

Article

Environmental Impact Assessment of Banagrass-Based Cellulosic Ethanol Production on Hawaii Island: A Spatial Analysis of Re-Suspended Soil Dust and Carbon Dioxide Emission

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Abstract: Environmental impacts from the development of banagrass (*Pennisetum purpureum*)-based ethanol production on Hawaii Island may create air quality problems. Air pollutants considered in this study include re-suspended soil dust (also known as PM_{2.5} and PM₁₀) and carbon dioxide (CO₂) emission. The resulting pollutant emissions are then compared against the Federal Prevention of Significant Deterioration (PSD) significant standard for the environmental impact assessment. This study combines GIS and a mathematical computational model to logically and effectively examine potential spatial impacts of ethanol development on air quality on Hawaii Island. This study found that mechanical harvesting of banagrass generates higher dust emission than other agricultural crops. The total PM₁₀ emission of 248.18 tons per year was found statistically equivalent to the PSD significant permitting requirement limit of 250 tons per year (tpy) and thus considered as a major stationary source of fugitive dust pollution. The annual CO₂ emission amount of 19,371.72 tons is less than the PSD significant permitting requirement of 75,000 tons of CO₂ per year. As a result, this estimated amount is not considered as a major stationary source of pollution.

Keywords: Hawaii Island; banagrass; PM₁₀; PM_{2.5}; CO₂

1. Introduction

Environmental impacts from the development of banagrass (*Pennisetum purpureum*)-based ethanol production on Hawaii Island may create air quality problems. Tran and Yanagida (2016) [1] suggested that a cellulosic ethanol plant with a 9 million gallons of ethanol per year (MGY) capacity would meet about 2% of the State's highway fuel demand. This facility is designed to operate at full capacity 24 h/day, 7 days/week and 52 weeks/year (using references from the Pacific Biodiesel facility on Hawaii Island) (Pacific Biodiesel (PBD) was consulted for their operation schedule. PBD operates 24 h/day divided into three shifts and operate all year around. They also perform regular maintenance [2]). The daily target production level was estimated at approximately 24,657 gallons of ethanol. A total land area of 3080 ha was optimally located on the northern part of Hawaii Island in order to provide enough feedstock for the ethanol processing plant. Given an ethanol conversion rate of 80 gallons per dry ton of banagrass [3] and moisture content of banagrass at harvesting time of 70% [4], a total amount of 1056 wet tons of banagrass feedstock is required to meet the daily target amount of ethanol produced. Banagrass is hauled directly from the production site to the processing plant. The processed ethanol is then transported from the processing plant to Kawaihae port and shipped to Oahu for blending. A large number of harvesters and heavy-duty trucks/trailers are required for these operations which

can cause adverse impacts on air quality around feedstock production and ethanol processing areas due to daily extensive operations.

Mechanical agricultural harvesting has been increasingly scrutinized as a major source of fugitive dust emissions, in the form of particulate matter (PM), in the air [5–8]. California's Senate Bill 700 included agricultural operations as sources of air pollution for the state [5,8]. In 1995, the EPA estimated PM from mechanical harvesting of three different crops—cotton, wheat and sorghum (see Section 9 of Compilation of Air Pollutant Emission Factors: Stationary Point And Area Sources [7]). The California Air Resources Board (CARB) calculated PM₁₀ emission for a number of crops such as almonds, corn, cotton, walnuts and wheat. However, PM₁₀ emission has not been estimated for banagrass harvesting on a commercial scale. Additionally, the Federal Prevention of Significant Deterioration (PSD) established the pollutant emission limitation standard to determine whether a proposed project should be considered as a major stationary pollutant source [9–11]. Proposed projects that potentially emit 250 tons per year (tpy) or more of fugitive emission are considered as major stationary sources of pollution and require further PSD review [9–11].

Carbon dioxide (CO₂) emission from transportation is the second largest source of CO₂ emission in the U.S, following electricity generation [12]. In 2014, transportation's share was about 31% of total U.S. CO₂ emissions [12]. CO₂ is also known as the primary greenhouse gas comprising about 80.9% of all the U.S. greenhouse gas emissions. Transportation produced approximately 25% of total U.S. greenhouse gas emissions in the same year [12]. By EPA standards, any proposed project that has the potential of emitting 75,000 tpy of CO₂ equivalent or more is defined as having a significant PSD level and considered a major stationary pollution source [9,11]. Harvesting and transporting of feedstock and transporting of ethanol fuel are the likely operations that will impact air quality due to CO₂ emission.

This study examines the potential environmental impacts from the harvesting and transporting of banagrass from production areas to a banagrass-based ethanol producing plant and transporting ethanol from the processing plant to the port for shipment to Oahu for blending. Air pollutants considered in this study include re-suspended soil dust from in-field feedstock transport during harvesting (also known as PM_{2.5} and PM₁₀) (PM₁₀ and PM_{2.5} include particulate matter less than 10 and 2.5 microns in aerodynamic diameter, respectively [13]); and carbon dioxide (CO₂) emission from combusted fuel released during harvesting and transporting feedstock from production fields to the ethanol processing plant and from the distribution of ethanol. The resulting pollutant emissions are then compared against the PSD significant standard (the PSD significant standards for fugitive dust emissions and CO₂ emissions are respectively 250 and 75,000 tpy [9]) for the environmental impact assessment.

