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SPATIAL ANALYSIS OF TORNADO VULNERABILITY TRENDS IN OKLAHOMA AND NORTHERN TEXAS

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ABSTRACT

Determination of effective ways to reduce vulnerability from tornadoes is one of the fundamental drivers for tornado research. This study analyzes spatial vulnerability in the context of past tornado events with aims to enhance the understanding of tornado casualties in Oklahoma and Northern Texas. Many previous studies have provided insight on how individual factors influence tornado vulnerability. However, few studies have been conducted to evaluate the aggregated effect when these factors coincide. Additionally, a definition of vulnerability has been absent from the meteorological literature. Thus, to provide a more comprehensive view, this study proposes a mathematical definition for spatial vulnerability, and then uses tornado casualty data from 1950 through 2009 to calculate vulnerability on a county level for seven time periods. Overall vulnerability trends are then calculated and visualized by averaging changes and by k-means clustering. This study shows the existence of spatial patterns in vulnerability between counties both when analyzing each individual F-scale and when all F-scales are combined. These spatial patterns are likely caused by the existence of multiple variables working together.

1. INTRODUCTION

A key component of disaster research involves understanding vulnerability. Previous studies have provided much insight on identifying individual factors affecting vulnerability to tornado casualties. The false alarm rate (FAR) is one such factor. Simmons and Sutter (2009) noted tornadoes occurring in areas with a higher FAR tend to cause more death and injury than in areas with a lower FAR. For example, a one standard deviation increase in the FAR raised death rates between 12 and 29% and raised injury rates between 14 and 32%. Ashley (2007) identified several other variables contributing to vulnerability, including land cover, population density, and seasonality. Other studies have analyzed F-scale as a factor of vulnerability. Merrell et al. (2005) found an increase by one F-scale ranking raised expected fatalities by factors of seven or nine, depending on the model being examined. Finally, structure type, particularly mobile home density, has been analyzed as a factor contributing to vulnerability. Brooks and Doswell (2002) analyzed mobile home fatalities in the May 3, 1999 Oklahoma City tornado outbreak and compared with national trends, finding in both cases the likelihood of fatality to those in a mobile home is twenty times greater than to those in a permanent home.

Vulnerability has also been examined from a spatial perspective. In particular, past studies have identified the southern United States as a region prevalent in factors contributing to vulnerability to tornado casualties. Sims and Baumann (1972) analyzed the psychological mindsets of residents in the northern and southern U.S., using Illinois to represent the North and Alabama to represent the South. The results of this study find attitudes of fatalism and passivity to be prevalent in Alabama, which could help contribute to high tornado fatality rates in this region. Ashley (2007) also identified the American South as a region with high vulnerability to tornadoes. Ashley attributes high fatality rates in the South to the presence of many variables, such as mobile home density, seasonality, the time of day a tornado strikes, and resident attitudes. With the presence of these factors, Ashley argues, the South has a higher vulnerability than other areas of the country. In addition to identifying the spatial region of the South to be vulnerable to tornadoes, Borden et al. (2007) analyzed the vulnerability of cities to hazards, finding vulnerability to vary from location to location, thus highlighting the need for disaster preparation and management to vary over spatial regions.

Though these previous studies have provided much insight into factors contributing to tornado vulnerability, much work still needs to be done in understanding this complex topic. In particular, a solid definition of

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vulnerability is currently absent from the meteorological literature. Frequently, vulnerability is subjective and has a different meaning depending on the context it is used in (Cutter 1996). Cutter and Finch (2008) attest to the complexity of vulnerability. Often, they say, the exact meaning of vulnerability differs between disciplines. Within the meteorological community, a commonly accepted definition of vulnerability appears to be missing.

Additionally, a more comprehensive approach of vulnerability needs to be taken in the meteorological community. Though previous studies have provided much insight into analyzing individual factors contributing to vulnerability, few studies have been conducted to evaluate the effects when these factors coincide. A study by Merrell, Simmons, and Sutter (2005) provides one example of the need to consider a more holistic vulnerability approach. In the study, a model was developed incorporating tornado intensity, population density, income, housing type, time of day, tornado season, and time trend to calculate potential tornado casualties and thereby evaluate the benefits of constructing tornado shelters. As this study shows, several factors together often elevate the potential for harm during disaster. As another example, Hall and Ashley (2008) outline a scenario where several factors could coincide in the event of a tornado outbreak in the Chicago area. The study finds high vulnerability to tornadoes for minorities living in newly developed areas, describing the factors of high population density, weaker housing types, and racial background of the minorities living in these areas as all contributing to a lessened ability to respond in disaster. Phillips and Morrow (2007) share similar viewpoints, stating it is often difficult to separate one population attribute from another in disaster research. These authors cite race as an example of this, calling on the need for race to be coalesced with other factors like gender, income, and family structures.

