Details:
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Modeling the Impact of Storm Surge Flooding and Associated Costs on North Carolina Coastal Region Corn and Soybean Fields via Remote Sensing

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Abstract: Hurricane and tropical storm-driven storm surge flooding places coastal farmlands at high risk of crop damage and soil salinization. The damage can total to millions of dollars in costs and force farmers to abandon coastal fields. Additionally, many agricultural, and often rural, areas are unable to access accurate and reliable flood-risk projection maps and analyses that can inform prevention and mitigation strategies. This study developed a simplistic methodology for cropland loss analysis that can be utilized by those in regions without advanced GIS specialists, but still wish to explore flood analysis. While similar studies have been conducted in the past, few focus on North Carolina, and most use techniques that require years of expertise and formal training to be able to execute. Soybean and corn, two crops that are critical suppliers to the state economy and have a multitude of uses, were selected to be analyzed. Soybean and corn fields in three of North Carolina's coastal counties were evaluated under various storm surge models. Cropland maps were taken from CroplandCROS, a geospatial database maintained by the United States Department of Agriculture (USDA) for the selected counties. Storm surge models of one, three, five, and nine meters in elevation were overlaid with crop data, and total farmland area submerged by the models was calculated. Models were validated with official flood risk projections and high-risk cropland areas were identified. Under the highest storm surge model, an estimated 672,226,470 m^2, or 86.775% of farmland across all three counties is at risk of flooding. Economic losses were calculated under each model, resulting in damages as high as $135,148,007.30. Further research will be conducted to include more data layers in order to produce more holistic risk projections and enhance the accessibility of flood risk assessment, as well as improving the accuracy and efficiency of the current methodology.

1. Introduction

Coastal farmlands play an essential role in supporting global food systems, providing ideal climate and soil conditions for many crops to grow. [1] [2] However, as changing climate patterns and sea level rise lead to increased flooding risk from natural disasters, coastal farmlands are left especially vulnerable. [3] [4] Many farmers favor the fertile and rich soil conditions in coastal areas, which present ideal conditions to grow staple crops including corn, wheat, and soybeans. [5] Coastal areas are also more heavily affected by hurricanes and other major storms, which can lead to tsunami-like waves flooding inland farmlands, in addition to flooding from heavy rainfall. [6]

As climate change and rising sea levels worsen, hurricanes, and similar storms, are becoming more frequent and severe. [4] As a result, flooding can oversaturate coastal farmland with salt water, leading to waterlogged soils, spread of plant pathogens, and large-scale crop damage. Flooding can also lead to increased soil salinity, threatening consequences including osmotic stress, ion toxicity, and nutrient deficiencies, among others. [7] Furthermore, the introduction of salt in soil is destructive to plant development in every stage of growth, and has harmful long and short-term implications for the surrounding environment. [8] In the short-term, farmers lose crops and profit, negatively impacting local economies, especially those reliant on the agricultural sector. In the long-term, the impacts are amplified, potentially risking widespread famine, global supply chain collapse, and increased food insecurity among low income communities. [9] [10]

North Carolina, in particular, is an essential supplier of crops such as sweet potatoes, soybeans, and corn to the United States, with an estimated economic value of around $103.2 billion. [11] North Carolina's eastern coastal plains are ideal locations for the growth of such crops, due to the nutrient-rich soils in the area, which places these farmlands at increased risk of crop failure and high soil salinity levels. Soybeans and corn are among North Carolina's most profitable crops, and play an integral role in livestock and commodity production; depleting them would cause devastating consequences to local communities. [12] For example, aside from being sold for raw consumption, soybeans are also used in oils, condiments, and a primary source of livestock feed. [13]

In recent years, there has been interest among those in natural resource management, climatology, and agriculture in understanding and identifying key locations of increased flooding risk, on both the regional and national level. [14] However, severe roadblocks impede the formation of universalized flood risk projections, including lack of data and miscommunication between organizations. The rise in remote sensing data accessibility has made the process more attainable for organizations, particularly those that are smaller in size. Regardless, many modern-day maps solely compute areas at high risk of inland flooding. [15] [16]

Additionally, there is a lack of research analyzing trends and patterns in risk areas, leading to the lack of well-researched mitigation and prevention strategies. Without examining the agricultural implications of storm surge flooding, coastal farmers are unable to take proper preventative measures to minimize the impact of flooding on their farmlands. Similarly, there has also been the need for additional research in examining trends in risk projection models. [17] [18]

2. Background

2.1 Agricultural Farmland Flooding

Coastal flooding is a critical concern for farmers globally. Studies indicate that despite accounting for more than 17 million km^2 of damage, research on the issue is lacking. Current agricultural policies are also impractical, and put coastal farmlands at an increased risk of flooding. Not only do floods negatively affect local ecosystems, but can also introduce toxic pollutants into rivers, sewage systems, and other key water sources. [19]

Roughly 10% of global arable land is impacted by waterlogged soil, and 16% in the United States. Flooding is primarily caused by severe wind and precipitation, but man-made constructions on waterways can amplify the impacts.

Aside from crop damage, flooding also causes waterlogged soil and compaction, both of which disrupt typical plant growth. The damage extends to local habitats and ecosystems, as well as sewage systems, posing potential threats to the environmental health of local communities. [20] In addition, the flooded farmland can harm seed germination, interfering with plant growth. The issue is exacerbated by the potential threat of flooding from streams in the spring. Risk management and proper land use are essential mitigations to preventing crop loss. [21]

2.2 Risk Quantification and Mapping

The identification of flood risk areas is crucial to proper flood risk management and the estimation of crop and resource losses. Machine learning and GIS-systems can provide useful platforms to build risk assessments, and spatial analysis can further inform flood mitigation strategies. Currently, predictive modeling is primarily applied to urban locations. However, machine learning models can also be used for rural areas. Public datasets can model pluvial flooding, which is induced by rain. Corn and soybean yields were the most heavily impacted by the models. [22]

A powerful framework is needed for successful disaster management and the calculation of crop and economic damage. The convolutional neural network in this study was applied to corn and soybean yields, which are heavily impacted by flooding. The model was able to predict future areas at risk of damage and inform agricultural policies. [23] Spatial analysis can aid in flood mitigation of croplands.