2. Materials and Methods

2.1. Study Areas and Data

The study areas include banagrass feedstock production areas, the processing plant location, Kawaihae port and the surrounding road network on Hawaii Island (Figure 1). Land locations for feedstock production and the ethanol processing plant site were selected by using a cost minimization procedure done in an earlier study by Tran and Yanagida (2016). Land for feedstock production consisted of areas on Hawaii Island where banagrass would potentially have the highest yields. This amounted to cultivation of 3080 ha and with an average yield estimated at 37.56 dry tons/ha. The ethanol processing plant was situated near to the biomass feedstock production areas. Land area for the processing plant required at least 40 acres in size [14].

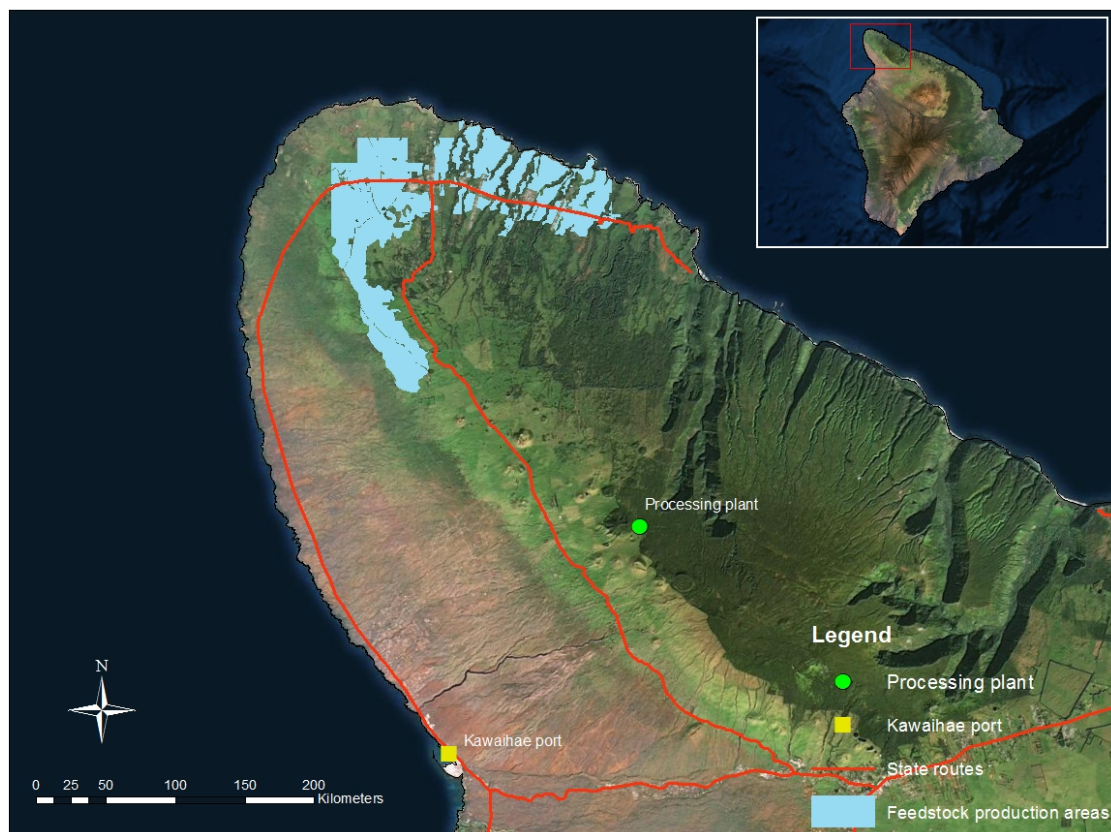


Figure 1. Study areas on Hawaii Island.

Other data for this study include detailed street maps for the study areas extracted from the U.S. and Canada detailed street data [15] and State Routes updated in 2011 [16]; 2011 precipitation data from the online Rainfall Atlas of Hawaii, Department of Geography, University of Hawaii at Manoa [17]; 2010 daily precipitation from the National Climatic Data Center's (NCDC) Climate Data Online (CDO) [18]; detailed 2003 soil maps from the National Cooperative Soil Survey, U.S Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) [19]; and soil characterization obtained from the National Cooperative Soil Survey (NCSS)—Soil Characterization Database [20].

2.2. Methods

This study combines Geographic Information System (GIS) and a mathematical computational model to logically and effectively examine potential spatial impacts of ethanol development on air quality in terms of dust and CO₂ emissions within the proposed ethanol production areas on Hawaii Island. These areas include locations of banagrass feedstock production, ethanol processing plant, Kawaihae port and the transportation road network for transporting feedstock and ethanol.

