Spatial analysis of United States ethanol production infrastructure vulnerability to flooding

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Abstract

Early-growing season, long duration floods are harmful to the cultivation of maize, the source of 80% of the US bioethanol fuel. Due to the centrality of this industry to US government efforts to bolster domestic energy production, Midwest flooding has implications for US energy production. This paper uses spatial statistics to characterize the spatial distribution of ethanol plants relative to maize production in twelve Midwestern US states which account for approximately 90% of US corn production. County-based territories are delineated for each of the 176 plants in these states, and the total maize production and average annual production are summed for each plant. Multi-decadal flooding data from the Dartmouth Flood Observatory (1982-2007) are used in conjunction with data from the US Department of Agriculture National Agricultural Statistical Service to derive flood risk levels for each plant, and for total production capacity in the region.

Keywords

Risks/Hazards, Bioethanol, Flooding, GIS

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1 INTRODUCTION

1.1 Context & Research question

Springtime flooding is a frequent threat to wide areas of farmland in the American Midwest. Early-growing season, long duration floods are particularly harmful to the cultivation of maize (Kanwar et al. 1988), the source of 80% of the US bioethanol fuel. Bioethanol is a typical kind of biofuel, and is produced by fermenting the sugar components of plant materials (Balat and Balat 2009). Bioethanol is most widely used in the U.S. and in Brazil (Ernst & Young's Renewable Energy Group 2007). In addition to being used in its pure form as a replacement for gasoline in vehicles, ethanol can also be used as a gasoline additive to increase octane and improve vehicle emissions (Hill et al. 2006).

Prompted by a desire for octane boosters after the ban on leaded fuel, ethanol production for fuel or as a fuel additive in the United States has risen for more than 30 years (Tyner and Taheripour 2007, US Energy Information Agency 2011). During this period growers have received billions in annual government subsidies (Hahn 2008), and in the past decade the biofuels industry has experienced rapid growth in the United States as the Bush administration invested in biofuels to combat dependence on foreign oil and address global warming concerns (Ernst & Young's Renewable Energy Group 2007). Currently in the United States, processing maize/corn is the main bioethanol production model (Hahn 2008).

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The risks accompanying a reliance on foreign sources of fuel are illustrated by the rise in crude oil prices which coincided with turmoil in Libya, Yemen, and Nigeria during the spring of 2011, but domestically sourced bioethanol may have its own set of attendant risks as a fuel source. Rising demand for food corn inflates the costs of biofuel production, as do destructive weather events such as droughts and floods (Trostle 2008). The location of an ethanol plant has a major impact on the total product costs, pricing, and profitability because these firms are highly dependent on access to raw materials, which affect costs through delivery cost, commodity price of the raw materials, and the cost to process them (Noon et al. 2002). This paper uses spatial statistics to characterize the spatial distribution of ethanol plants relative to corn production in twelve Midwestern US states which account for approximately 90% of US corn production. GIS is then used to characterize flood risk exposure of the Midwest bioethanol production infrastructure at a geographically granular level.

1.3 Study area

This study examines flooding and bioethanol production in the 11 US states[2] that contain some portion of the region of intensive maize cultivation known as the Corn Belt. These states comprise a majority of corn production in the United States, and are subject to seasonal and potentially severe flooding on waterways such as the Mississippi, Missouri, Ohio, and Red Rivers. The location of ethanol plants, and their total capacity,

[2] Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, North Dakota, Nebraska, Ohio, South Dakota, Wisconsin.

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appears to concentrate in the center of this study region (Figure 1). The basic geographic unit of analysis is the county.

