used for the analysis was ArcGIS 9.2 and the ArcGIS Spatial Analyst extension from Environmental Systems Research Institute (ESRI) and it was used to perform the various spatial analyses and to develop a site suitability analysis model. Microsoft Excel was used to create the tables and spreadsheet data used for analysis.

Projection

All data used for GIS analyses used of the following parameters:

- Projection: Albers
- False Easting: 0.000000
- False Northing: 0.000000
- Central Meridian: 25.000000
- Standard Parallel_1: 20.000000
- Standard Parallel_2: -23.000000
- Latitude of Origin: 0.000000
- Linear Unit: Kilometer (1.000000)
- Geographic Coordinate System: GCS_WGS_1984
- Angular Unit: Degree (0.017453292519943299)
- Prime Meridian: Greenwich (0.00000000000000000000)
- Datum: D_WGS_1984
- Spheroid: WGS_1984
Semi major Axis: 6378137.0000000000000000
Semi minor Axis: 6356752.314245179300000000
Inverse Flattening: 298.257223563000030000

**Data Manipulation & Analysis**

The ArcGIS Spatial Analyst was used for suitability modeling. Suitability modeling involves calculating optimal site locations by identifying possible influential factors, creating new data sets from existing data, reclassifying data to identify areas with high suitability, and finally aggregating these data into one logical result of optimal suitability.

The suitability model served as an excellent technique to generate suitable potential bioethanol processing plant sites in Nyanza province. The model predicts areas that can economically accommodate future maize development as well as other agricultural land uses. For this analysis new data was formulated from existing data using vector and raster data to create various criteria to serve as input for a site suitability model.

The use of GIS analysis made it possible to consider bioethanol plant sites based on a variety of factors and criteria such as proximity to agricultural farms, because a large amount of food crops such as maize would have to be transported for biofuel production. Bioethanol production also requires the availability of raw materials such as maize, and accessibility to cost-effective means of transportation. To identify locations within Nyanza province that could serve as feasible locations for bioethanol processing plants, the model examined several suitability factors.

**Suitability Modeling**

The suitability model involved three steps: 1) identify site selection suitability factors, 2) rating and ranking the suitability factors, and 3) weighing the factors selected and finally implementing the suitability model.

1. **Identifying Biofuel Energy Site Selection Suitability Factors**

The starting point for the analysis was to define the characteristics that make land suitable for developing a bioethanol plant in Nyanza province. For this analysis the following factors were considered:

1. Find areas with a close proximity to maize farms and/or fields for easy access and availability of maize.
2. Close access to major roads and highways to promote ease of transportation to and from bioethanol plant sites.
3. Easy access to railway lines to facilitate transportation of raw materials in bulk to and from other neighboring provinces.
4. Availability and proximity to water resources (i.e. rivers and lakes).
5. Close proximity to existing developed areas such as major towns where a range of services would be available to support consumers.
6. Availability of sufficient electric power supply to operate the bioethanol processing plant.
7. Proximity to airports to serve as an additional means of transportation and access to other developed areas.

2. **Ranking Suitability Factors**

The suitability analysis was used to
Table 1. Bioethanol plant site selection suitability criteria and ranking values.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Reclass Values</th>
<th>Assigned Influence</th>
<th>Decimal Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suitability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>&lt; 0.5 mi</td>
<td>1</td>
<td>0.1764706</td>
</tr>
<tr>
<td>Medium</td>
<td>0.5 - 1 mi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>&gt; 1 mi</td>
<td>2</td>
<td>0.1764706</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 mi</td>
<td>3</td>
<td>0.1176471</td>
</tr>
<tr>
<td></td>
<td>1.0 - 3 mi</td>
<td>3</td>
<td>0.1764706</td>
</tr>
<tr>
<td></td>
<td>&gt; 3 mi</td>
<td>3</td>
<td>0.1764706</td>
</tr>
<tr>
<td></td>
<td>&gt; 5 mi</td>
<td>1</td>
<td>0.0588235</td>
</tr>
<tr>
<td></td>
<td>1.0 - 5 mi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

determine the best areas for developing a biofuel processing plant site. The data layers used for the analysis and ranking of these layers are displayed in Table 1. The ranking metrics for the suitability preferences listed in Table 1 were organized according to criterion for suitability development and were rated as high (3), medium (2) and low (1). They were defined according to the following factors:

1. **Proximity to Major Roads**: Areas within a half-mile of major roads had the highest suitability; areas within a half-mile to a mile were given medium suitability; and areas greater than one mile outside of primary roads were rated as low suitability. Figure 2 illustrates access to major roads ranked accordingly from high to low suitability.