2.2.1. Dust Pollution

Air pollutant emission factors have been periodically documented and published by the U.S. Environmental Protection Agency (EPA) since 1972 through the document “Compilation of Air Pollutant Emission Factors” (AP-42) [13]. This document provides essential background information on how to quantify various types of pollutants released to the atmosphere. AP-42 Section 13.2.2 reports measurement of the dust emission factor in the form of particulate matter (PM). The formula for estimating PM emission on unpaved surfaces has also been used to estimate PM emission from soil in farming operations [21].

The dust emission factor is measured as pounds per vehicle-mile-traveled (lbs/VMT) on unpaved surfaces in dry condition with precipitation less than 0.01 inch per day [22]. The proposed

analytical procedure, combining a mathematical computational model with GIS, is shown in Figure 2. The prediction of dust emission is based on vehicles traveling on unpaved surfaces at industrial sites in the Emission Factor Documentation for AP-42, Section 13.2.2 (see equation 1a on page 13.2.2-4) for U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards [22]. Parameters used in the model include a particle size multiplier k , silt content of surface areas S measured in % and mean vehicle weight W measured in tons.

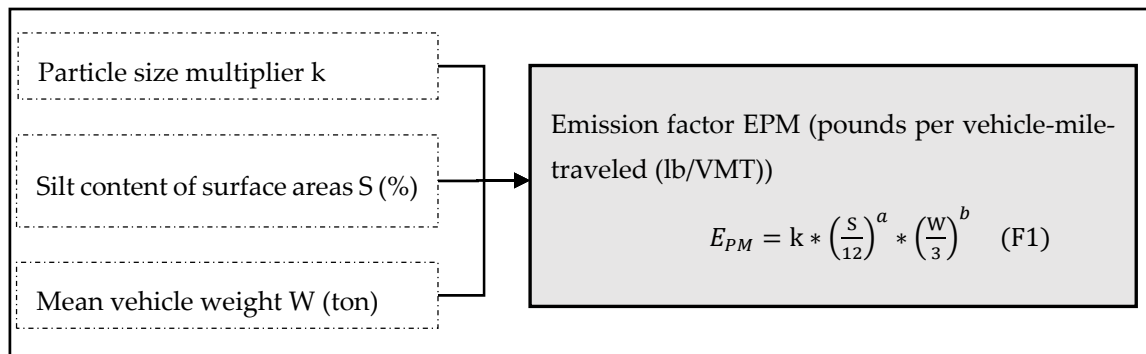


Figure 2. Flowchart for estimating spatial distribution of dust emission. Note: k is equal to 1.5 for PM_{10} and 0.15 for $PM_{2.5}$; a and b are empirical constants and equal to 0.9 and 0.45, respectively, for both PM_{10} and $PM_{2.5}$ [22].

Dust is created through the operations of heavy-duty machines during banagrass harvesting and in-field transporting. Kinoshita and Zhou (1999) provided a demonstration of in-field banagrass harvesting and transporting using different systems on a 10-acre demonstration plot on Molokai, Hawaii. The harvesting and transporting systems were primarily based on machines used in industrialized sugarcane production [4]. The system selected used a Claas CC 1400 harvester to directly transfer chopped banagrass into truck trailers for highway delivery. This system was more cost efficient as compared to other systems since it reduces labor and equipment requirements [4]. Technical aspects of this harvesting system are presented in Table 1.

Table 1. In-field banagrass harvesting technical specifications.

Type of Machines	Unit	Values	Sources
Production land areas	Ha	3080	Tran and Yanagida (2016) [1]
Daily feedstock required	Wet tons	1056	Calculated by authors
Daily harvested areas	Ha	16.88	Calculated by authors
Claas CC 1400 harvester			
Numbers of harvesters	Harvester	8	Biomass Research and Development Initiative (BRDI) project at the University of Hawaii, Manoa.
Weight per harvester	Tons	11	Pari et al. (2008) [23]
Mean harvester speed	Mph	1	Osgood et al. (1996) [24]
Adjusted biomass harvest rate per machine	Ton/hour	16.28	Osgood et al. (1996) [24]
Adjusted harvester productivity per machine	Ha/hour	0.26	Osgood et al. (1996) [24]
Trucks/trailers			
Numbers of trucks/trailers per day	Trucks	18	Calculated by authors
Weight per truck/trailer	Tons	23.65	Salassi et al. (2014) [25]
Capacity per truck/trailer	Tons	4.86	Kinoshita and Zhou (1999) [4]

The estimated PM emission factor is based on average vehicle weight (W) for all vehicles on the field (harvesters and truck/trailers) and silt content of the production areas (S). The average vehicle weight is estimated at 20.58 tons based on the characteristics of the machine harvesting system. Spatial

distribution of silt content is interpolated by using Bayesian kriging for interpolating silt content data for PM_{2.5} and PM₁₀ measured at 22 locations surrounding the banagrass production areas. These 22 sample points were obtained from Soil Characterization Database [20]. Bayesian kriging has been known as an appropriate interpolation technique in context of limited data since it employs a large number of simulations via Markov chain and Monte Carlo techniques [26,27]. The Bayesian prediction approach considers variogram parameters as random variables. It estimates variogram models directly from data by using restricted maximum likelihood (REML). As a result, it yields more accurate predictions [26].

