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TITLE PAGE

A Geospatial Biomass Supply Model Adjusted For Risk

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ABSTRACT

Assessing the economic supply of biomass in a geospatial context while accounting for risk from natural disasters was studied. Risk levels were estimated from a component of factors which included: population density, road density, federal ownership, U.S. Environmental Protection Agency ecoregions, and *Presidential Disaster Declarations*. The *Presidential Disaster Declarations* included risks due to: coastal storm, drought, fire, flood, freezing, hurricane, mud land slide, severe ices, severe storms, snow, tornado, and tropical storm. *Presidential Disaster Declarations* included summaries based on a short-term time period from 2000-2011, and on a long-term time period from 1964-2011. Risk categories were developed as a function of the number of disaster declarations, agricultural-to-forest land ratio, average road density, and average population density. A significant contribution of the research was the allocation of spatially explicit data using GIS technology at the 5-digit zip code tabulation area. The average area for 5-digit ZCTAs in the Eastern U.S. study region was approximately 169 kilometers^2.

Long-term risk (1964-2011) from disaster declarations had a greater impact on the economic availability of biomass supply relative to short-term declarations (2000-2011). The greatest risk to biomass supply came from population density relative to the other risk factors studies. Of the 25,044 total ZCTAs, 12,256 ZCTAs were in locations that did not include population density $\geq$ 150/km^2, road density $\geq$ 14 km/km^2, federal ownership, and US Environmental Protection Agency Level III ecoregions. Of the remaining 12,256 ZCTAs, 26.8% were considered to be moderate-to-high risk based on short-term declarations (2000-2011) and 29.4% were considered to be moderate-to-high risk based on long-term declarations (1964-2011). Lower risk locations for procuring biomass supply for both short-term and long-term declarations, across all risk factors, were in southern Georgia, South Carolina, and Texas.

Keywords. – Geospatial economic supply; biomass; risk assessment; vulnerability

INTRODUCTION

The world witnessed rapid growth and increased prosperity from the early 1900s through the early 2000s [1]. Even with a global economic recession throughout 2008/2009, the world's energy demand in 2020 is forecast to be 40% higher than it is today [2]. There are an abundance of research inquiries around the use of cellulosic feedstocks for energy and fuels, however, replacing oil-derived energy and co-products with bio-based energy and products presents numerous technical, economic, and research challenges [3, 4]. A major obstacle is a reliable supply of biomass feedstock [5]. Better understanding of potential limitations of biomass feedstocks includes the productive capacity of land, high production costs, logistics, and transportation [5]. Formation of markets and industrial supply chains involves managing many contingences [6]. As markets develop assessing the economic capability and stability of evolving supply chains is necessary for market organization. Sustainable solutions involve the assessment of the local interrelationships between the environmental, social, economic, and risk conditions linked with broader regional characteristics.

Accounting for risk from natural disasters in assessing the economic supply of biomass in a geospatial context was the goal of this research. Despite an abundance of literature on the economic availability of biomass [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]; risk from natural disasters has not been documented in prior research as related to assessing biomass supply. For example, recent reports by the U.S. Department of Agriculture and Department of Energy did not adjust for risk in the estimate of the 1.3 billion tons of biomass supply needed to meet energy goals [21 22].

Human geography will likely be a key indicator for predicting future biomass supply zones. Also, one must give pertinent indicators the weight they merit, in providing insight, to spot opportunity and recognize risk. Data selected as variable attributes include the natural, built, economic and social environments connected with naturally occurring risks. Recent information must be equitably weighed against historical information to determine the reliability for detecting landscape transformation.

In 2004, the United Nations Develop Program (UNDP) developed a Disaster Risk Index (DRI) to measure the risk of human deaths in disasters at a global and national level with respect to three main disaster types (earthquakes, tropical cyclones and floods). The DRI is a mortality-calibrated index, and countries are indexed for each disaster type according to their degree of *physical exposure* and their degree of relative *vulnerability for survival*. The concept of physical exposure refers to the number of humans located in areas where disaster events occur in conjunction with the frequency of disaster events [23]. Vulnerability is the concept that explains why people are more or less at risk with a given level of physical exposure. In theory, vulnerability is modified by coping capacity and adaptive capacity, which encompasses the idea of a community's ability to prepare for; respond to, or recover from a disaster [24, 25, 26].