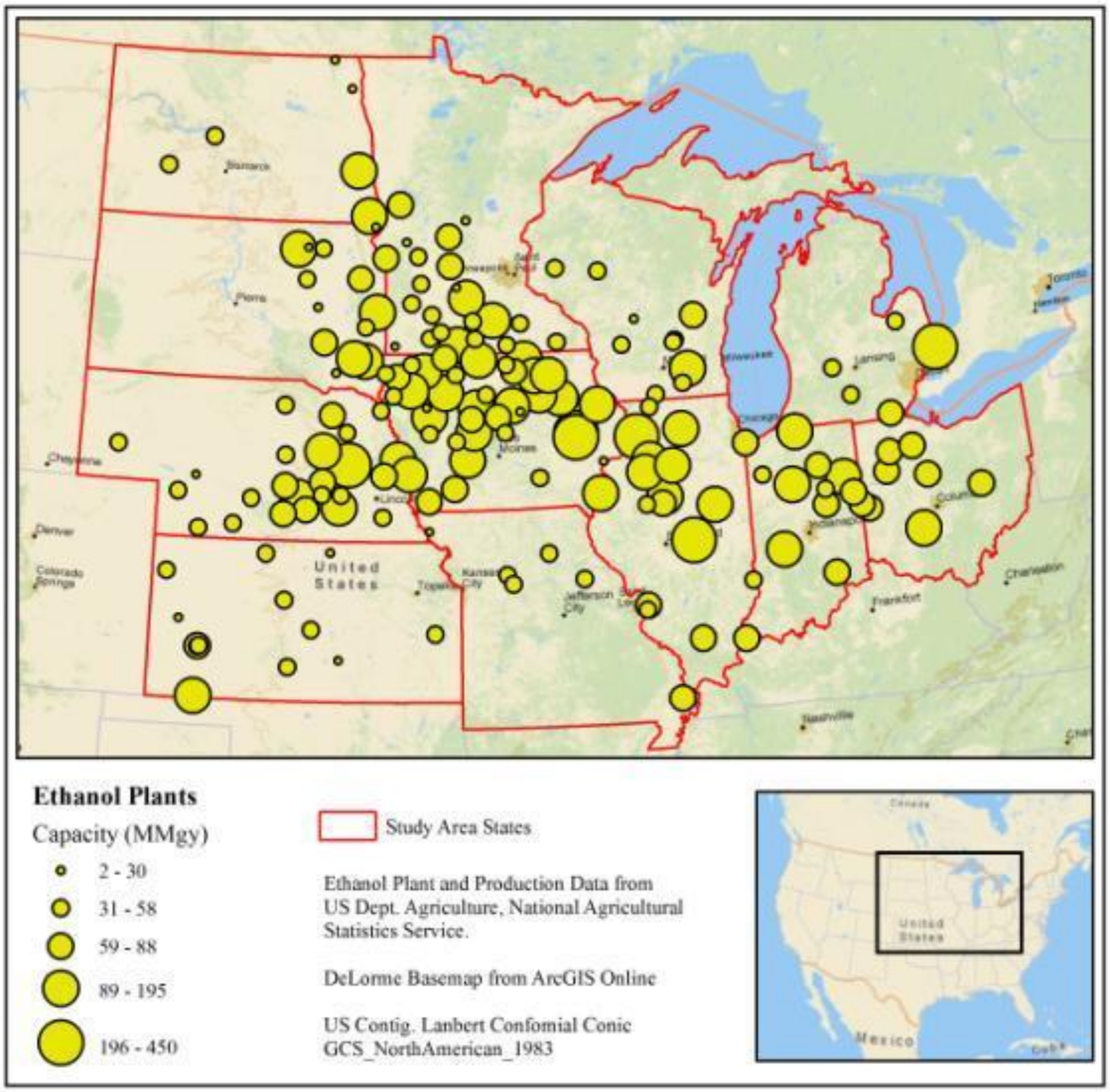

Figure 1. Map of study area states with existing bioethanol plants, sized according to their production

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2 METHODS

2.1 Data

Corn production measurements by county, in bushels, are obtained from the United States Department of Agriculture (USDA) National Agricultural Statistical Survey (NASS) agricultural censuses from the years 2002 and 2007. These production amounts were averaged for each county to produce a single measurement of corn production for each county. Ethanol plant location data, and plant capacity in millions of gallons per year, were also obtained from USDA NASS and the Ethanol Producer Magazine, the ethanol industry's premier trade journal published by BBI Internaional. Agricultural census data were joined to a US Census Bureau county shapefile, and ethanol plant addresses were geocoded to street, or to town, precision using ESRI's online geocoding services.

Historic flood data comes from the Dartmouth Flood Observatory database, currently administered by the University of Colorado (Brackenridge, 2007). Flooding events are delineated using remotely sensed data, and information about each flooding event, such as date, duration, area, estimated return interval, number of people killed, and number of people displaced is recorded. Flood events from the years 1982-2007 were chosen so that data spanned from the earliest available events to the timing of the 2007 agricultural census. The data used were distributed in shapefile format. The measurement of flood severity is used in this work as an overall descriptor of the impact of flood events (Table 1).

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Severity	Description
1	Significant damage to structures or agriculture, 10-20 year return period
1.5	Affects large geographic region, 20-100 year return period
2	Extreme Events, >100 year return period

Table 1. Interpretation of flood severity, from Dartmouth Flood Observatory.

2.2 Methodology

2.2.1 Corn Production Hot Spots

Using ESRI's ArcMap 9.3.1, a map is produced that shows averaged 2002 and 2007 corn production by country, as well as a map of regional corn production hot spots, as indicated by the Getis-Ord Gi* index (Mitchell 2005). For the hot spot analysis a fixed distance band of 75 km is used to define the neighborhood for analysis of similarity. An Average Nearest Neighbor ratio test is used to determine whether clustering of ethanol plants exists in the region.

2.2.2 Derivation of Flood Vulnerability Maps

In order to capture those floods likely to have a pronounced, adverse effect on corn crops, the complete DFO database was filtered to contain only flooding events that affected the United States, that occurred in the months March to June, and that were greater than 2 days in duration. These remaining flood shapefiles were joined to the county map using a summarized spatial join, where the count of flood events and the sum of severity for all floods intersecting each county, were joined to the county layer.