In light of these weaknesses, this study seeks to provide a more comprehensive view on vulnerability. In particular, changes in spatial vulnerability are analyzed over Oklahoma and parts of Texas from 1950-2009. A definition of vulnerability is proposed in order to provide an index with which to measure the overall aggregated effects of factors contributing to vulnerability. Then, after calculating changes in spatial vulnerability, an analysis of possible factors contributing to these changes is presented.

2. SPATIAL VULNERABILITY EXPLANATION

Spatial vulnerability can be thought of as the ease to which one place can be harmed by tornadoes compared to other places. Changes in the vulnerability of different spaces between time periods can be analyzed to determine overall vulnerability trends. However, before any vulnerability trends can be analyzed, it is important to define vulnerability mathematically.

2.1 *Definition of Spatial Vulnerability*

Previous meteorological studies have looked at vulnerability in terms of risk and hazard. According to Cutter (1996), risk can be looked at in terms of hazard and vulnerability. In other words,

$$Risk = Hazard * Vulnerability \qquad (1)$$

Outside the meteorological realm, risk has been defined in terms of assets and threats (Independent Security Consulting 2010; Federal Emergency Management Agency 2010). Specifically, risk is found by multiplying together a unit's assets, threats, and vulnerability. This multiplication can be rearranged to show:

$$Vulnerability = \frac{Risk}{Assets * Threats} \qquad (2)$$

Incorporating (1), a hazard is seen to include assets and threats.

In order to define spatial vulnerability, various attributes of any particular space are incorporated into equation (2). In this study, any particular tornado constitutes the threat. Since threat relates to hazard, it should be understood what constitutes a greater or lesser hazard. By intuition, it makes sense that more assets in a place with the same threat create a greater hazard. Assets can be thought of in terms of people. If more people live in one space, and more tornadoes go through that same space, the hazard must be greater. Hazard is therefore defined to be the number of people multiplied by the number of tornadoes, meaning population is the asset. If assets are defined to be population, a greater number of people means more assets, which intuitively makes sense. Casualties are assumed to be a direct indicator of the vulnerability of a particular place, where any casualties from each tornado in a given spatial unit resulted from tornadoes taking advantage of the vulnerabilities present there. It makes sense to measure vulnerability over spatial units with the same extent, so risk must normalize for differing place sizes.

Using the preceding discussion and incorporating into equation (2), the vulnerability of a particular spatial unit to a tornado in a particular time period is defined as:

$$Vulnerability = \frac{Casualties}{Area * Population * Tornadoes} \qquad (3)$$

Casualties refers to the total casualties in a space in a time period, area refers to the geographical extent of the space, population refers to the total population of a particular space in a particular time period, and tornadoes refers to the total number of tornadoes during the time period. Alternatively, (3) can also be seen as:

$$Vulnerability = \frac{\left(\frac{\left(\frac{Casualties}{Population}\right)}{Area}\right)}{Tornadoes} \qquad (4)$$

In other words, for any particular tornado, the vulnerability of a spatial unit to that tornado is measured by the number of casualties occurring per population in a given area of space.

2.2 Explanation of Definition

The preceding definition is an indicator of the vulnerability of any spatial unit, with all vulnerability factors implicitly incorporated into the equation. The definition does not serve to test the degree to which individual factors, like population density or structure type for example, change the vulnerability of a particular space. Rather, it serves to show vulnerability at a particular time with all factors contributing to that vulnerability incorporated.

The preceding definition can look at a location's vulnerability to a tornado of any F-scale. By incorporating the total casualties caused by all tornado intensities, as well as including the total number of tornadoes, a composite vulnerability encompassing all F-scales can be obtained. Additionally, because it makes sense that each F-scale tornado ranking affects vulnerability differently, tornadoes can be separated based on their intensity to allow the definition to show the vulnerability of a place to any particular tornado of a certain F-scale.