The emission factor, originally measured in lbs/VMT, is used to calculate the amount of PM_{2.5} and PM₁₀ generated in an area. This measure is converted to pounds per acre (lbs/acre) in order to compare emission estimates with other studies. The Claas CC 1400 harvester can cut two rows with 5 feet spacing at a time [24]. The space between the centers of two rows is 9 feet [28]. The adjusted biomass harvest rate was estimated at 0.65 acre per hour, given the harvesting speed of 1 mph and consideration of time waiting for trucks [24]. Calculation of the emission factor EPM as measured in lbs/acre is equal to the product of the emission factor and length traveled and divided by the harvested area. The resulting spatial distribution of dust emission within banagrass production areas are presented in raster layers measuring emission factors for PM_{2.5} and PM₁₀.

These resulting emission factors are then converted to derive annual average emissions used to estimate the total amount of PM_{2.5} and PM₁₀ measured in tons per year. These amounts can be compared with the PSD permitting requirement standard [9] to determine whether the harvesting feedstock production areas are considered as a major stationary source of PM pollution as required by PSD. This is shown in Equation (1) below

$$E_{total} = E_{ext} * S_{prod}, \quad (1)$$

where E_{ext} is the annual average emission and S_{prod} is the total feedstock production area per year. The calculation of E_{ext} was provided in the AP-42 (Section 13.2.2.—Unpaved road) and is shown below [22]:

$$E_{ext} = E_{PM} * \left[\frac{365 - P}{365} \right], \quad (2)$$

where E_{PM} is the emission factors obtained from Figure 2 and P is the number of days in a year with at least 0.01 inch of precipitation. Data for P were obtained from daily precipitation data measured by NCDC CDO [18] from the weather station GHCND:USC00517312 station name: Paauilo 221 HI US which is located near the feedstock production areas.

2.2.2. CO₂ Pollution

CO₂ emission results from diesel fuel usage were determined for the harvesting and transporting of banagrass feedstock from production sites to the ethanol processing plant and transporting ethanol from the processing plant to Kawaihae port. The optimal transporting routes are determined through the route analysis in the ArcGIS network analyst toolbox using the Hawaii road network database. Determination of CO₂ emission is based on the studies by [29,30]. The amount of CO₂ emission depends on the level of fuel consumption (FC) and the carbon content (CC) released from fuel combustion during truck operations. Figure 3 shows the mathematical equation for quantifying CO₂ emission.

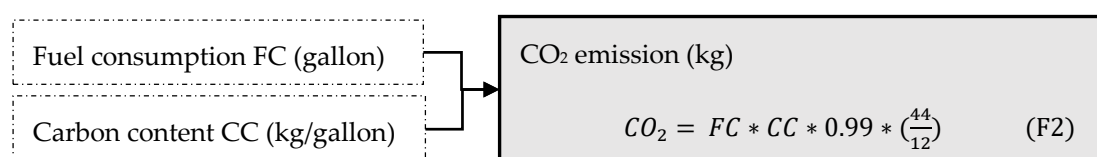


Figure 3. Flowchart for estimating spatial distribution of CO₂ emission.

The carbon content of diesel fuel was estimated at 2.778 kg/gallon [29]. The number 0.99 is the oxidation factor which indicates that 99% of the carbon is oxidized in the fuel. The ratio (44/12) is the ratio of the molecular weight of CO₂ to the molecular weight of carbon [29].

The banagrass harvesting system used in Hawaii is the same as the sugarcane harvesting system [4]. The harvesting component includes operations of harvesters and trucks/trailers for in-field feedstock transport. The harvesting operation uses a Claas CC 1400 harvester which has a fuel consumption rate of 8 gallons/hour [25]. Given the adjusted biomass harvest rate of 0.26 ha/hour (see Table 1), total estimated fuel consumed by eight harvesters over an area of 16.64 ha per day (see Table 1) is about 512.00 gallons/day. The fuel consumption rate of trucks/trailers was estimated at 7 gallons/hour for 1 ha of in-field transport [25]. This results in total daily consumption of 116.48 gallons/day for in-field trucks/trailers operations.