Several factors can be used to calculate projected flood damage, including land use, elevation, precipitation levels, and soil composition. A flood risk map can then be produced and analyze the association of cropland use and flood risk. The model indicates that crop loss also leads to significant water waste. Elevation played the largest role in determining flood risk, and can help inform legislators and other stakeholders in land management and disaster mitigation. [24]

In recent years, the increased availability of remote sensing data has allowed flood crop loss assessment to be used in a more robust, comprehensive manner. Previous crop loss assessments were restricted by time and data-collection restraints. Studies generally focus on either flood intensity, or crop condition. Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat datasets are the main sources used in generating assessments. Vegetation indices have seen a similar increase in usage. Loss assessment model validation data is lacking, though archival data can improve the model accuracy. [25]

2.3 Long-term Impacts of Crop Loss and Flooding

Aside from immediate crop failure and farmland damage, coastal flooding can also negatively impact local economies and food security. Flooding of agricultural land places strain on food systems, particularly those of rural and low-income communities. Evaluating the connection between the two can inform food supply chain management decisions and natural disaster mitigation. The need for effective modeling can inform risk mitigation and support farmers in building resilience against flooding, and other natural disasters. [26]

Crop yield success is reliant on land topography and soil quality. Soil properties accounted for nearly a third of yield variability, while topographic features account for a fifth. Other topographic features, such as the curvature, slope, and flow accumulation, only had significant influence in areas with extreme topography. [27]

The climate change-driven global increase in temperatures also correlates with the increase in frequency and severity of natural disasters. Nature-based solutions (NBS) have become popular in mitigation of flood damage in rural farmlands. Among them, agricultural practices such as no-till farming and agroforestry, wetland buffers, and structural defenses, help with water retention and damage mitigation. A combination of agricultural practices and man-made intervention systems can assist coastal farmers in remaining adaptable and well-equipped to manage farmland flooding. [28]

3. Methods

3.1 Study Area

Three coastal North Carolina counties, Beaufort, Carteret, and Pamlico, were used to generate storm surge models and assess flood risk in this study. All selected counties have large amounts of corn and soybean cropland. In 2022, Beaufort County held the highest farm cash receipts for soybeans in the state. [29] According to North Carolina state designations, Beaufort and Pamlico County are considered "rural"; this means that farmers in these counties are critical to sustaining both the local economy and state-wide food systems. [30] Their incomes also depend on the success of their crop, putting farmers and their communities at high risk of long-lasting, devastating damage if they are affected by storm surge flooding. [31] The study area also has low-lying elevation, making it vulnerable to potential flooding. Storm surge flooding is largely caused by strong winds resulting from hurricanes or tropical storms and nor'easters. As a result, hurricane incidence is often correlated with storm surge flooding. [32] The North Carolina coastal region has experienced numerous hurricanes in recent years. They occur most frequently in August and September. [33] [34] This coincides with the time period in which farmers prepare to harvest their crops, meaning that if a storm surge event were to happen, crops could be lost. Flooding risk is exacerbated by the presence of two rivers between the three counties: the Neuse and Pamlico, making the area a good choice for inclusion in this study.

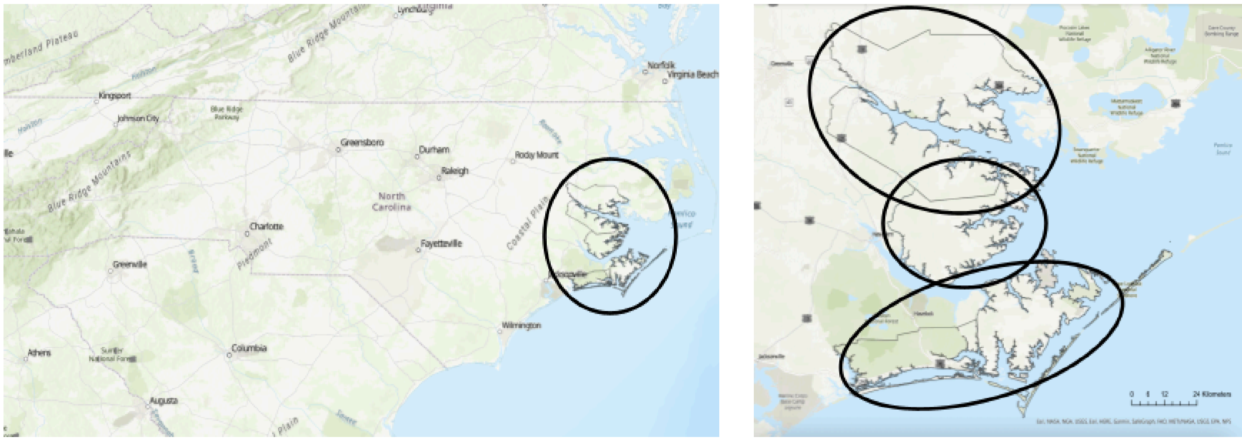


Figure 1. The study area, Beaufort County, Pamlico County, and Carteret County in North Carolina state. (Esri Topographic basemap imagery)

3.2 Storm Surge and Cropland Overlay

In order to obtain geospatial farmland data of the desired commodities, corn and soybean fields were isolated in the Cropland Collaborative Research Outcomes System (CroplandCROS) database of the United States Department of Agriculture (USDA). [35] Storm surge models of one, three, five, and nine meters in elevation were produced using geoprocessing tools in ArcGIS Pro 3.1. The Cropland CROS data of corn and soybeans were overlaid with the generated storm surge models. Total sums of crop damage under each model was generated for each county in square meters. All elevation and crop data were taken from databases updated in 2022.

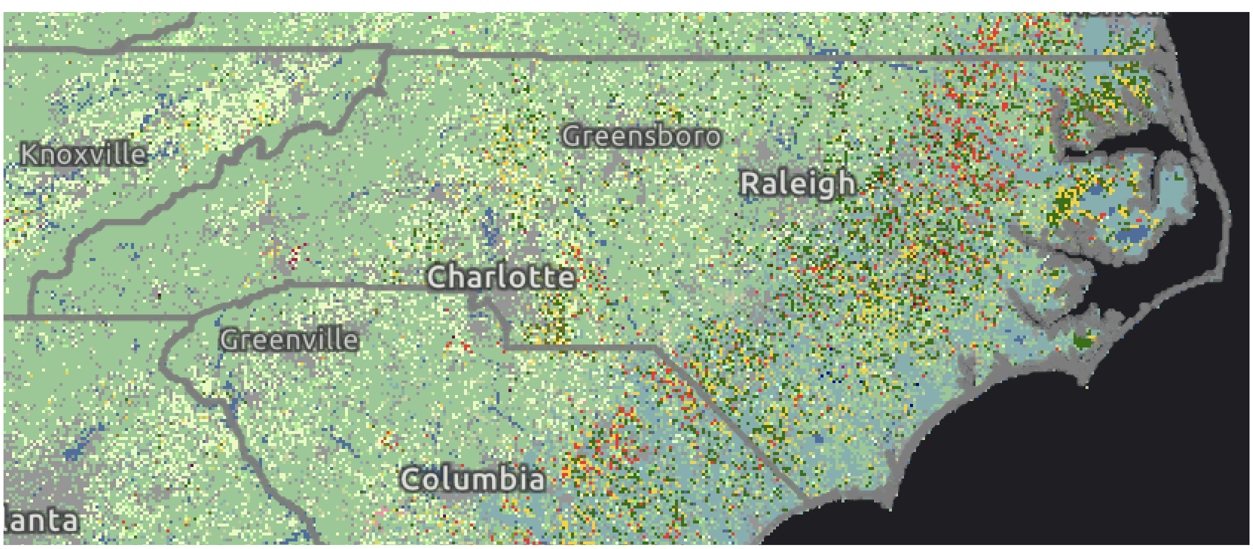


Figure 2. Agricultural commodity data in North Carolina. (USDA CroplandCROS)