2.2.3 Delineation of Ethanol Plant Territories

Because of the importance of raw material sourcing to the costs of bioethanol production, this paper assumes that the area from which each ethanol plant may potentially obtain input maize can be approximated as the area nearer to the particular ethanol plant than to another plant (Figure 2). Through the use of a summarized distance join in ArcMap, corn production for each county is attributed to the nearest bioethanol plant to derive a measure of the source maize abundance among bioethanol plants. The production amounts per county are summed to derive a total production per territory. Then, counties' sum of flood severity values are averaged within each plant's territory to describe the vulnerability of each plant's corn supply to flooding (Equation 1).

$$Flood\ vulnerability_{territory} = \frac{\sum_{i=1}^{N} Total\ Flood\ Severity_{county\ i}}{N} \quad (1)$$

Where N equals the number of counties in the territory.

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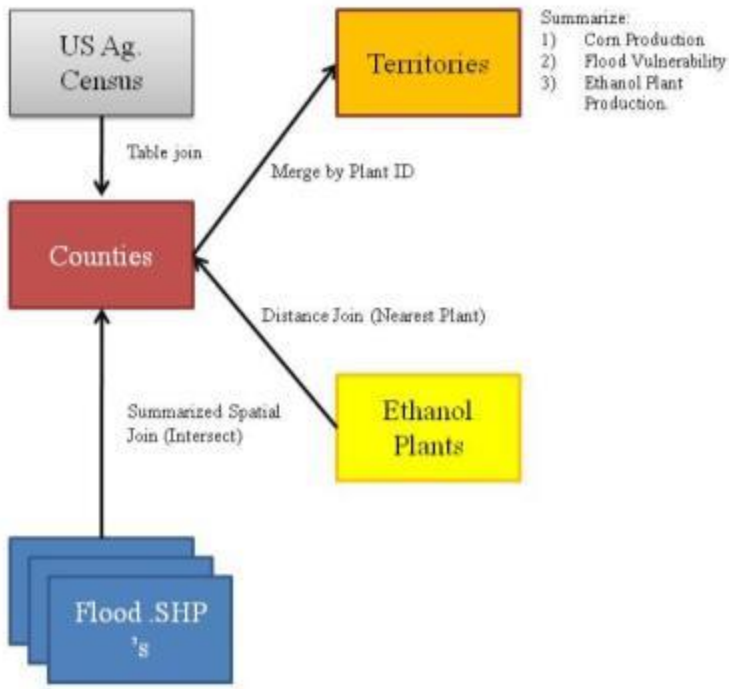

Figure 2. Workflow used to delineate ethanol plant territories.

2.2.4 Approximating Risk

Finally, a risk index value was calculated for each ethanol plant on the basis of its ethanol capacity, and the amount of corn supply and long-term flood vulnerability in its corresponding territory. The following equation is used to calculate the risk index for each plant:

$$Risk\ Index = 10^6 * \frac{Total\ Corn\ Production\ in\ Territory * \ Flood\ Vulnerability\ of\ Territory}{Ethanol\ Capacity} \qquad (2)$$

where a constant coefficient of one million is added to enhance interpretation. The resultant indices provide a relative indicator of which plants have a low ratio of corn supply to production capacity, a factor that may exacerbate supply chain disruptions caused by early season flooding.

3 RESULTS

3.1 Corn Production Hot Spot Maps

Maps showing the original corn production in study region counties, as well as hotspots of corn production (Figure 3), indicate that the areas of highest corn production are in the states of Illinois, western Indiana, Iowa, southern Minnesota, east-central Nebraska, and southern Wisconsin. Areas with below average corn production in the region are situated in the peripheral areas of the study region, such as southern Missouri, northern Michigan, and eastern Ohio. The Average Nearest Neighbor ratio for ethanol plant locations is 0.945 with a Z-score of -1.39 (p-value 0.165).