An average empty 45 cubic yard (yd³) truck/trailer's weight was estimated at 37,300 lbs or 18.65 tons [31]. Chopped banagrass has a bulk density of about 8 pounds per cubic foot (lbs/ft³) or 216 pounds per cubic yard (lbs/yd³) (1 ft³ = 0.03703704 yd³). As a result, a truck/trailer can carry approximately 4.86 tons of wet banagrass (see Table 1). The average weight of a loaded truck/trailer is estimated at 23.65 tons. This results in an estimated 217 truckloads daily to meet the daily requirement of 1056 tons of feedstock for ethanol processing. For the transport of ethanol fuel, assuming that ethanol is transported using tanker trucks with a capacity up to 9000 gallons. This would require three roundtrips to transport 24,657 gallons of ethanol daily. The average weights of an empty and loaded truck tanker are respectively estimated at about 20,000 and 80,000 lbs.

Truck/trailers and tanker trucks are categorized as class 8 - heavy duty vehicles [32,33]. These vehicles have a gross loaded weight range from 33,001 to 80,000 lbs. Fuel consumption ranges from 4 to 7.5 mpg for this class [32,33]. Therefore, the average fuel consumption rates for an empty and loaded tanker truck are respectively 7.5 and 4 mpg. The adjusted fuel consumption rates of 6.5 and 5 mpg were also estimated for an empty and loaded truck/trailer.

The information on fuel consumption is used in Equation (F2) (Figure 3) to estimate CO₂ emission and its spatial distribution from harvesting and transporting banagrass feedstock and ethanol fuel. Spatial results were generated based on ArcGIS version 10.3.1 (ESRI, Redlands, CA, USA) which shows the spatial distribution of dust and CO₂ emissions within the study area.

3. Results and Discussion

3.1. Dust Emission

The exposure of re-suspended soil dust emissions from harvesting operations varies across the production land area. The spatial distribution of dust emission primarily depends on the distribution of silt content in the soil which ranges from 28.76% to 31.70% for PM_{2.5} and from 33.34% to 40.36% for PM₁₀ across the production areas (assuming the same harvesting system is applied to all production areas). The estimation of the emission factor was based on dry day conditions with precipitation less than 0.01 inch per day and extrapolated for the entire production areas. Figure 4 shows expected spatial distribution of emission factor for PM_{2.5} (Figure 4a) and PM₁₀ (Figure 4b).

The emission level released from vehicle movement within the feedstock production land varies according to location. The spatial distribution of PM₁₀ emission is not equally spread across the production land area. The color trend displayed in the figure moves from dark blue to yellow and then to red which represents an increasing emission factor across the areas. Higher emission results for areas where production is highly concentrated due to intensive harvesting operations. These higher production areas (in red) are located at higher elevation levels and farther away from the coast. The highest emission factor which appears as a dark red color has a value of 46.74 lbs/VMT while the lowest emission factor is 39.36 lbs/VMT and appears as a dark blue color (Figure 4b). Although there are differences in PM_{2.5} emission across the production areas, the variation is small, ranging from 3.45

to 3.76 lbs/VMT. The average emission factor across the production areas is estimated at 3.62 lbs/VMT for PM_{2.5} and 42.73 lbs/VMT for PM₁₀ (see Table 2)