A sustainable and secure domestic energy supply requires consideration of bioenergy as vital part of a long-term solution. This study supports the research goals and priorities of the U.S. Department of Agriculture, U.S. Forest Service, *i.e., USDA 2014-2018 Strategic Plan noted: "Biomass from farms, forests, and rangelands could supply a significant portion of U.S. transportation fuels, heat, power, and biobased products. Research, development, and demonstration are necessary to realize the potential of biomass resources. Efforts in this area will help reduce investor risk, support market development, and contribute to energy security,*

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environmental quality, and economic opportunity" [27]. Our motivation was to improve a cellulosic feedstocks decision tools, which assesses the economic comparative advantages of the biomass supply at the regional, inter-state, and intra-state levels, by accounting for natural disaster risks to the supply.

RESULTS

The frequency of '*Disaster Declarations*' in the short-term (2000-2011) and the long-term (1964-2011) were allocated by ZCTA for estimating risk at the ZCTA-level (Fig. 1)

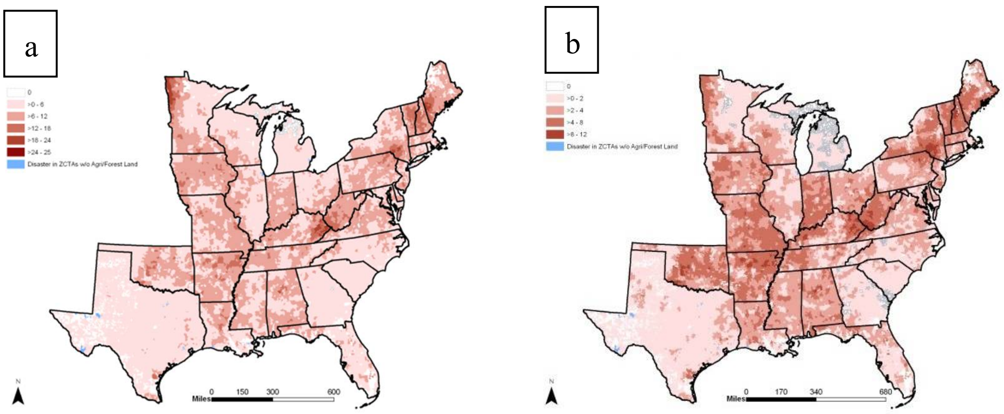

Figure 1. Disaster '*potential*' to biomass land in the (a) short-term (2000-2011) and (b) long-term (1964-2011).

Risk Assessment without Weighting

Given that potential users of this information may have their own weighting system for road density and population density, risk was initially allocated without weighting, as reported below. Note, for this part of the analysis high impacts were contained within severe impacts in the presence of population density ≥ 58/km^2 and EPA level III ecoregions, *i.e.,* exclusion zones with these categories could not be distinguished from severe impacts. Combining the vulnerability data with the disaster declarations (exposure) resulted in risk zones. Using the short-term exposure data, "high impact" zones emerged along the eastern seaboard, and inland areas of Arkansas,

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Missouri and Oklahoma (Fig. 2). There were some “moderate impact” zones in Alabama, Indiana, and Iowa. Twenty-two percent of the ZCTAs were assessed to be “low impacts” and 20.5% were assessed to be “moderate impacts” in the short-term (Table 1).

Table 1. Risk impacts and ZCTAs by category of risk for short-term-term disaster declarations.