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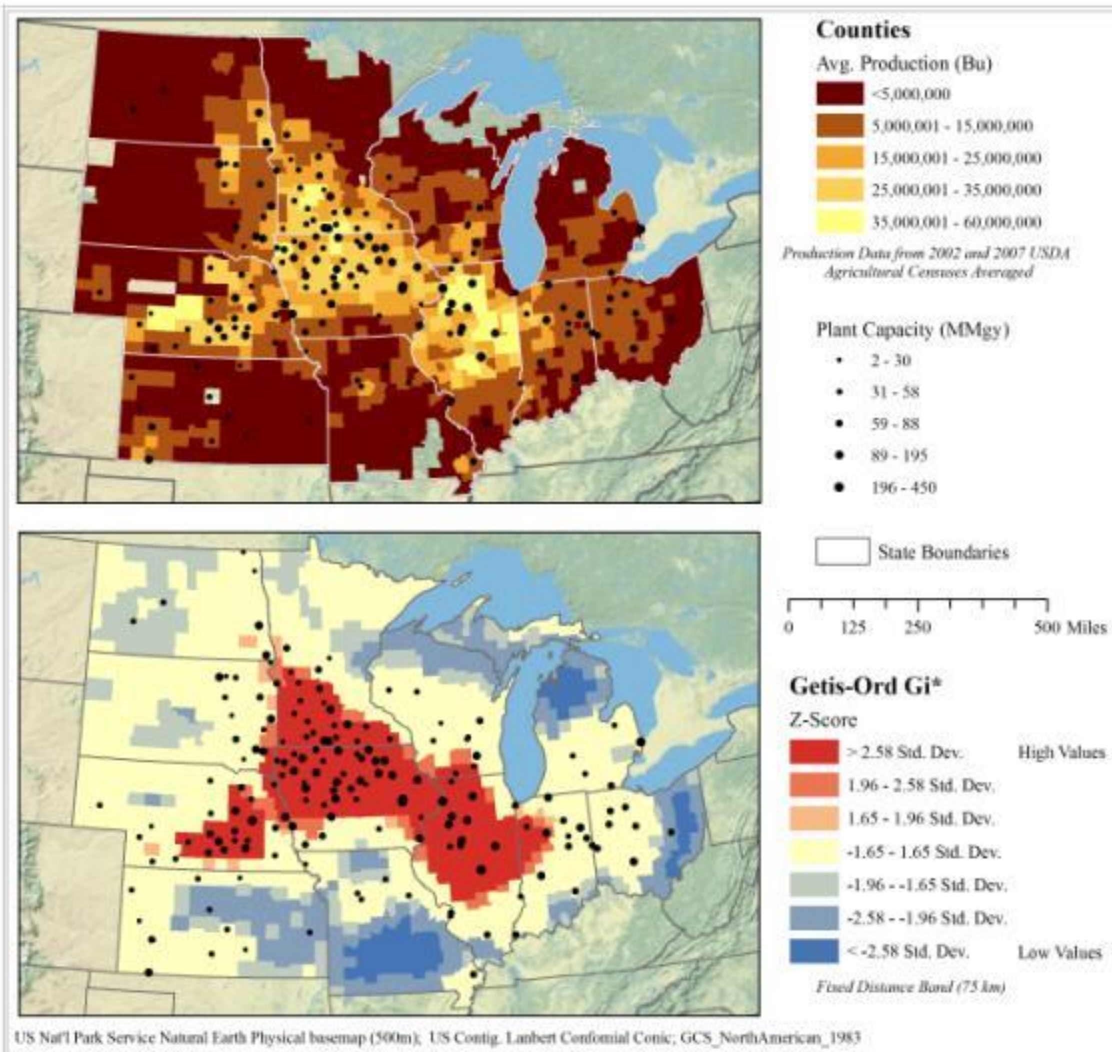

Figure 3. Corn production by county in study region.

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3.2 Flood Vulnerability Maps

A map showing by county the sum of severity for all intersecting flood event reveals that areas in Missouri, Illinois, North Dakota, and Minnesota experience the most severe flooding during the period 1982-2007 (Figure 4). Areas in Michigan, Nebraska, and South Dakota experience the least severe flooding during the time period.

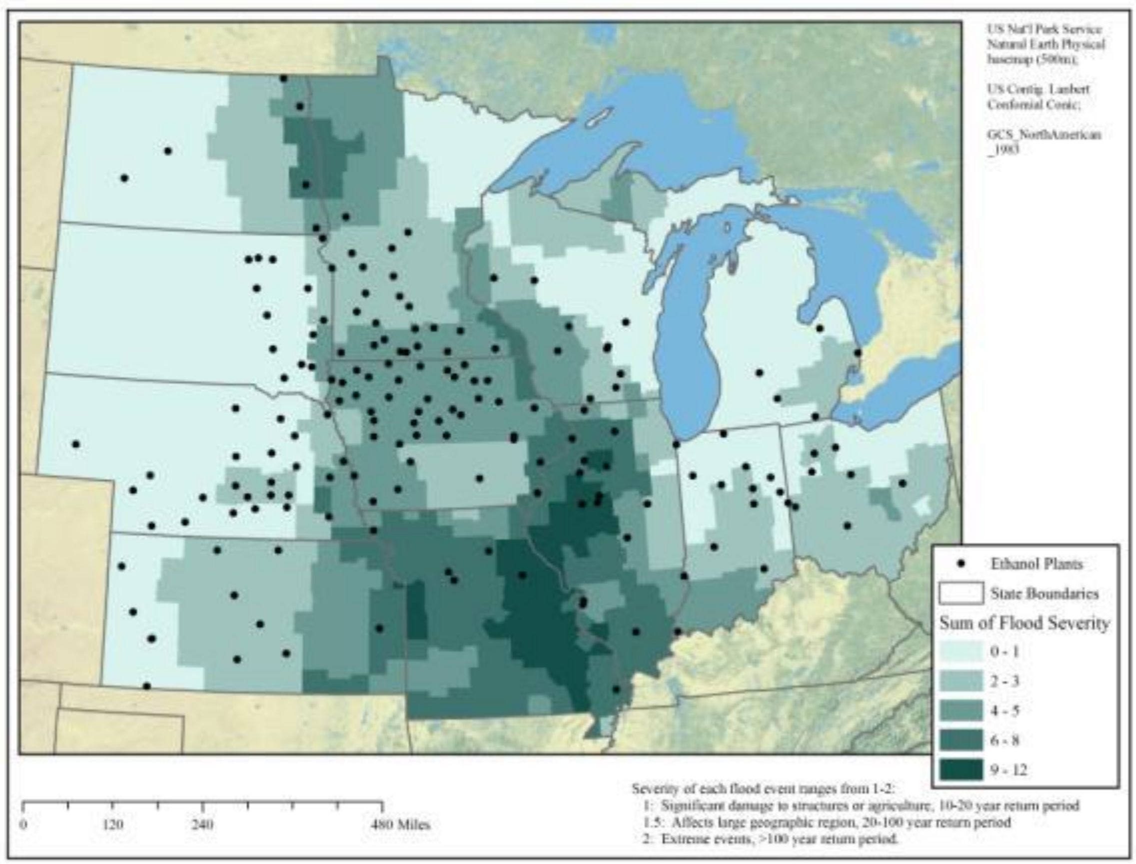

Figure 4. Flood vulnerability, expressed as sum of flood events' severities, for counties in study region.