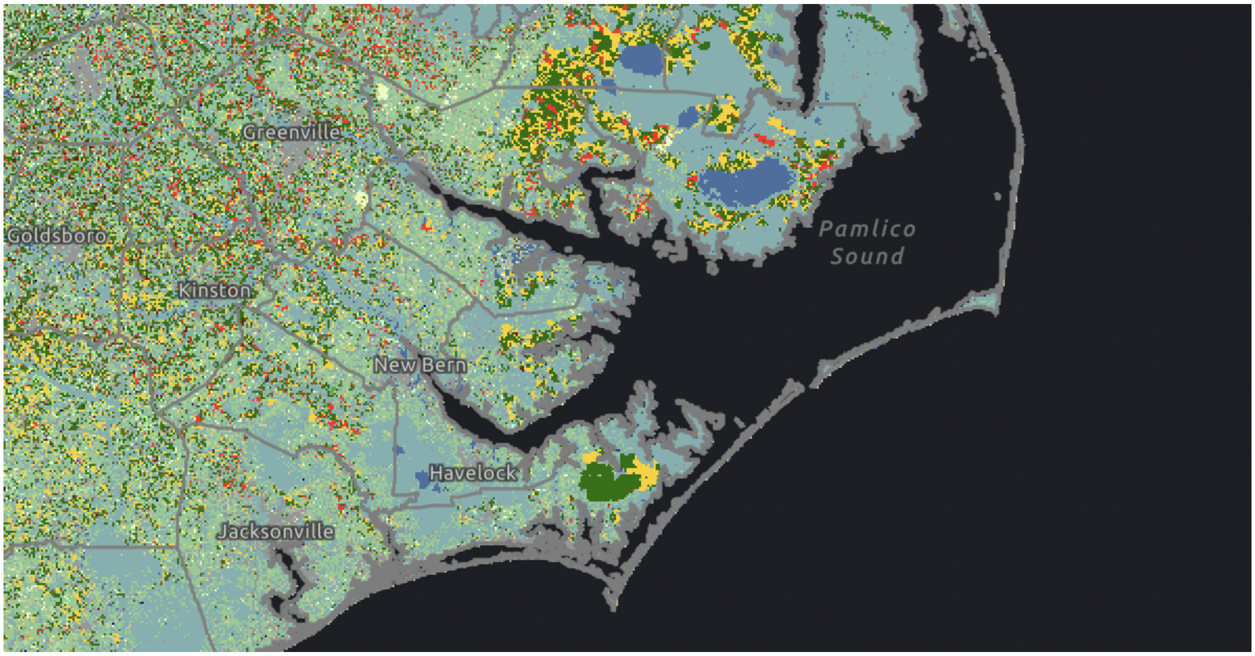


Figure 3. Data of common agricultural commodities in Beaufort County, Pamlico County, and Carteret County in North Carolina. Green areas indicate soybean fields; yellow indicates corn fields; red indicates cotton fields. (USDA CroplandCROS)

3.3 Model Analysis

The storm surge models were compared with those generated by the North Carolina Flood Risk Information System (FRIS). [36] Then, maps of each model were examined in order to identify areas at high risk of flooding. Data on total cropland without storm surge models and flooded cropland area were collected for each scenario, and examined.