Risk Impacts Degree Level	Risk Impacts Value	ZCTA Counts for Risk	Percent by ZCTA
Severe Impacts*	≥ 6	12,788	51.1%
High Impacts	≥ 4 - 6	1,578	6.3%
Moderate Impacts	≥ 3 – 4	5,128	20.5%
Low Impacts	≥ 0 – 3	5,466	21.8%
No Impacts	0	84	0.3%

*All severe impacts were contained within exclusion zones, primarily people ≥ 58/km^2

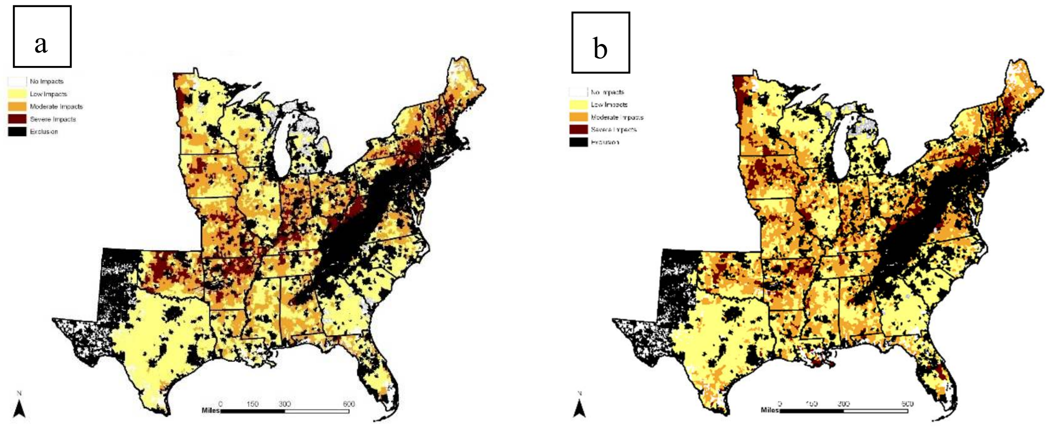

Figure 2. Risk impacts by ZCTA without weights for (a) short-term ‘*disaster declarations* and (b) long-term disaster declarations.

In the long-term, the “high-to-severe impact” zones emerge along the eastern seaboard, and inland areas of Arkansas, Missouri and Oklahoma (Fig. 2b). “Moderate impact” zones also occur in Alabama, Indiana, and Iowa. However, there is an increase in the “moderate impact” zones in Minnesota and Wisconsin. Eighteen percent of the ZCTAs were assessed to be “low impacts” and 23.2% were assessed to be “moderate impacts” in the long-term (Table 2).

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Table 2. Risk impacts and ZCTAs by category of risk for long-term disaster declarations.

Risk Impacts Degree Level	Risk Impacts Value	ZCTA Counts for Risk	Percent by ZCTA
Severe Impacts*	≥ 6	12,788	51.1%
High Impacts	≥ 4 - 6	1,549	6.2%
Moderate Impacts	≥ 3 – 4	5,820	23.2%
Low Impacts	≥ 0 – 3	4,482	17.9%
No Impacts	0	405	1.6%

*All severe impacts were contained with exclusion zones, primarily people $\geq 58/\text{km}^2$

Risk Assessment with Weights

Equal Weights for Road and Population Densities. – Using equal weights of $w_E = 0.5$ (*average road density*) and $w_S = 0.5$ (*average population density*), the short-term “high impact” zones emerge along the eastern seaboard, Arkansas, Missouri and Oklahoma (Fig. 3a). For this portion of the analysis, the data for EPA level III ecoregion and population density greater than $58/\text{km}^2$ were not included because population density would have $w_S = 1.0$ and would have an extreme influence on risk. There are some “moderate impact” zones in Alabama, Indiana, and Iowa. This is in contrast to the long-term “high impact” zones which designated more ZCTAs in the “high impact” and “moderate impact” risk zones (Fig. 3b). Preferred locations for biomass-using facilities in the long-term appeared to be in southern Georgia, South Carolina, and Texas. The severity of risk in the long-term was higher given the influence of the “*disaster declaration*” which accounted for more impacts and risk over time.