3.3 Ethanol Plant Territory Delineation

Ethanol plant territories determined by a summarized distance join of counties to ethanol plants yields a study region composed of 176 territories (Figure 5). The number of counties contained within a territory ranges from 59 to 0.5 (where county contains two plants, it is considered within both plants' territories and its total production values are split equally between the plants). Territories contain fewer counties in the center of the study region, while territories on the periphery of the study region tend to contain a higher number of counties.

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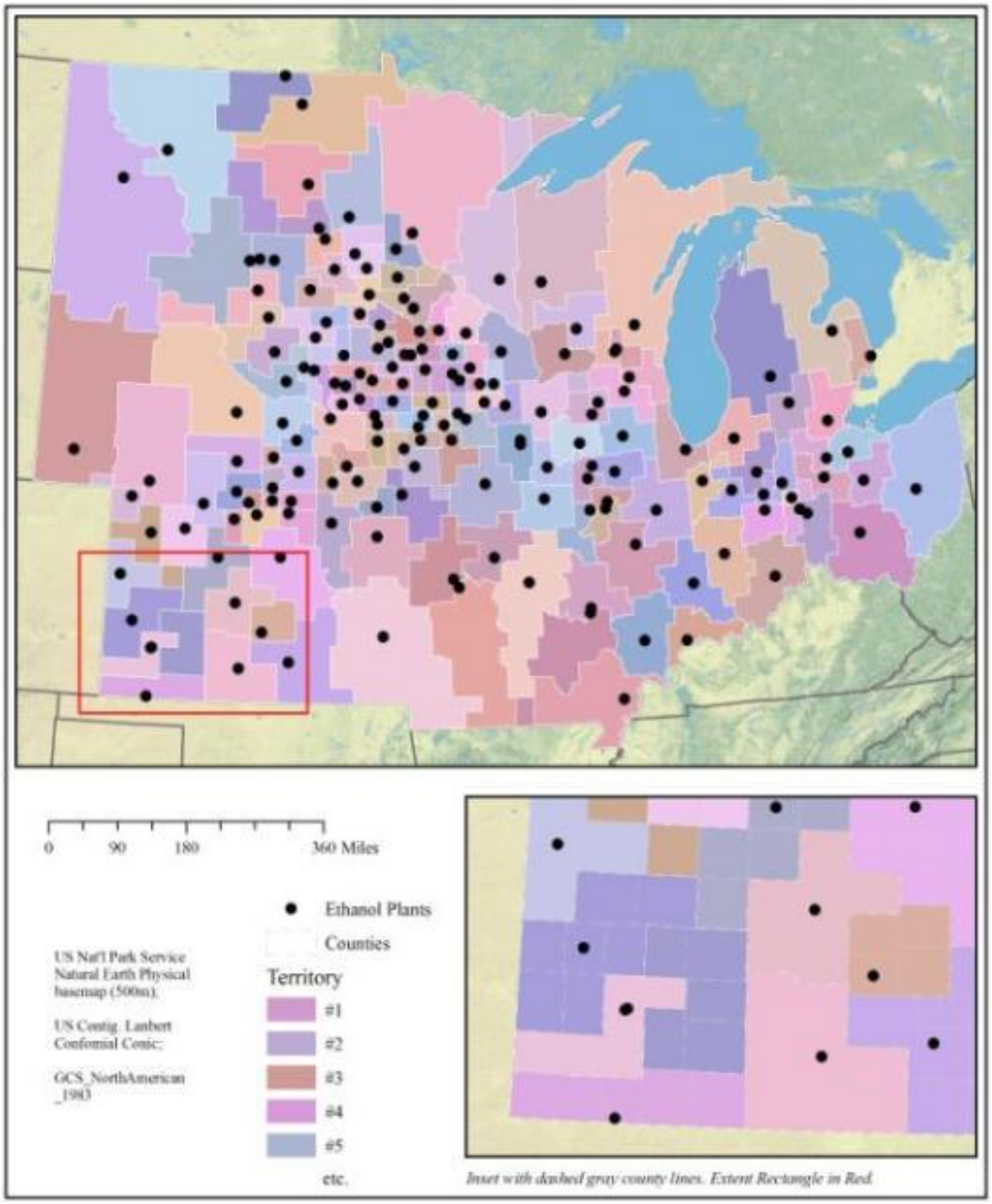

Figure 5. Delineation of ethanol plant territories in study region.