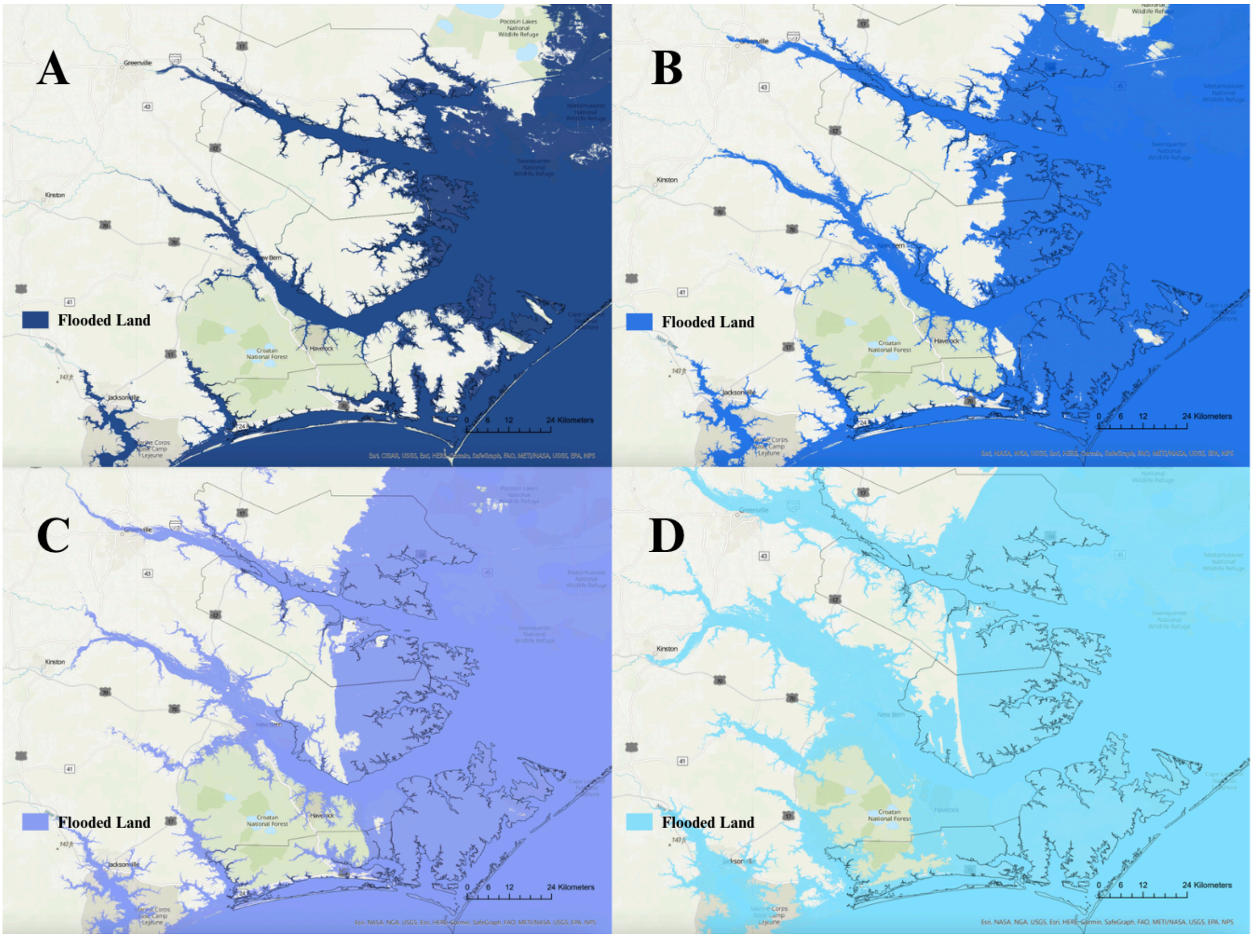


Figure 4. Storm surge models of one (A), three (B), five (C), and nine (D) meters in height. (Made by author with Esri World Elevation Layers)

3.4 Production Costs Loss

Next, to estimate the amount of money lost in production of flooded fields, assuming that all flooded cropland is unable to be harvested, data taken from the 2022 USDA Commodity Costs and Returns reports was compiled for both soybeans and corn. Factors including seed, fertilizers, repairs, fuel, equipment, purchased irrigation, hired labor, taxes, and insurance were considered. [37] The following formulas were used to estimate the total amount of loss for each crop. [38]

Soybean Production Loss

$S_T = 0.15231562248 \times S_1$

where S_T= Estimated total loss in production costs of soybean crops, in dollars per square meter and S_1= Soybean cropland, in square meters

Corn Production Loss

$C_T = 0.28607117617 \times C_1$

where C_T = Estimated total loss in production costs of corn crops, in dollars per square meter and C_1= Corn cropland, in square meters

4. Results

4.1 Soybean and Corn Cropland

In total, 493,083,008.10 m^2 of soybean farmland was found across all three counties, with 276,933,723.40 m^2 in Beaufort County, 143,032,669.50 m^2 in Carteret County, and 73,116,615.16 m^2 in Pamlico County. Corn farmland totaled to 281,598,116.30 m^2, with 169,608,845.9 m^2 in Beaufort County, 55,126,325.42 m^2 in Carteret County, and 56,862,944.97 m^2 in Pamlico County. The ratio of corn to soybean cropland, without accounting for storm surge damage, across all three counties averaged to roughly 1:1.75.

Location	Total Area of Cropland	Percentage Soybeans	Percentage Corn Cropland
All Counties	774,681,124.30 m^2	63.649 %	36.350 %
Beaufort	446,542,569.30 m^2	62.017 %	37.982 %
Carteret	198,158,994.90 m^2	72.181 %	27.819 %
Pamlico	129,979,560.10 m^2	56.252 %	43.747 %

Table 1. Total areas of corn and soybean fields in three North Carolina counties, and the percentage of soybean and corn fields out of the total. (Made by author)

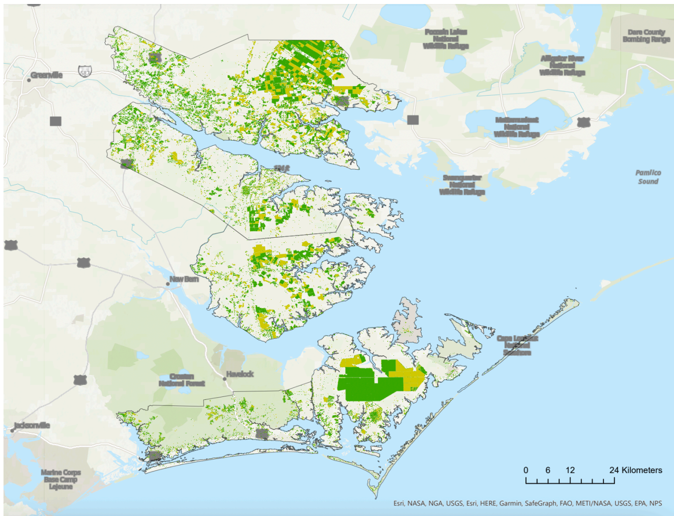


Figure 5. USDA CroplandCROS corn and soybean data. (CroplandCROS)

4.2 Storm Surge Model Validation

The generated storm surge models of one, three, five, and nine meters in height were compared to existing models from the North Carolina Flood Risk Information System (FRIS). In Figure 8, the side-by-side comparisons are shown. The overlaid maps show similar flooding areas around large bodies of water and streams, as well as similar flow patterns based on topographic data (Fig. 9).

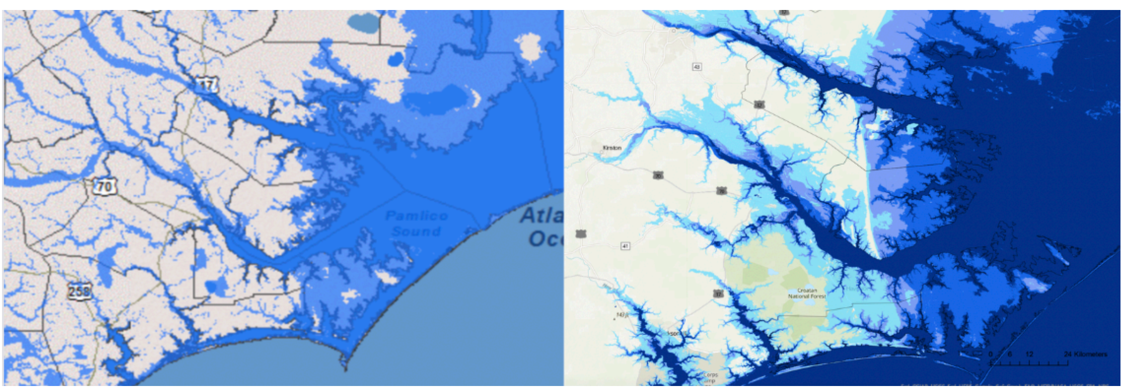


Figure 6. North Carolina FRIS flood risk maps (left) in comparison with storm surge models (right). (North Carolina Floodplain Mapping Program)