2. **Accessibility to Railway Lines**: Areas within one mile of railway lines were given the highest suitability; areas within one mile to three miles were noted as medium suitability; and areas further than three miles away from railway lines were noted as low suitability. Figure 3 shows the proximity and access to railway lines categorized from high to low suitability areas.

3. **Closeness to Major Towns**: Areas within one mile of major towns were given the highest suitability; areas within one-mile to three miles were noted as medium suitability; and areas further than three miles were noted as low suitability. Figure 4 illustrates the proximity and access...
to major towns ranked from high to low.

Figure 3. Access to railway transportation.

4. **Availability of Electric Power Lines**: Areas within a half-mile of power lines were given the highest suitability; areas within a half-mile to a mile of power lines were noted as medium suitability; and areas further than one mile were noted as low suitability. Figure 5 illustrates the proximity and access to electric power lines that were ranked from high to low.

5. **Close proximity to raw materials**: Regions within one mile of maize fields were given the highest suitability; areas within one mile and three miles of power lines were noted as medium suitability; and areas further than three miles were noted as low suitability. Figure 6 illustrates the close proximity and access to maize production areas that were ranked from high to low.

6. **Accessibility to water resources**: Locations within one mile of water resources such as rivers were noted as highly suitability; areas within one mile to three miles of rivers as medium suitability; and areas further
than three miles from rivers as low suitability. Figure 7 shows proximity and accessibility to major rivers in Nyanza province that were categorized from high to low.

7. **Proximity to Airports**: Areas within one mile of airports were noted as highly suitability; areas within one mile to five miles of airports were rated as medium suitability; and areas further than five miles were given low suitability. Figure 8 shows proximity and accessibility to airports categorized accordingly from high to low.

![Figure 6. Proximity to maize fields.](image)

![Figure 7. Proximity to water resources.](image)

![Figure 8. Proximity to major airports.](image)

3. **Measuring and Weighing Suitability Factors**

The data layers used for suitability analysis were weighted according to how important they were to the overall analysis. These were subjective weights and rankings used via judgment and knowledge of the area. The assigned importance-influence displayed in Table 1 shows data layers ranked as 1, 2 and 3. The data layers were assigned influence and were ranked according to relative importance with 3 classified as extremely important, 2 was classified as
very important and 1 as important. The assigned influence-importance values were used to calculate the decimal weights (Table 1). The process of ranking suitability factors was listed on the assigned influence-importance column and was used to define a scale of suitability from 1 to 3; where 1 represents low suitability, 2 represents medium suitability and 3 represents high suitability.

4. GIS-Based Site Suitability Analysis

Suitability analysis steps and operations used consisted of the following methods:

1. Vector Data to Raster Data
   Conversion: The first step in the spatial analysis involved the creation of raster data. All layers had to be converted from vector to rasters before the Spatial Analyst could be used to perform any type of analyses. The conversion of vector data to raster layers was completed using the Spatial Analyst conversion tool. The rasters created were in floating point format which represented continuous data that possessed no attribute tables. The Raster calculator was used to convert floating point raster data to integer raster data, which was then used for reclassification in the subsequent phase.

2. Distance Buffers: The second step comprised creating multiple ring buffers for some of the layers. Distance buffers were created for the major roads, power supply lines, rivers and railway lines according to the distance criteria noted in the suitability criteria and ranking table (Table 1).

3. Reclassifying Values: Once all the data sets were buffered and converted to raster data, the reclassify tool was used to reclassify the data sets using the criteria of Table 1. The suitability values ranged from high to low and a summation of the values for every raster cell was calculated. The reclassification values used ranged from 1 to 3, with 3 being the most suitable for sites for bioethanol processing plants and 1 being the least suitable. The areas that did not fall within the 3 reclassified groups were reclassified as NoData.

4. Weighing Data: To establish a logical assessment of optimal suitability, there were certain features that were deemed to be more important than others in the suitability model. Each input layer was weighted and assigned a decimal weight based on its importance. The total influence for all inputs had to equal 100 percent. To determine the decimal weight for each input data layer the following formula was used:

   \[
   \text{Assigned Influence-Importance/Total} \times 100
   \]

   The assigned influence-importance values were multiplied by 100 and divided by the total which is 17. To find the suitable sites the data was calculated using the weighted overlay suitability model.