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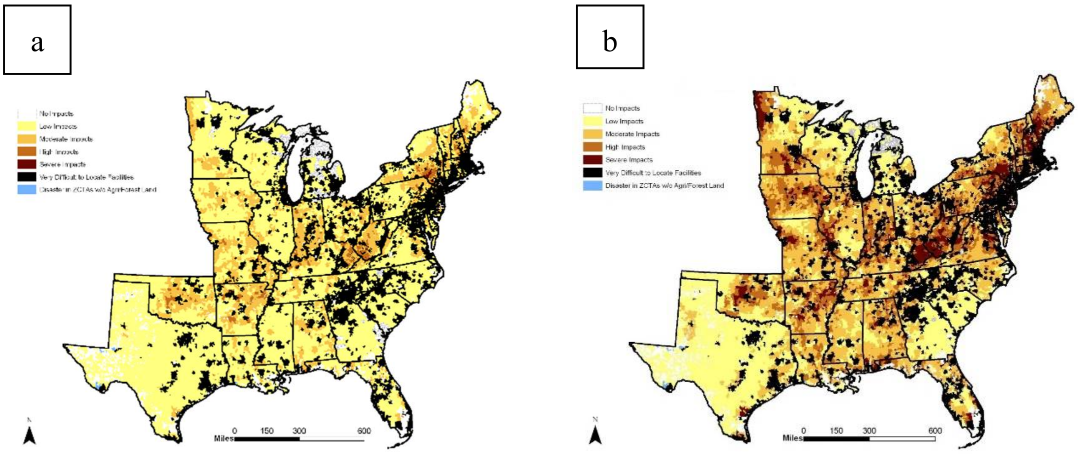

Figure 3. Equal weighting for road and population densities ($w_E = 0.5$ and $w_S = 0.5$) for (a) short-term risk impacts (2000-2011) and (b) long-term risk impacts (1964-2011).

<u>Greater Weight for Road Density, Less Weight for Population Density</u>. If greater weight is given to road density ($w_E = 0.7$) and less is given to population density ($w_S = 0.3$), there were fewer ZCTAs impacted by risk for both the short-term and long-term "*disaster declaration*" impacts (Fig. 4). The eastern seaboard was still impacted by population density. Higher risk areas were in Arkansas, Missouri and Oklahoma for the short-term "*disaster declaration*" impacts. For the long-term "*disaster declaration*" impacts, higher risk zones appeared throughout the study area, with the exceptions of southern Georgia, South Carolina, and Texas.

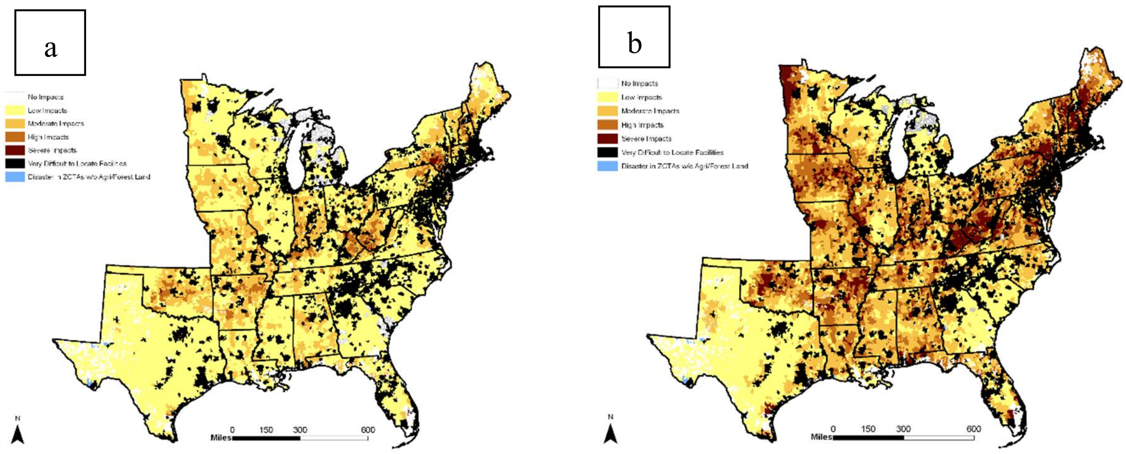

Figure 4. Greater weighting for road density ($w_E = 0.7$) than population density ($w_S = 0.3$) for (a) short-term risk impacts (2000-2011) and (b) Long-term risk impacts (1964-2011).