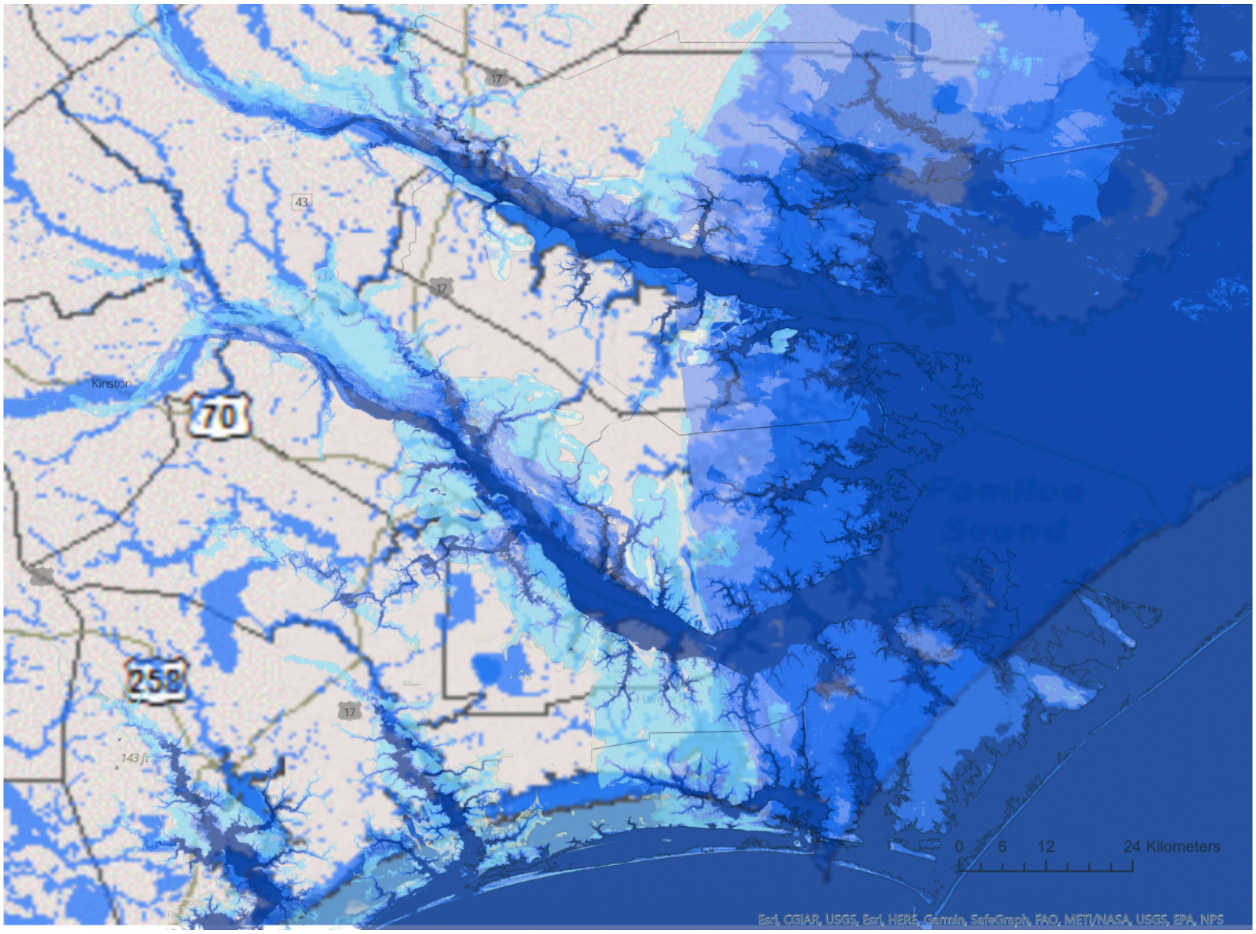


Figure 7. Overlay of storm surge models and North Carolina FRIS maps. (Made by author)

4.3 Flood Risk Assessment

In order to assess areas at high risk of storm surge floods, maps of the lowest storm surge model, one meter, were examined. Areas close to large bodies of water, such as the Neuse or Pamlico river, are at highest risk of flooding. Elevation of land also tends to increase inland, resulting in elevated risk of flooding for land directly by the coast, as well.

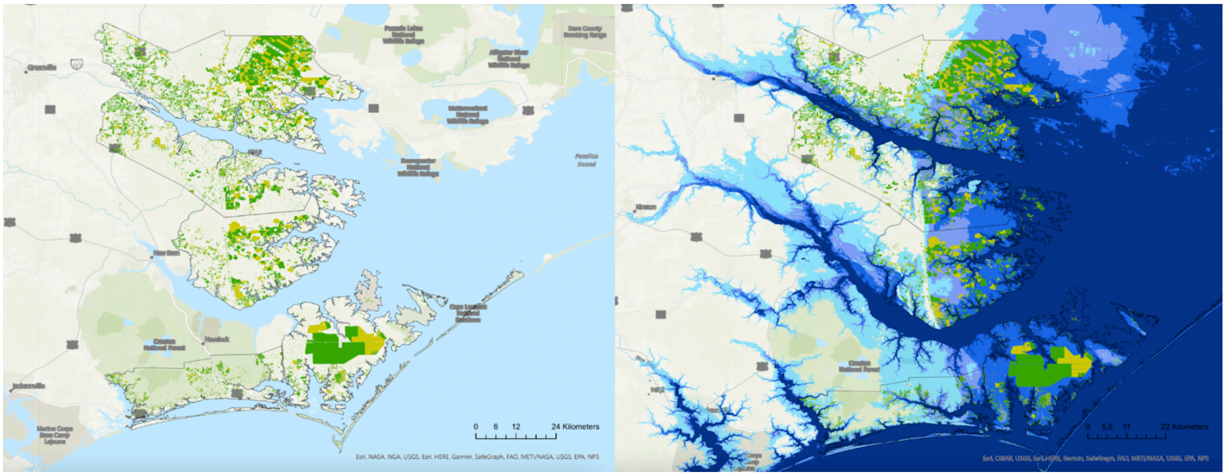


Figure 8. Storm surge models overlaid onto CroplandCROS maps. (Made by author)