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When total corn production by county is summed by ethanol plant territory, the resulting map shows a similar pattern as was seen in original county distributions (Figure 6). The lowest values are seen in territories close the edge of the study region, while the highest values appear in Illinois, Indiana, and Iowa.

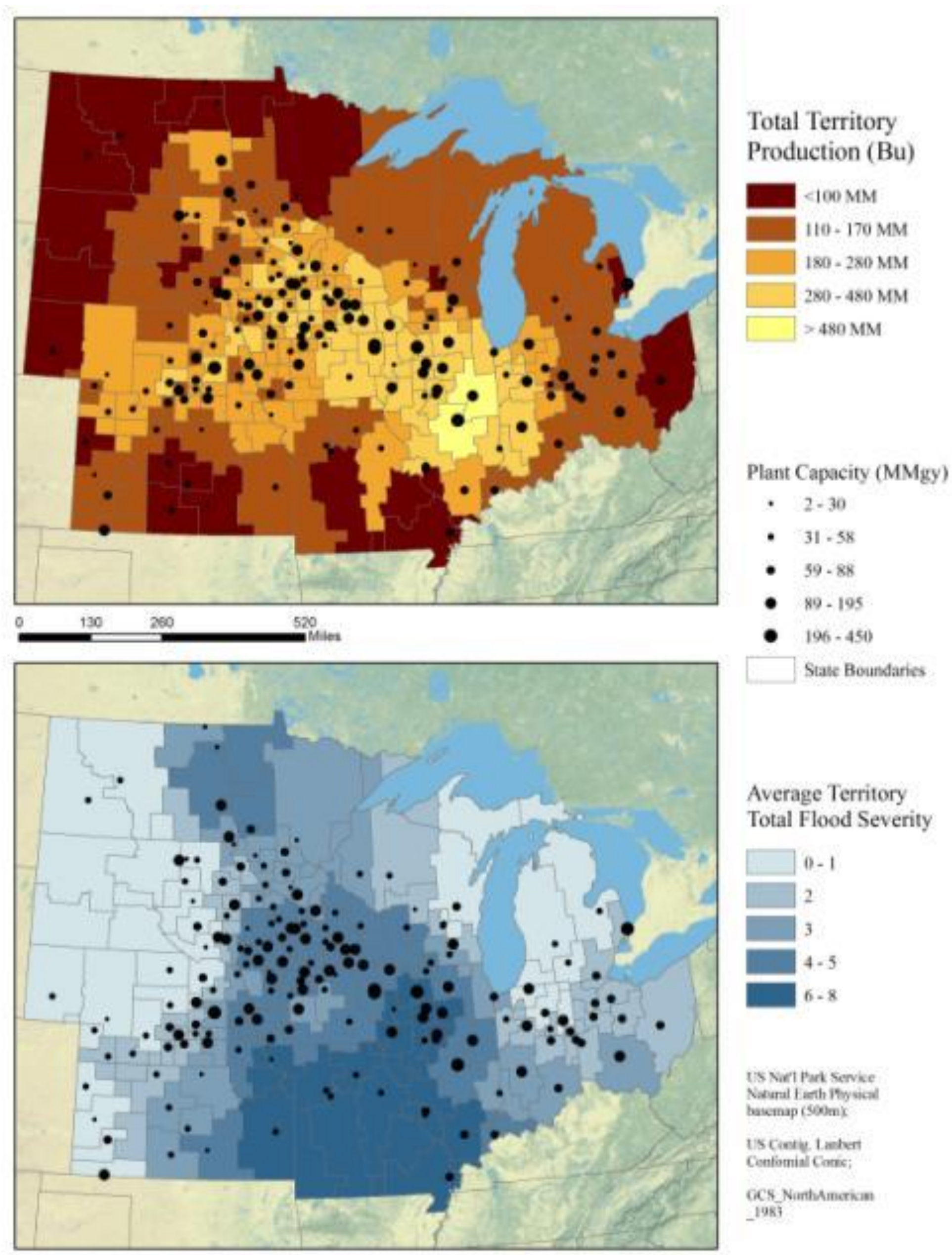

Figure 6. Summarized values by plant territory.

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When total flood severity by county is averaged within ethanol plant territory, the map shows territories in the south-central area of the study region, in Missouri, Kansas, and Illinois, to have the highest flood risk (Figure 6). If territories are grouped into deciles by average flood vulnerability, it is seen that over 50% of corn production occurs in the top 40% flood vulnerable territories (Figure 7).

3.4 Supply/Capacity Ratio and Risk Index

When the ratio of total territory corn production and ethanol capacity is mapped for each plant, the plants with the highest ratio are Kansas Ethanol and White Energy Russell (KS), Red Trail Energy (ND), and Suncor St. Clair (MI) (Figure 8). These four plants comprise 555 MMgy of ethanol capacity.

When flood vulnerability is considered and a Risk Index is calculated, the plants with the highest index are Suncor St. Clair (MI), Center Ethanol (MO), and Penfor Products (IA). These three plants comprise 900 MMgy of capacity.