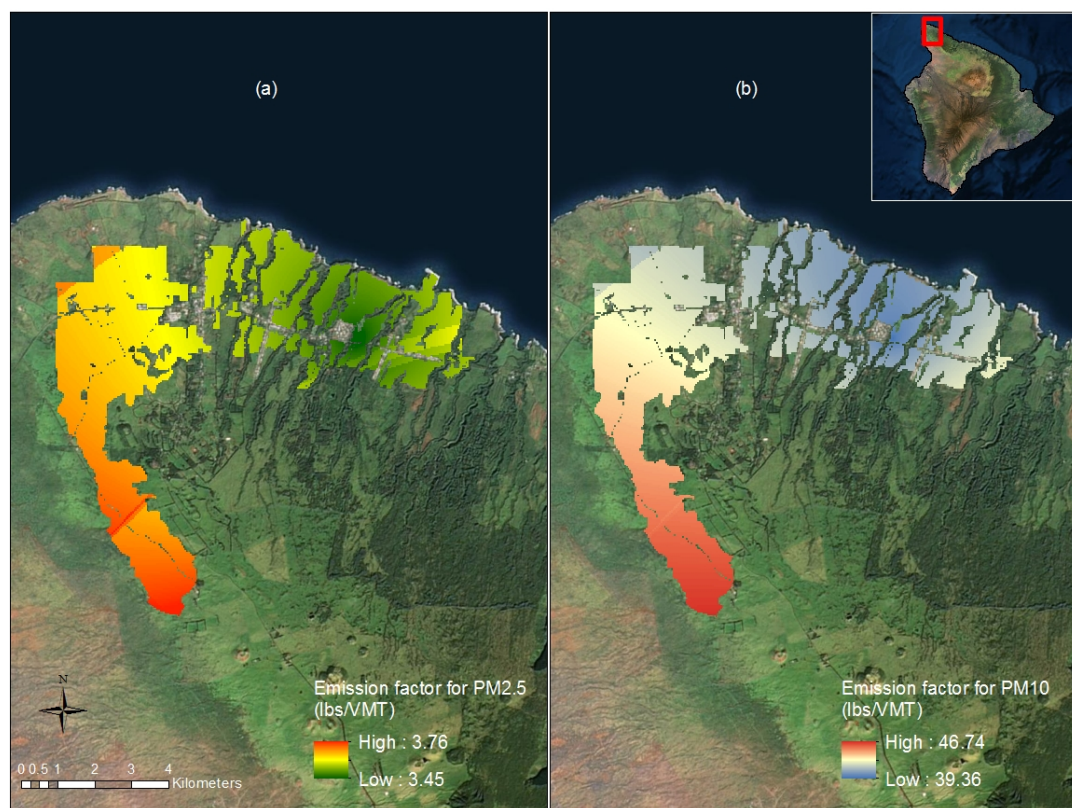


Figure 4. (a) Expected spatial distribution of emission factor for PM_{2.5} and (b) PM₁₀ within the feedstock production areas.

Table 2. Emission factor for PM_{2.5} and PM₁₀ produced by mechanical harvesting operations.

Content	Unit	EPM _{2.5}	EPM ₁₀
Emission factor per vehicle mile traveled	lbs/VMT		
Minimum		3.45	39.36
Maximum		3.76	46.74
Average		3.62	42.73
Standard deviation		0.06	1.78
Emission factor per acre	lbs/acre		
Minimum		5.30	60.56
Maximum		5.79	71.90
Average		5.57	65.74
Standard deviation		0.09	2.73
Total emission factor per year	Tons/year	21.84	248.18

Re-suspended dust emissions originating from mechanical harvesting consist of three operations: (i) crop handling by the harvesting machine, (ii) transloading of the harvested crop into trucks/trailers and (iii) field transport [6,34]. Given limited data on the technical aspects of machine harvesting, estimation of crop handling and truck transloading processes are not included in this study. The above dust emission analysis (Table 2) is calculated for dust emitted from in-field movement of harvesters and trucks/trailers only.

A number of studies have conducted analyses on dust emission factors for agricultural mechanical harvesting. Section 9 of EPA's Compilation of Air Pollutant Emission Factors (AP-42) reported detailed dust emission for PM₇ from each operation for cotton, wheat and sorghum crops [6,34]. The highest

PM₇ emission was found for harvesting cotton with an emission level of 0.0086 lb/acre [6,34]. This number is much smaller than the average PM_{2.5} emission of 5.57 lbs/acre as analyzed in this study. Usually one would expect the emission level to be higher for PM₇ as compared to PM_{2.5}. This comparison suggests that dust emission from banagrass harvesting is much higher than cotton, wheat and sorghum crops as reported in the EPA (2006b). CARB's PM₁₀ emission factors were developed in 2003 for a number of crops in California, including almond, cotton, sorghum and wheat, etc. [6]. The highest PM₁₀ emission level of 40.78 lbs/acre was found for almond mechanical harvesting. This almond emission level is smaller than the PM₁₀ emission of 65.74 lbs/acre for banagrass. These results suggest that mechanical harvesting of banagrass on Hawaii Island would generate higher dust emission levels than mechanical harvesting of other agricultural crops reported previously.

Total annual emissions for PM_{2.5} and PM₁₀ were estimated at 21.84 and 248.18 tpy. Given the PSD permitting requirement of 250 tpy for fugitive dust emission [9], the PM₁₀ emission of 248.18 tpy is statistically equivalent to this requirement limit which would probably trigger an emission level violation. It should be noted that factors affecting the emission level include biomass harvesting rate, the number of vehicles on the field and precipitation conditions.

Sensitivity analysis shows that if the probability for the number of days in a year with precipitation more than 0.01 inch per day decreases by 0.37% (about 1.36 days), *ceteris paribus*, the total PM₁₀ emission reaches the calculated 250 tpy limit which automatically cites a major stationary source of pollution. Additionally, an increase in the emission level can occur from lowering the biomass harvest rate which reduces harvest efficiency and requires more machines on the field. The result of this sensitivity analysis suggests that it is highly likely that the feedstock production area will become a major stationary source of pollution requiring a PSD permit in order to continue operations.

3.2. CO₂ Emission

The estimation of CO₂ emission is derived from three components—(i) harvesting operations, (ii) highway transporting/hauling of feedstock and (iii) highway transporting of ethanol fuel. The estimation results are presented in Table 3 and Figure 5.

The harvesting component includes operating harvesters and trucks/trailers for in-field feedstock transport. Table 3 shows that total daily fuel consumption (FC) for the harvesting operation is about 637.54 gallons per day. Given CC = 2.778 kg/gallon and using Equation (F2), the estimated daily emission amount is 6429.04 kg of CO₂ per day which adds up to 2,346,599.6 kg of CO₂ annually. An annual 2,586.66 tons of CO₂ are released from harvesting operations.