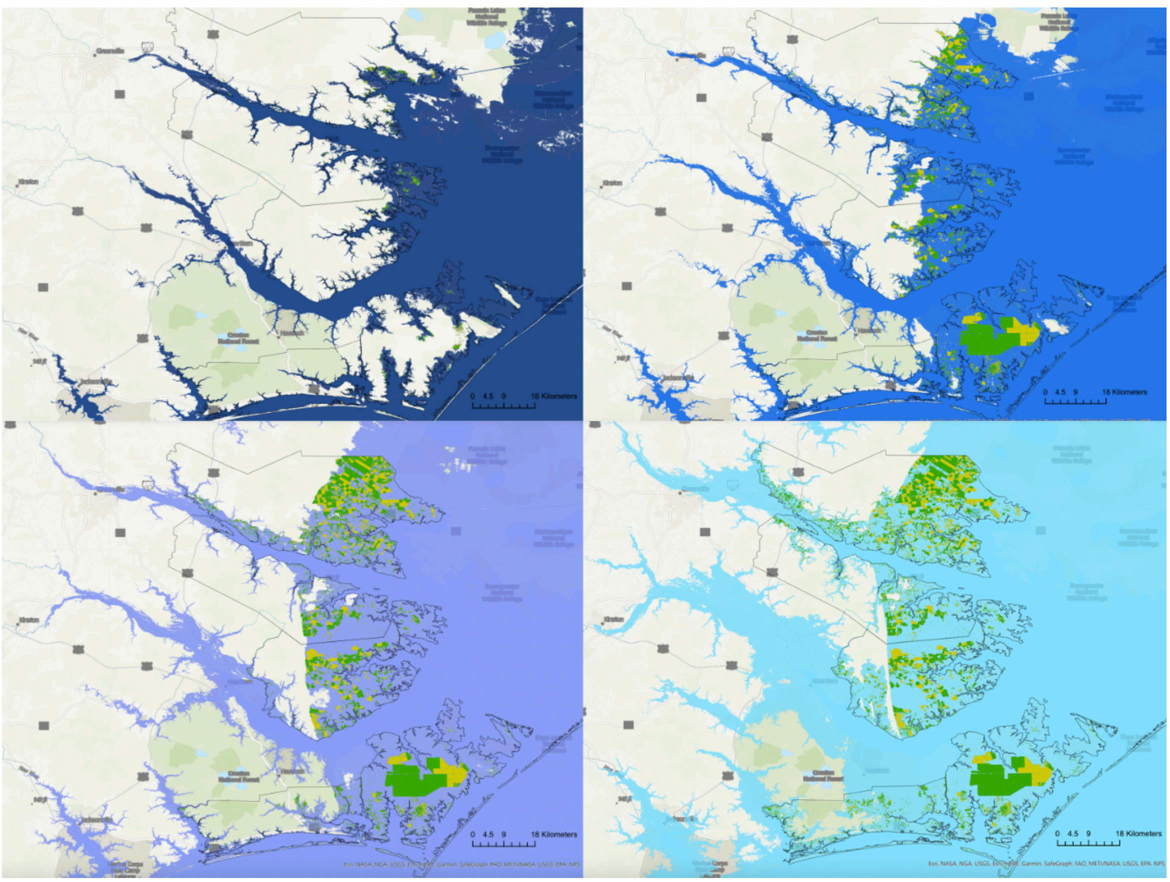


Figure 9. Extent of damage to cropland under each storm surge model. (Made by author)

The one meter storm surge impacted roughly 3.579% of all soybean and corn crop fields across three counties. The surge also flooded 3.330% of total soybean field area and 3.330% of total corn field area. The individual impacts on counties varied, ranging from 5.756% of total Pamlico County soybean and corn cropland, to 2.583% of Beaufort County soybean and corn cropland.

The three meter storm surge flooded roughly 48.174% of total farmland across Beaufort, Carteret, and Pamlico. The variability of impact between counties increased, ranging from 89.818% of Carteret County being flooded, to 29.320% of Beaufort County. Flooding in Pamlico County remained close to the total percentage of damaged cropland area, at 49.460%, compared to the average of 48.174% of flooded farmland.

The five and nine meter storm surges followed a similarly increasing trend as previous models, with an average percentage of crop loss at 77.462% and 86.775%, respectively. Beaufort County had a considerably lower percentage of crops damaged under the three, five, and nine meter model as compared to the other two counties. This could be a result of the geographic dispersion and size of the county; in Pamlico County and Carteret County, farmland is seen in clusters concentrated in smaller areas. Beaufort County also has clusters, but to a lesser extent than Carteret County, in addition to being spread across a larger amount of land.

A.)

Location	**Damaged Cropland Area**	**Damaged Soybean Area**	**Damaged Corn Area**
All Counties	27,730,590.10 m^2 (3.579%)	16,420,336.37 m^2 (3.330%)	11,310,253.76 m^2 (3.330%)
Beaufort	11,535,450.20 m^2 (2.583%)	5,654,202.65 m^2 (2.042%)	5,881,247.56 m^2 (3.467%)
Carteret	8,713,750.80 m^2 (4.397%)	5578267.95 m^2 (3.900%)	3135482.89 m^2 (5.688%)
Pamlico	7,481,389.10 m^2 (5.756%)	5187865.77 m^2 (7.095%)	2293523.30 m^2 (4.033%)

B.)

Location	Damaged Cropland Area	Damaged Soybean Area	Damaged Corn Area
All Counties	373,199,097.90 m^2 (48.175%)	240,032,084.90 m^2 (48.680%)	133,167,013.00 m^2 (47.290%)
Beaufort	130,927,253.40 m^2 (29.320%)	71,267,286.93 m^2 (25.734%)	59,659,966.50 m^2 (21.186%)
Carteret	177,984,149.70 m^2 (89.818%)	128,400,945.80 m^2 (89.770%)	49,583,203.9 m^2 (89.945%)
Pamlico	64,287,694.80 m^2 (49.460%)	40,363,852.18 m^2 (55.205%)	23,923,842.62 m^2 (42.073%)

C.)

Location	Damaged Cropland Area	Damaged Soybean Area	Damaged Corn Area
All Counties	600,080,984.00 m^2 (77.462%)	381,703,028.10 m^2 (77.416%)	218,377,955.70 m^2 (77.550%)
Beaufort	301,276,214.50 m^2 (67.469%)	183,898,080.90 m^2 (66.405%)	117,378,133.50 m^2 (69.205%)
Carteret	186,246,957.30 m^2 (93.989%)	135,123,621.40 m^2 (94.470%)	51,123,335.84 m^2 (92.739%)
Pamlico	112,557,812.20 m^2 (86.597%)	62,681,325.81 m^2 (85.728%)	49,876,486.35 m^2 (87.714%)

D.)

Location	Damaged Cropland Area	Damaged Soybean Area	Damaged Corn Area
All Counties	672,226,469.90 m^2 (86.775%)	427,321,393.60 m^2 (86.663%)	244,905,076.30 m^2 (86.970%)
Beaufort	347,817,131.10 m^2 (77.891%)	213,685,538.40 m^2 (77.161%)	134,131,592.70 m^2 (79.083%)
Carteret	196,420,908.70 m^2 (99.123%)	141,582,104.00 m^2 (98.986%)	54,838,804.72 m^2 (99.478%)
Pamlico	127,988,430.10 m^2 (98.468%)	72,053,751.21 m^2 (98.546%)	55,934,678.85 m^2 (98.367%)

Table 2. Cropland damage in m^2 under each model: one (A), three (B), five (C), and nine (D) meter surges, respectively. (Made by author)

The ratio of corn to soybean fields, whether a storm surge was simulated or not, didn't drastically change; across the three counties, fluctuations were relatively insignificant. The ratio of farmland between the three counties also showed little variability. The proportion of farmland in each county remained nearly identical, except for the three-meter storm surge, which saw a noticeable increase in flooded soybean and corn farmland in Carteret County, relative to the other two counties.