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<u>Greater Weight for Population Density, Less Weight for Road Density.</u> If more weight is given to population density (w_S= 0.7) and less is given to road density (w_E = 0.3), there were more ZCTAs impacted by risk for both the short-term and long-term "*disaster declaration*" impacts, relative to the previous scenario (Fig. 5). More ZCTAs were affected by risk as population density weighting increased, which is a scenario supported by the literature [28, 29, 30]. Preferred locations for biomass-using facilities in the long-term, in the presence of higher population density, appeared to be in southern Georgia, South Carolina, and Texas.

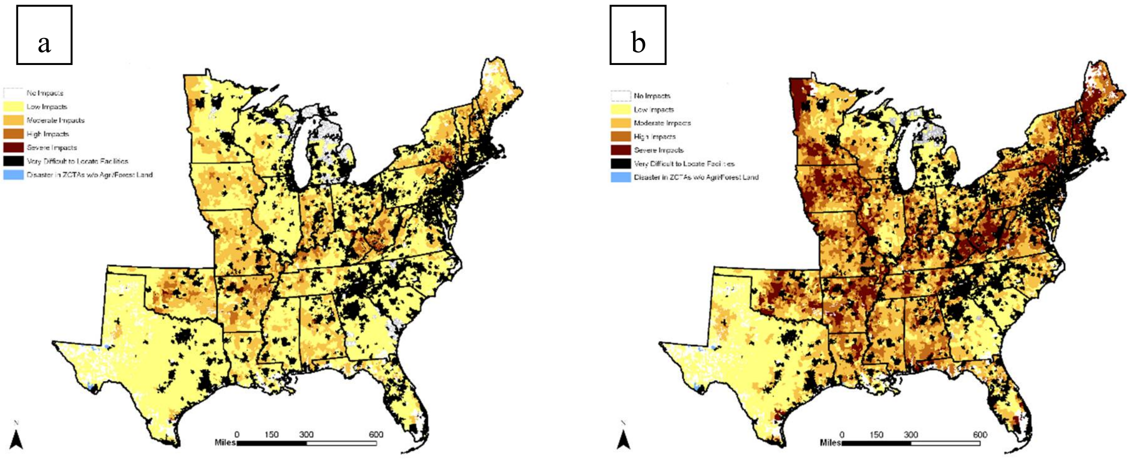

Figure 5. Greater weighting for population density (w_S = 0.7 and w_E = 0.3) for (a) short-term risk impacts (2000-2011) and (b) long-term risk impacts (1964-2011).

MATERIALS AND METHODS

Our approach augments the **<u>Bio</u>**mass **<u>S</u>**upply **<u>A</u>**ssessment **<u>T</u>**ool (**BioSAT**), which is a web-based system available at http://www.biosat.net/ [31]. We combined available datasets for land-use, forest biomass, road density, population levels, and natural hazards defined as *Presidential Disaster Declarations* to produce an aggregated risk impact map that shows the degree of natural disaster risk associated with decisions for locating biomass-using facilities.

<u>Data Sets</u>

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The BioSAT application encompasses transportation, harvesting, and resource cost models that provide spatially referenced biomass economic supply curves within the 33 eastern U.S. states at a 5-digit ZIP Code Tabulation Area (ZCTA) resolution. The average area for 5-digit ZCTAs in the 33-state study region was approximately 169 kilometers^2. The 5-digit ZCTAs provide 25,307 potential analytical polygons or site locations. BioSAT output provides sub-county, spatially-defined groupings and comparisons of environmental, economic, and societal factors that impact landscape capability and biomass access [31]. This study used the BioSAT database collected from numerous sources [32, 33, 34, 35, 36, 37], and state-level mill directories [31]. The cost data derived by the BioSAT model were also used [31].