The spatial distribution of CO₂ emission depends on the concentration of land used for feedstock production. Figure 5 presents the spatial distribution of CO₂ shown as the column length of each created grid cell for the banagrass production area. There are 61 grid cells created across the entire production land area with the largest cell of 1 km² in size. CO₂ emission is aggregated for each cell and stacked into columns. Longer columns indicate higher levels of emission. CO₂ emission in each cell ranges from 30.18 to 75,837.96 kg per year depending on the cell size, given that there are two harvested crops per year. The average CO₂ produced in each cell is approximately 38,000 kg/year. Higher emission levels are found where the concentration of production land is higher. These production land areas are located on the northwest side of the Kohala Mountain road. CO₂ emission is lower for land near coastal areas, northwest of Hawi, where production lands are more scattered.

Transporting feedstock and ethanol fuel is a source of CO₂ emission. Figure 5 shows the three trip segments for the highway transporting/hauling of feedstock and ethanol fuel. The transport of feedstock with truck trailers involves trip segments 1 and 2. Trip segment 1 (shown in dark red) is the 26.69 mile road segment that runs from the feedstock production areas on Kohala mountain road to the road leading to the ethanol processing plant. Trip segment 2 connects Kohala Mountain road and the ethanol processing plant (shown in green). The 1.69 mile trip segment 2 is also the initial transport route of ethanol fuel produced at the processing plant back to Kohala Mountain road. This intersection

is the beginning of trip segment 3 which measures 25.67 miles in length (shown in purple) and runs to the final destination at Kawaihae port.

Table 3. Estimation of CO₂ emission.

Content	Unit	Values
Harvesting operations		
Daily fuel consumption	Gallon/day	637.54
CO ₂ emissions per day	Kg/day	6429.04
CO ₂ emissions per year from harvesting operations	Tons/year	2586.66
Transporting/hauling operations		
Transporting routes		
Length of the first segment	Miles	26.69
Length of the second segment	Miles	1.69
Length of the third segment	Miles	25.67
Daily feedstock transporting		
Number of trips	Round-trips	217
CO ₂ emissions from the first segment per day	Kg/day	38,856.36
CO ₂ emissions from the second segment	Kg/day	2460.37
Total daily CO ₂ emissions	Kg/day	41,316.73
Daily ethanol transporting		
Number of trips	Round-trips	3
CO ₂ emissions on the second segment	Kg/day	13.63
CO ₂ emissions on the third segment	Kg/day	388.30
Total daily CO ₂ emissions	Kg/day	401.93
CO ₂ emissions per day from transporting operations	Kg/day	41,718.66
CO ₂ emissions per year from transporting operations	Tons/year	16,785.22
Total daily CO ₂ emission (including harvesting and transporting operations)	Kg/day	48,147.70
Total yearly CO ₂ emission (including harvesting and transporting operations)	Tons/year	19,371.72

A large amount of CO₂ is emitted during trip segment 1 due to encountering heavy traffic from trucks carrying feedstock to the processing plant (217 daily trips). An estimated 38,856.36 kg/day of CO₂ is released on this trip segment. Although trip segment 2 is relatively shorter (in distance), the road and the area surrounding the processing plant is fairly congested with trucks arriving and unloading banagrass and tankers loading and leaving filled with ethanol. For the second segment, the daily amount of CO₂ emission is approximately 2460.37 kg for transporting feedstock and 13.63 kg for transporting ethanol fuel. This results in a daily total CO₂ amount of 2474 kg (for segment 2). The third trip segment yields the least CO₂ emission of the three trip segments. This lower emission amount is due to less tanker operations with three round trips per day and an estimated daily total of 388.30 kg of CO₂ for the entire 25.67 mile trip segment. Total daily CO₂ emission is 41,718.66 kg/day for the entire three trip segments. Annually, this amounts to 16,785.22 tons of CO₂.

Transport of feedstock with truck trailers has the largest contribution to total CO₂ emission with 41,316.73 kg/day and followed by harvesting operations on banagrass production fields with emission of 6429.04 kg/day. Transporting ethanol fuel from the processing plant to Kawaihae port emits 401.93 kg of CO₂ per day. Total daily CO₂ emission resulting from transporting feedstock and ethanol is approximately 48,147.70 kg. This results in a total of 19,371.72 tons of CO₂ emission per year. This emission amount is much less than the PSD significant permitting requirement of 75,000 tons of CO₂ equivalent per year. As a result, it is not considered a major stationary source of pollution.