2.3 Sensibility of Definition

To see why the preceding definition makes sense, the vulnerability of a place can be analyzed by changing one variable in the equation while holding all other variables constant. If two spaces have the same area, same population, and same number of tornadoes, the location with the higher number of casualties should be the more vulnerable place. This holds with the previous assumption of casualties being an indicator of vulnerability. In looking at area, a spatial unit with a greater area, all else being the same, should face a lower vulnerability to any particular tornado, because one tornado is more likely to cause greater harm to a smaller place than to a larger one. When population is seen with casualties, population should be indirectly related to vulnerability. In the definition, population is an attribute of a particular place. Thus, any changes in population will reflect changes in the vulnerability of the place, even though population totals may not necessarily be factors contributing to the place's vulnerability. If the population of a county increases while a tornado still causes the same number of casualties as before, the vulnerability of the county must decrease. In analyzing the number of tornadoes, if more tornadoes occur in a place with the same area, population, and casualties as another place, the vulnerability of the place to any one particular tornado is diminished.

3. METHODOLOGY

Using the previous definition of spatial vulnerability, this study calculates vulnerability over seven time periods for each spatial unit in the study area. Using the changes in vulnerability over each time period, an average vulnerability trend is calculated and visualized. A k-means analysis using the vulnerability changes is also completed, the results of which are also visualized.

3.1 Overview of Methods

A casualty from a tornado is defined to be the sum of the injuries and fatalities caused by that tornado. Additionally, the spatial analysis for this study is on the county level. The individual spatial units are therefore defined to be the counties in the study area.

The period from 1950 to 2009 was chosen for this study since the database containing tornado information

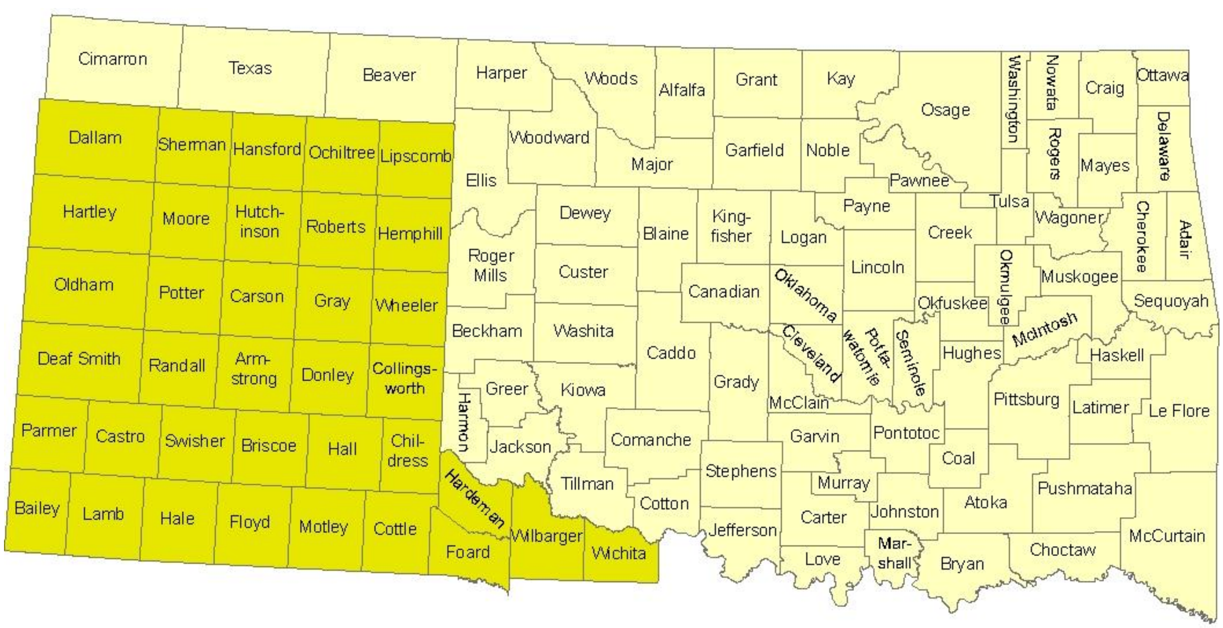

Fig. 1 – The study area and county names, with Oklahoma counties in light shading and Texas counties in dark shading

applied only to those years. Additionally, the study area was chosen to be the region of the U.S. encompassing the state of Oklahoma and thirty-six counties in Texas including the panhandle and other parts of northern Texas (Figure 1). This study area was chosen:

1) due to the large number of tornadoes occurring in this area since 1950, and
2) since no counties in the area had ever changed boundaries during the study time, which would thereby not change the areas when the vulnerability definition was applied.