Spatially-Explicit Biomass Estimation

The Forest Inventory and Analysis Database (FIADB) version 3.0 was used for forest biomass annual growth and removal data. Geographic information system (GIS) technology was applied to reallocate the FIADB data to each 5-digit ZCTA (Fig. 6a). Forestland was identified using digital raster map data from national land cover data [32]. Each pixel represented a particular land cover class, *i.e.,* forest, cropland, water, or urban, etc. on the digital raster map (Fig. 6b). The forest biomass from the FIADB in each county was split into multiple areas by the use of the 5-digit ZCTA area shape file and assigned a unique 5-digit ZCTA identifier due to misalignments of county boundaries with 5-digit ZCTA boundaries. The numbers of pixels for all land cover classes in each 5-digit ZCTA were estimated by overlaying each area with the land cover image layer (Fig. 6c). A forestland pixel ratio was calculated by aggregating the pixels of deciduous, coniferous, and mixed deciduous-coniferous forests, which collectively represents total forestland (Fig. 6d). By proportionally allocating land cover data at the 5-digit ZCTA level, the resolution of the U.S.

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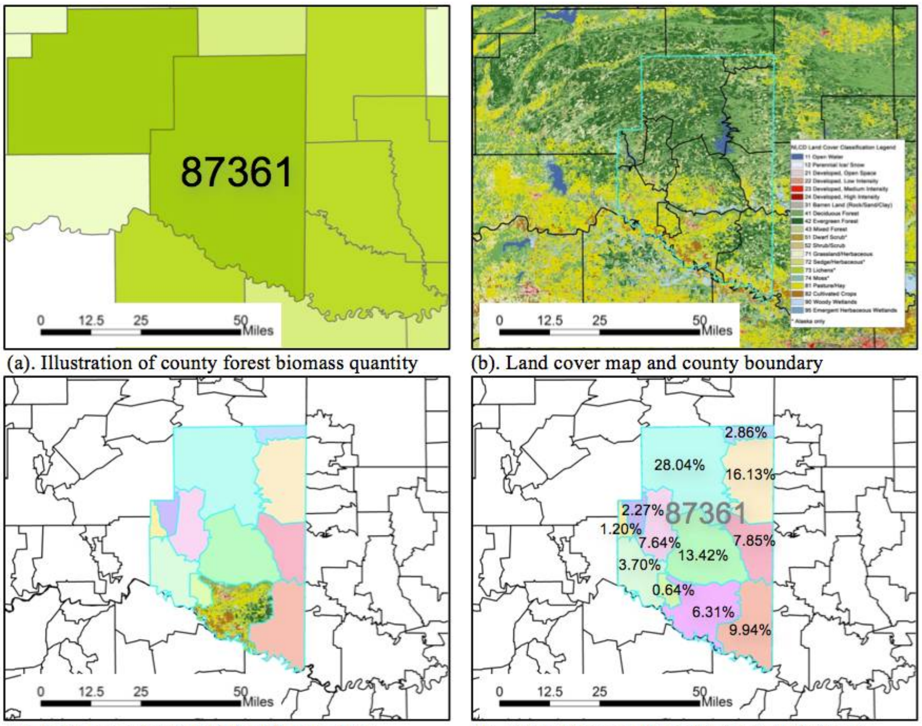
Census data was maintained; and also other socio-economic factors such as urban areas, road network density, park boundaries, waterways, etc. [21, 31, 38].



(a). Illustration of county forest biomass quantity (b). Land cover map and county boundary

(c). Land cover for 5-digit ZCTA boundary (d). Forest biomass allocation by 5-digit ZCTA

Figure 6. Forest biomass allocation illustration at the 5-digit ZCTA level.

<u>Risk Impact</u>

In this study, the primary goal was to produce an aggregated risk impact map, which would show the degree of natural disaster risk for locating biomass-using facilities in terms of risk to the biomass supply. The study defines *risk impacts* as the combination of disaster potential to biomass and vulnerability:

$$Risk\ Impacts = Disaster\ Potential \times Vulnerability. \qquad [1]$$

Disaster potential here takes the similar meaning of physical exposure [25]. The disaster potential refers to the conditions of biomass cultivated land where hazardous events occur. Specifically, forest land and crop cultivated land were used to produce woody and agricultural biomass, respectively. Disaster potential was defined as the frequency of Presidential Disaster Declarations over the short- and long-term (respectively 1964-2011 and 2000-2011). The main types of disasters included coastal storm, drought, earthquake, fire, flood, freezing, hurricane, mud land slide, severe ices, severe storms, snow, tornado, and tropical storms (Table 3). County-level data were not available prior to 1964.