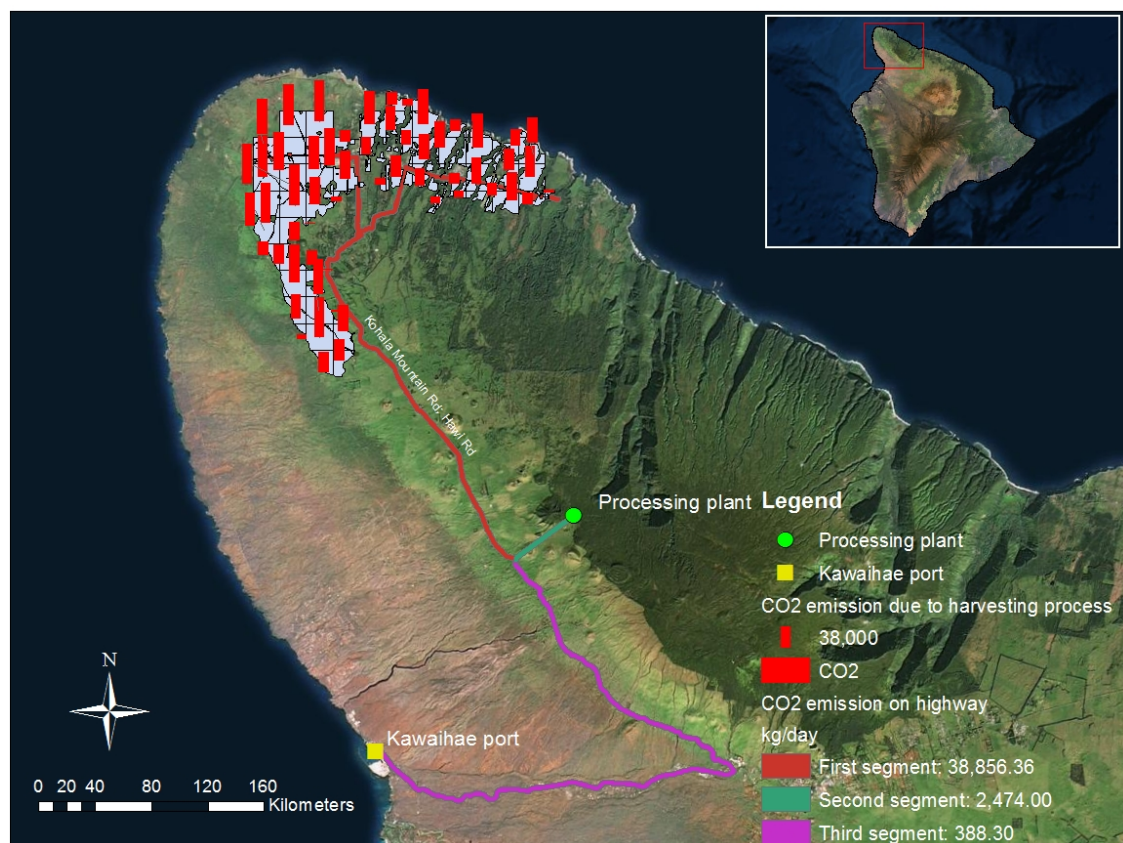


Figure 5. Spatial distribution of CO₂ emission for feedstock production and highway routes for transporting feedstock and ethanol.

4. Conclusions

Environmental impacts from the development of banagrass-based ethanol production on Hawaii island may create air quality problems. This study analyzes impacts on air quality in terms of re-suspended soil dust emission (PM_{2.5} and PM₁₀) from in-field feedstock transport during harvesting and carbon dioxide (CO₂) emission from combusted fuel released during harvesting and transporting of feedstock and ethanol fuel.

The calculation of PM_{2.5} and PM₁₀ emission is based on the dry day condition with precipitation less than 0.01 inch per day and extrapolated for the entire production area. The results show that emission varies across the production areas. The emission levels range from 3.45 to 3.76 lbs/VMT for PM_{2.5} and from 39.36 to 46.74 lbs/VMT. Higher emission is produced in areas where feedstock production is more concentrated. These areas appear to be at higher elevation and farther away from the coast.

The emission level, however, is estimated for soil dust emission originating from in-field feedstock harvesting and transportation only. By comparing with emission levels from agricultural harvesting of other crops which take into account all harvesting operations (including crop handling by the harvesting machine, transloading of the harvested crop into trucks/trailers and in-field transport), mechanical harvesting of banagrass generates higher dust emission than for other previously analyzed agricultural crops.

Total PM₁₀ emission for banagrass is estimated at 248.18 tpy which was found to be statistically equivalent to the PSD significant permitting requirement limit of 250 tpy and thus considered a major stationary source of fugitive dust pollution. Sensitivity analysis suggests that the feedstock production areas would likely become a major stationary source if *P* (probability of the number of days in a year

with precipitation greater than 0.01 inch per day) decreases by 0.37%. Additionally, emission levels can increase by lowering the biomass harvest rate.

Estimation of CO₂ emissions from mechanical harvesting operations on the field, the transport of banagrass feedstock from production areas to the processing plant and the transportation of ethanol from the processing plant to Kawaihae port resulted in a total of 19,371.72 tons of CO₂ per year. This annual emission amount is less than the PSD significant permitting requirement of 75,000 tons of CO₂ per year and not considered a major stationary source of pollution.

Although data are limited for this type of analysis, preliminary results indicate a possible pollution violation in the case of re-suspended soil dust. We recognize that this result may be location specific, however, policy makers and biofuel producers should examine this type of environmental impact from biofuel production.

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Conflicts of Interest: The authors declare no conflict of interest.

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