   A binary suitability model is easy to calculate but does not place low or high importance on layers, as all layers have the same importance, and consequently may not determine accurate results. Therefore, a weighted overlay suitability model was used because all data layers had assigned importance as illustrated in Table 1. The decimal weight displayed in Table 1 was the product
of a number associated with each raster layer and the sum of the decimal weights had to be 1. This decimal weight was derived by dividing the percentage weight for each layer by 100 and the result was used in the raster calculator to weigh all raster data sets. The raster calculator was used to perform the final weighted overlay analysis of the data sets using the decimal weights (Table 1). All variables were added in the raster calculator using a weighted overlay expression. The weighted overlay expression for all the data layers was determined by using the reclassified layers and multiplying each one by the decimal weight values for the factor listed in the suitability criteria and ranking table (Table 1). The following expression lists all percentage decimal weights used in the raster calculator using a simple output map algebra.

\[
((\text{Roadreclass2} \times 0.1764705882) + \\
(\text{Rail_Reclass} \times 0.1176470588) + \\
(\text{ReclassTowns} \times 0.1764705882) + \\
(\text{PowerLineRecl} \times 0.1764705882) + \\
(\text{MaizeReclass2} \times 0.1764705882) + \\
(\text{RiverReclass} \times 0.1176470588) + \\
(\text{AirportReclas} \times 0.5882352941))
\]

**Results**

The purpose of this research study was to analyze a set of spatial features in western Kenya by using a land suitability model created in ArcGIS to establish the potential sites for a bioethanol processing plant. The data layers used for this province were based on identifying areas of high maize production areas or potential production, proximity to major roads, rail, and airport transportation, availability of water resources and electric power supplies. The results of the weighted overlay suitability model indicated there were several towns in northern Nyanza province which may be excellent locations for bioethanol processing plants (Figure 9).

The suitable bioethanol plant sites from Figure 9 were converted from a raster to a vector to make it easier to show the potential biofuel sites. Figure 10 depicts a display of major towns that fell within the high suitability areas. This area was selected due to its close adherence to all the criteria and weights.

**Discussion**

This research project was designed to assess the physical potential of bioethanol processing plant sites by using GIS-based suitability modeling. The methodology used effectively located potential biofuel processing plants in several towns in northern Nyanza province namely: Nyakach, Ngaila, Ruba, Tulwet, Wangaya and Koyabei.

The research indicates that towns in northern Nyanza province can tap into the existing maize yields to create bioethanol processing systems that have the potential to move the region on a path of sustainable development path. Despite the fact that bioenergy is being used at a much larger scale all over the world, this province can use bioenergy to boost the region’s energy supply and demand.

According to this analysis, bioenergy would have a positive social, economic, and environmental impact to the towns in the region. By using various criteria, this project provided a structure for examining the availability, feasibility, economic viability, and sustainability of bioenergy sources and
can be applied to other similar regions of the Kenya where maize production is high. In conclusion, since the agricultural sector is one of the largest consumers of energy in Kenya, farmers in villages and small scale subsistence companies in Nyanza province can benefit from the local availability of biofuel from local bioenergy suppliers. However, this research shows regional energy solutions are available and can be produced at local levels.

Figure 9. Weighted suitability model result showing prospective areas for bioethanol plants.

Acknowledgments

I would like to extend my profound gratitude to God my Father who’s always been my rock and support throughout my life and who I will always rely on. I would like to thank all my instructors at Saint Mary’s University of Minnesota: John Ebert, Dr. David McConville, and Patrick Thorsell for their guidance, continued support and patience throughout the Resource Analysis GIS program and my education journey at Saint Mary’s University of Minnesota. To all my fellow classmates at Saint Mary’s University of Minnesota and friends that have continually supported me throughout my graduate school process I will always be grateful. Last but not least I would like to acknowledge my family for their support and understanding throughout my time in the Resource Analysis program; your assistance and encouragement has kept me going and will help me succeed as I continue to pursue a career in GIS.

Figure 10. Potential bioethanol sites close to major towns in northern Nyanza province.

References


Frombo, F., Minciardi, R., Robba, M., Rosso, F., and Sacile, R. 2008. A decision support system for planning