Table 3. Frequency of Presidential Disaster Declarations in 1964-2011 and 2000-2011 (FEMA, 2011).

Disaster Type	2000-2011	1964-2011
Coastal Storm	905	2042
Drought	0	1820
Earthquake	130	130
Fire	4785	5876
Flood	3624	68851
Freezing	1108	1108
Hurricane	19703	33145
Mud Land Slide	0	70
Severe Ices	5359	5543
Severe Storms	71377	106557
Snow	10984	25807
Tornado	1406	11185
Tropical Storm	1566	1566
Total	**120947**	**263700**

Combined with the frequency of Presidential Disaster Declarations in a short-term 2000-2011 and a long-term 1964-2011 [39], the disaster potential was expressed at a 5-digit ZCTA level as:

$$\textit{Disaster Potential} = \textit{number of Disaster Declarations} \times \textit{'Agri' and Forest Land Ratio} \quad [2]$$

where '*Agri*' and Forest Land Ratio are the area ratios of crop cultivated and forest land in each ZCTA.

Vulnerability (or susceptibility to supply disruptions) here refers to different variables that make biomass-using facilities less able to absorb the impact of a disruption in supply and recover from a disaster event. These include economic (such as potential economic damage of production,

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transportation and consumption), and social (such as different population groups' coping capability to the disaster), and environmental (such as the fragility of ecosystem) dimensions.

The economic dimension of *vulnerability* represents the risk to the biomass-using facility's production, transportation, and consumption, *i.e.,* vulnerability implies higher risk to increased costs and disruptions in the supply chain. Road density here is used to measure ability to transport biomass from the field to the facility, which is defined as:

$$Road\ Density = Total\ Road\ length\ (km) \,/\, Land\ Area\ (km^2). \qquad [3]$$

Average road density by 5-digit ZCTA within an 129 km one-way driving distance was calculated to represent its regional impacts, and is grouped into five levels by its quantile distribution with assigned vulnerability probability (Table 4) [40, 41].

Table 4. Average road density levels with assigned vulnerability probability.

Average Road Density Levels	**Vulnerability Probability**
> 14 km/square km	1.0
> 5.38 – 14 km/square km	0.75
> 2.7 – 5.38 km/square km	0.50
> 1 – 2.7 km/square km	0.25
> 0 – 1 km/square km	0

The social dimension of vulnerability assesses the effect on different population groups, and the emphasis is on '*coping capacity*.' [42] argues that "*people in small towns and rural communities are more vulnerable than people in large cities because of weaker preparedness*." In this study, the population density in each 5-digit ZCTA was used as an indicator of the social dimension of vulnerability [28, 29, 30]. We classify the population density in each ZCTA into five levels, and assign a vulnerability probability to each population density level (Table 5).

Table 5. Population density levels with assigned vulnerability probability.

Population Density Level	Vulnerability Probability
0	1.0
> 0 – 19 people/km^2	0.75
≥ 19 – 39 people/km^2	0.50
≥ 39 – 58 people/km^2	0.25
≥ 58 people/km^2	excluded *

*A ZCTA with population density ≥ 58 people/km^2 is not feasible for biomass-using facilities Wear *et al.* 1999).

The environmental dimension of vulnerability assesses the impact on fragile ecosystems. According to [42], "*environmental vulnerability can be seen as the inability of an ecosystem to tolerate stressors over time and space*." In this study, we used the agricultural and forest land ratio as an adjustment factor for disaster potential. Also, all 5-digit ZCTAs containing more than 50% of national parks or national forests area were excluded because of belonging in federal ownership and thus not a reliable biomass supply source. Lands with a slope greater than 45% were excluded because of its '*environmental fragility*'. ZCTAs classified as U.S. EPA Level III ecoregions that were not ecologically suitable for forest production (*e.g.,* Chihuahuan Deserts, Blue Ridge, Southwestern Tablelands, etc.) were excluded [33].