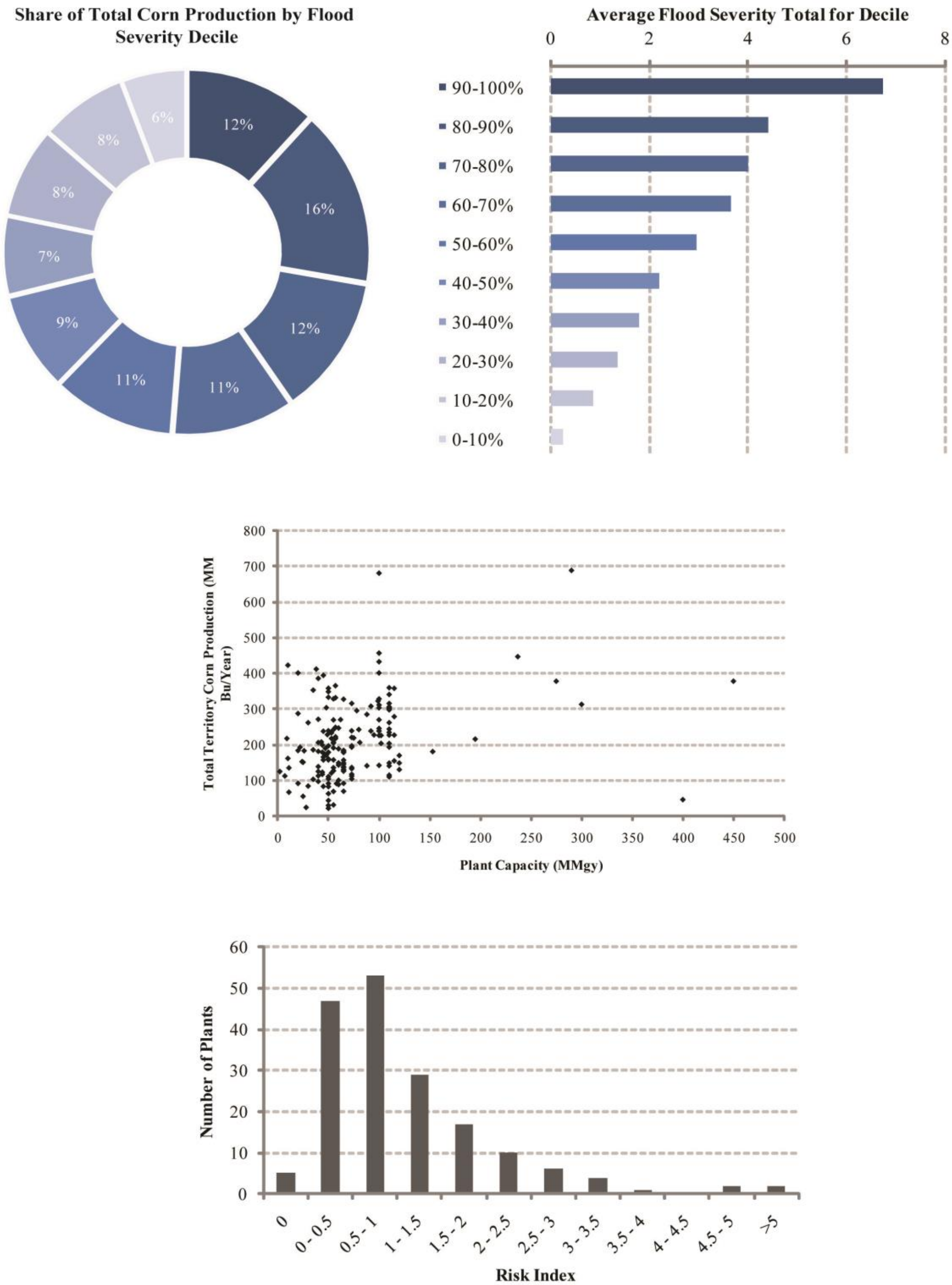

Figure 7. Summary measurements for study region.