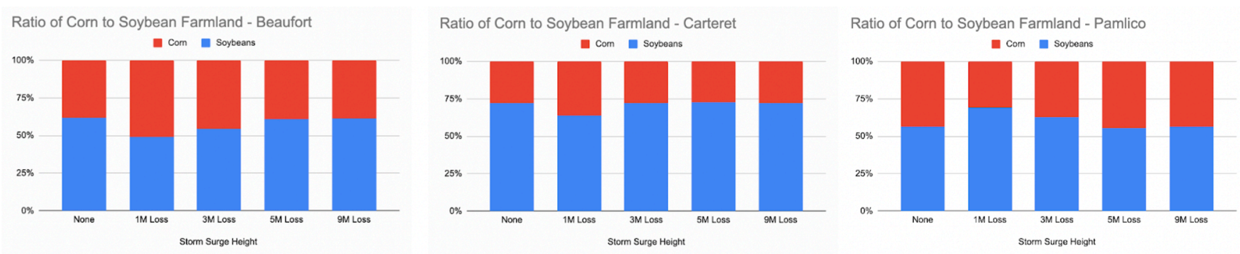


Figure 10. The amount of soybean to corn field ratio for each county under all surge models. (Made by author)

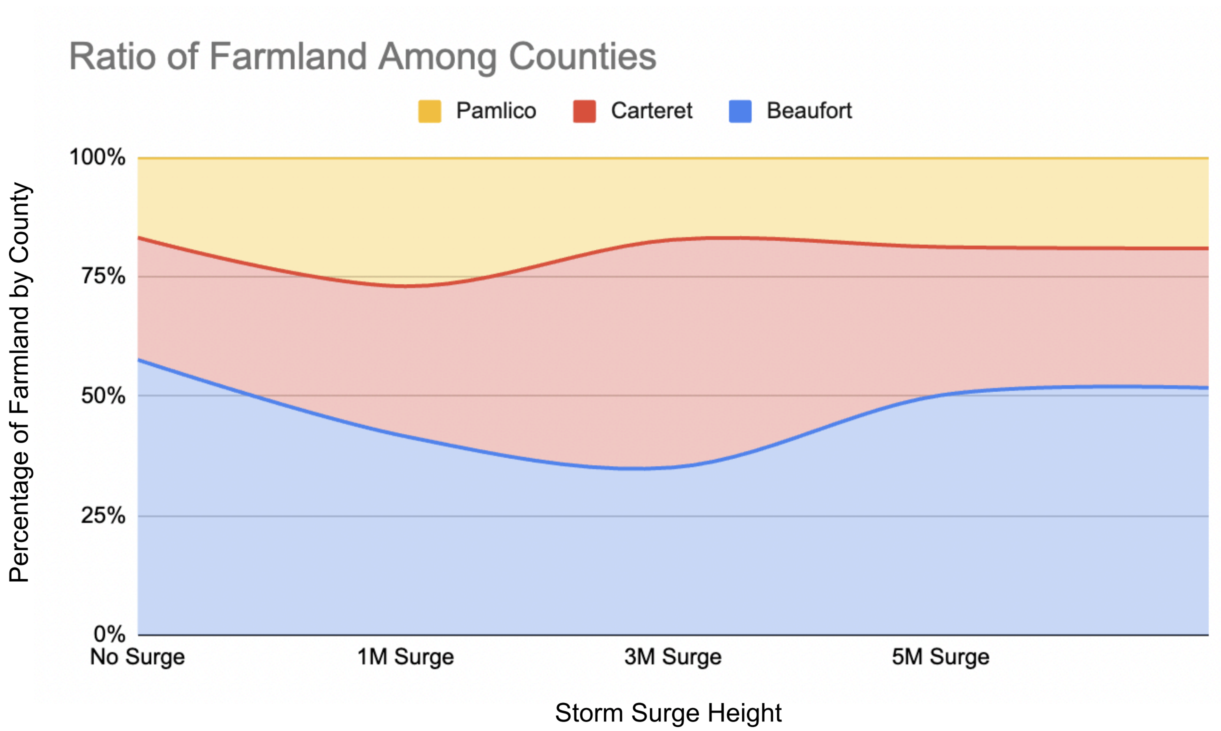


Figure 11. Ratio of farmland between Beaufort, Carteret, and Pamlico County under the different storm surge models. (Made by author)

4.4 Estimating Economic Implications

The economic loss from costs during production from flooded farmland, which is assumed to have resulted in crop failure, were calculated. Even under the lowest storm surge model, production losses amounted to $5,736,611.26. The highest model projected that $135,148,007.30 would be lost from crop production costs.

Model	Soybean Production Cost	Corn Production Cost	Total Production Cost
1 meter	$2,501,073.76	$3,235,537.60	$5,736,611.36
3 meters	$36,560,636.43	$38,095,244.04	$74,655,880.47
5 meters	$58,139,334.33	$62,471,638.64	$120,610,972.97
9 meters	$65,087,724.07	$70,060,283.23	$135,148,007.30

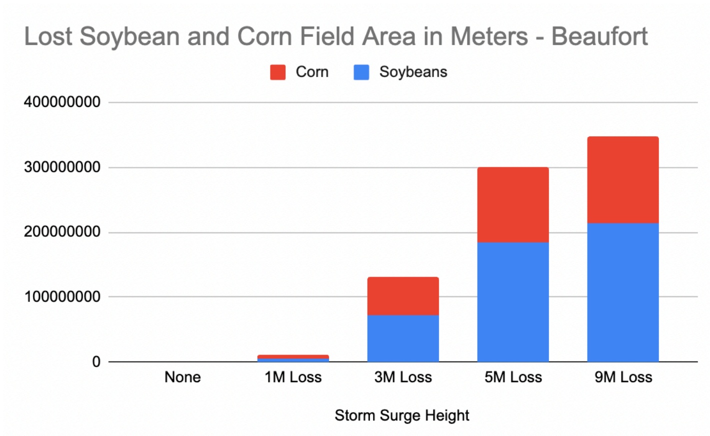
Table 3. Economic damages from crop loss calculated using formulas in Figure 5. (Made by author)