Using these economic, social and environmental indicators, we expressed *vulnerability* as:

$$Vulnerability = Average\ Road\ Density \times w_E + Population\ Density \times w_S, \quad [4]$$

where a weight (*w)* can be assigned to the respective economic and social indicator for its contribution to the overall vulnerability. The risk impacts were then calculated as:

$$Risk\ Impacts = Disaster\ Potential \times Vulnerability, \text{ or} \quad [5]$$

$$Risk\ Impacts = number\ of\ Disaster\ Declarations \times Agri\ and\ Forest\ Land\ Ratio \times (Average\ Road\ Density \times w_E + Population\ Density \times w_S). \quad [6]$$

This resulted in five levels of risk impact, *i.e.,* severe impacts, high impacts, moderate impacts, low impacts and no impacts based on the calculated value (Table 6).

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Table 6. Degree levels of risk impact.

Risk Impacts Degree Level	Risk Impacts Value
Severe Impacts	≥ 6
High Impacts	$\geq 4 - 6$
Moderate Impacts	$\geq 2 - 4$
Low Impacts	$> 0 - 2$
No Impacts	0

CONCLUSIONS

Domestic energy goals have targeted biomass as a renewable energy source that could contribute significantly to the nation's energy production (U.S. Dept. Energy 2016). Forest residues, that are materials left after cleaning, thinning or harvesting plus material damaged by insects, disease or fire, are the main source of woody biomass (U.S. Dept. Energy 2016). For bioenergy from these lignocellulosic sources to be sustainable, they must come from productive forests that are accessible. Additionally, the supply of residues must be reliable in the face of disturbances that affect forests directly or disrupt transportation of residues to processing facilities. We used national forest inventory data (FIADB) to estimate productivity by proportionally down-scaling county level biomass to the 5-digit ZCTA level and assessed potential availability by excluding federal forested land as unreliable sources, fragile lands on slopes over 45%, and land too unproductive for forestry operations.

To assess risk from natural hazards, we used a conservative measure of the risk of natural hazards such as hurricanes, windstorms, and floods; the frequency of *Presidential Disaster Declarations under the Stafford Act* [43]. Major disaster declarations are increasing; the long-term average of 35.5 annually from 1953 to 2014 increased to an average of 46 annually in the decade of the 1990s and 56 annually from 2000 to 2009 [43]. Severe storms, floods, hurricanes, and tornadoes were the primary causes. Notably, Presidential Disaster Declarations do not include wildfires, an increasingly serious disturbance [44, 45, 46]. The rise in disturbances could be related to increased severe weather incidents [47, 48, 49].

Even though the long-term dataset of *Presidential Disaster Declarations* does not capture low frequency, high severity events such as hurricanes on the Gulf Coast [50] and the likelihood that extreme events will increase [51, 52, 53], this research advances the study of risk to biomass supply for a large geographic region at a higher level of spatial resolution than previous research. A significant contribution of the research is the addition of major disturbances in a high resolution geospatial database at the 5-digit ZIP Code Tabulation Area to web-enabled bioenergy siting decision support tool, BioSAT [31]. Even in the presence of risk due to natural disasters, population density had the greatest level of risk to biomass supply. Preferred locations of procuring biomass supply across both short-term and long-term risk, for all risk factors, are in southern Georgia, South Carolina, and Texas. These are also areas with fire-adapted vegetation subject to risk from wildfires, mitigated by aggressive prescribed burning [46].

New research should assess risk to supply from especially mega-fires due to management practices [54, 55] or changes in species composition [56]. Our approach relied on historical data for disasters to estimate exposure as part of our risk assessment [57]. The best geo-referenced data available are aggregates of different types of disturbance; these data exclude other significant disturbances that could affect biomass supply including wildfire, insects, and diseases. Future research could use models of different disturbances to refine the impact zones we identified and disaggregated disturbance data would be useful to develop adaptations that reduce vulnerability.

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