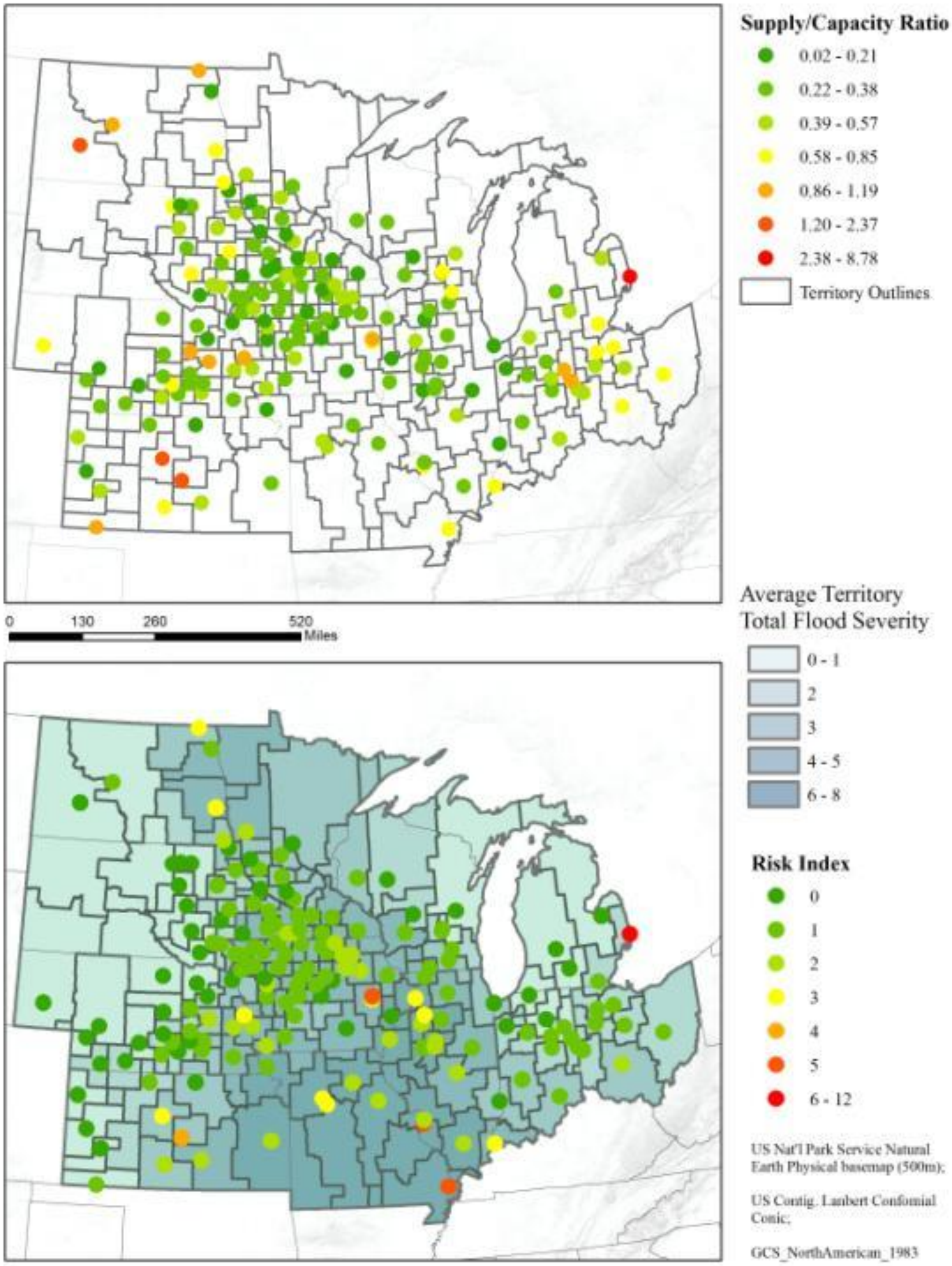

Figure 8. Maps showing the supply/capacity ratio and the Risk Index for each plant.

4 DISCUSSION

4.1 Corn Production Hot Spot Maps

A comparison of ethanol plant locations and a hot-spot map of corn production by county suggests a concentration of processing plants in the counties where the most corn is grown. This co-occurrence highlights the usefulness of examining the support base of ethanol plants through territory delineation.

4.2 Flood Vulnerability Maps

The counties with highest vulnerability are located in peripheral areas of the study region. As we see that most ethanol plants are located in central areas of the study area, and that the territories of plants near the periphery of the study area tend to be larger, high flood vulnerability in areas such as Missouri and central Illinois may impact ethanol product elsewhere in those states due to plants' dispersed supply territory.

4.3 Ethanol Plant Territory Delineation

When territories are created for each plant, and the summary values of corn production and flood vulnerability are linked to plants, patterns emerge which are slightly different from what is suggested by a county-level map. Figure 5 reveals that the ethanol plants with the most productive territories are located in central Illinois, and suggests that the plant concentrations in Iowa, Nebraska, and southern Minnesota lead to less potential low-cost corn supply for these plants. Flooding vulnerability by territory reveals the most threatened areas to be in the south, central, and north areas of the study region, including high production territories in western Illinois and southeastern Iowa.

4.4 Supply/Capacity Ratio and Risk Index

The final Risk Index map suggest that flood risk to ethanol capacity varies along a smooth gradient within the study region, highest in the eastern Iowa, western Illinois area and least in peripheral areas such as western Kansas. However, we also see that the highest risks are affecting individual plants, which are sometime surrounded by plants with much lower Risk Index. Many of these individual high Risk Index plants appear to be situated along waterways prone to flooding. Overall data suggests that most of the corn production occurs in flood-vulnerable areas, but that this production does not appear overly concentrated in these areas.

5 CONCLUSIONS

When domestically produced, corn-based ethanol fuels are relied on as a stable source of energy it is important to examine potential risks to the production of such fuels, and potential chokepoints. Use of a summarized distance join to delineate supply territories for each ethanol plant in the Corn Belt states was a useful device to approximate the potential effect of long term flood vulnerability on ethanol production. Centrally located, high production areas of the study region were seen to be of higher risk, and certain plants, distributed throughout the study region, were seen to have exceptionally high risk to flooding. It is likely that in the event of floods these plants

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would access unharmed corn from more distant, unaffected areas, but the high cost associated with transport of supply corn would have implications for cost effective ethanol production at these locations.

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