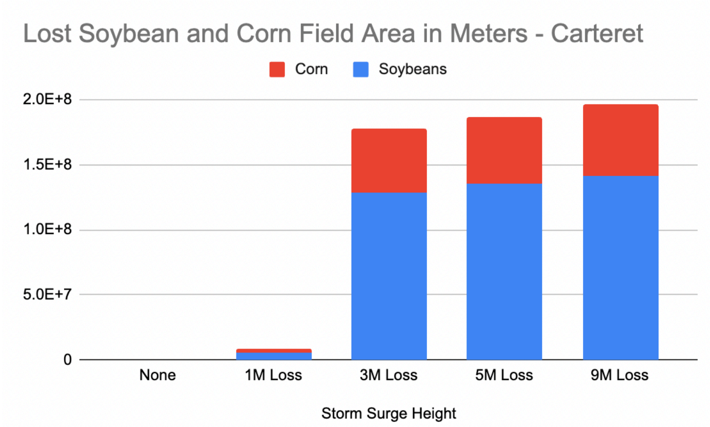
5. Discussion

This study confirmed the correlation between proximity to large bodies of water and risk of flooding, as well as a relationship between low elevation and high risk of flooding. The results also demonstrated a positive correlation between storm surge height and farmland flooding. With each increase in simulated storm surge height, flooded cropland for both soybeans and corn, increases across all counties.

The modeled loss of cropland in each county under the various storm surge models contains some disparities. A one meter storm surge yields similar cropland loss percentages in all three counties, while the three meter surge model reveals more drastic differences of up to sixty percentage points. Further analysis also reveals that while the rate of farmland loss for both soybean and corn fields of Beaufort and Pamlico County remained relatively constant as storm surge height increased, the rate of farmland loss of Carteret County increased rapidly from the amount of cropland flooded under the one meter storm surge model, as compared to the flooded cropland under the three meter storm surge model. This indicates that there is a large, likely concentrated, amount of farmland in Carteret County, with a low elevation between one and three meters. This effect is also shown in the ratio between the farmland of the three counties;

although the proportion between the three remains similar to the model with no storm surge under the one, five, and nine meter models, the three meter storm surge model demonstrated an increase in the ratio of Carteret farmland lost. This could be a potential location to prioritize the implementation of mitigation strategies, and conduct, more in-depth, further flood risk assessments.





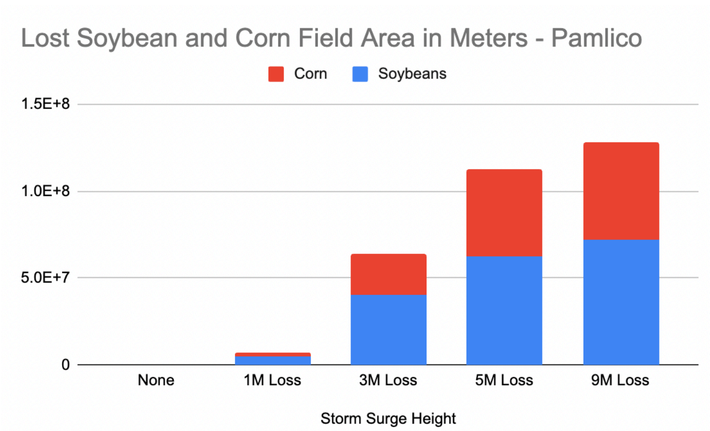


Figure 12. Amount of damaged corn and soybean land for each county, under each storm surge model. (Made by author)

The variability between the amount of soybean and corn crops remained relatively consistent throughout all models. The amount of corn to soybean-field land ratio ranged from an estimated 50-62.5% in Beaufort County, 63-74% in Carteret County, and 54-71% in Pamlico County, implying that storm surge flooding across all simulated heights and geographic locations, harms both soybean and corn fields relatively equally. This suggests that neither crop is immune to the damages posed by storm surge flooding, a principle that could extend to other crops in the state, such as sweet potatoes, cotton, or wheat, although further investigation into the topic is required.

Additionally, the economic implications of estimated damage costs demonstrate the impact that storm surge events could have on both communities at the local economy. Beaufort County harvested approximately 40,000 acres (161,874,256.90 m^2) of corn crop and 70,000 acres (283,279,949.57 m^2) of soybean crop in 2021. The agricultural industry is also a notable contributor to the economies and livelihoods of rural areas, of which farmlands in Beaufort, Carteret, and Pamlico are often located [39]. The economic damage of storm surge flooding under any of the four scenarios would cause large losses of profit, which would in turn affect local and state-wide food supply, as Beaufort is a leading producer of soybeans in North Carolina. While the possibility of biotechnologies, such as salt-tolerant plants, could reduce damage in the short-term, the long-term implications require extensive support and research from scientists, legislators, and communities. [40] Assessing flood model maps, analyzing resulting data, and estimating economic impacts enhances understanding of the complexity of the issue at hand, and better allows for the development of resilient flood-risk management systems.

The simplicity with which these methodologies can be applied presents novel methods for the transfer and facilitation of the use of this technology in areas without GIS analysts and experts to conduct flood risk analysis. In essence, it is a method that most can do with a simple tutorial.

6. Conclusion

This study demonstrates the importance of evaluating coastal farmland areas under storm surges. Not only does this allow for the evaluation of high-risk flood regions, but it also estimates potential economic loss. The accessibility of current remote sensing data and satellite imagery allows for natural disaster management agencies, agronomists, and farmers to be able to estimate storm surge flooding, the risks associated with such events, and analyze data that could inform mitigation strategies. [41] This technique is especially useful for more frequently grown commodities, such as wheat, maize, and cotton, while data for less popular crops may be harder to obtain.

A primary limitation of this study is the factors taken into consideration when generating storm surge models. Because only land elevation data was used in mapping flood risk, the lack of other factors, including soil quality, precipitation level, and location-specific climate patterns, may have skewed calculations. The varying cost of crop production and resource use, dependent on the time of storm surge occurrence, is another limiting factor. This, however, is a trade-off in order to prioritize the accessibility of the research. It is suggested that future research studies focus on reducing the level of background education required, computer processing times, and enabling more factors to be inserted into analysis without too much work.

Future studies could expand the area analyzed for storm surge flood risk, and account for other crops that are essential for local economies and food systems; this would prove invaluable to combating the damage of natural disasters. Furthermore, improvements upon remote sensing and geospatial analysis techniques could make farmland flood risk analysis more accurate and accessible to non-GIS analysts; such improvements could assist poorly funded disaster management offices in accessing quality risk assessments for rural farmers. Research can also investigate non-monetary damage losses, notably, nitrogen depletion in soil, freshwater irrigation resources, herbicide and pesticide use, the spread of invasive species, and the spread of pollutants. These studies can produce holistic overviews of storm surge flood impacts and assist in future conservation and mitigation efforts.

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