3.2 Data Preparation

Using data from the National Historical Geographic Information System, population totals were compiled for each county in the study area from each U.S. census from 1970 through 2000 (Minnesota 2004). Additionally, 1950 and 1960 population counts (Forstall 1995) and 2009 population estimates (U.S. Census Bureau Population Division 2010) for each county were obtained from the U.S. Census Bureau. Shapefiles of tornado tracks containing fatality and injury counts per tornado were downloaded from the Storm Prediction Center (SPC) (Smith 2006, Smith 2010) and filtered to include only the tornadoes within the study area. These tornadoes were then further filtered based on the time period in which they occurred to match each tornado with the nearest population data. Table 1 shows the time periods each tornado was assigned to.

Using a Geographic Information System (GIS), information was then obtained for each county's area and total casualties that occurred in each county during each time period. Since the definition requires the total number of casualties in each county to be found, and since a great number of tornadoes in each study period crossed county lines, an approximate number of casualties in each county for each tornado was determined by proportioning the casualties according to the length of the tornado track in each county. The above process was then repeated for each individual F-scale in order to calculate vulnerabilities compositely and for each tornado intensity.

Some tornadoes were listed in the SPC database as having an unknown F-scale. These tornadoes were excluded from the individual F-scale analyses but were included in the composite analysis. None of the tornadoes with an unknown F-scale caused any casualties.

Vulnerability calculations were then completed at the county level for each of the seven time periods. Because the resulting vulnerability values were extremely small, they were scaled by a factor of 10^9 to give more manageable values. As implied by the vulnerability definition, a problem arose if a county had no tornado occurrences during a time period. In these cases, vulnerability was defined to be zero. This is reasonable, since if no tornado threat occurred, the potential for a county to be harmed by a threat was nonexistent.

3.3 Data Analysis

Because this study looks at the changes in vulnerability over time, the differences between scaled vulnerabilities between each time period for each F-scale and compositely were calculated. To determine the overall vulnerability trend for each county, these changes were averaged. Visualization of the averages using GIS showed whether or not the overall trend was positive, negative, or very nearly zero. The spatial patterns of the average vulnerability increases and decreases were then analyzed. Additionally, interpretation of vulnerability changes between time periods was difficult due to much variation in the calculated values. Thus, k-means analyses were used to identify counties with similar changes in vulnerability over time. The k-means analysis clustered counties together with similar vulnerability changes over time. After the clusters were visualized, their distribution was analyzed to determine the spatial patterns of counties within each cluster.

4. RESULTS

Figure 2 shows the composite average trend in vulnerability of the study area. It should be noted only the counties of Cimarron, OK, Woodward, OK, and Hartley, TX truly had no change in vulnerability. This resulted because these were the only counties in the study area with no casualties during any of the seven time periods. The rest of the counties portrayed as "no change" in Figure 2 had average vulnerability changes very close to zero. As the figure shows, the majority of counties in the central portion of the study area have decreased in vulnerability. Patterns also exist for the counties showing increased vulnerability, with northeastern Oklahoma being one noticeable region of increase.

Figures 3 through 6 show the average trend for F1 through F4 tornadoes respectively. With any of these F-scales, distinct patterns of both increased and decreased vulnerabilities appeared. All counties in the study area showed no overall change in vulnerability to F0 tornadoes. This can be explained by the minimal number of casualties caused by these types of tornadoes. Only in a rare event did a F0 tornado cause injury or death. If a county did experience casualties with these types of tornadoes, no casualties occurred in that county during the next time period, allowing for zero average vulnerability. Similar results occurred for F5 tornadoes. Though many F5 events caused large numbers of casualties during the study period, any county experiencing F5 tornadoes during one time period did not experience any during the next period

Time period when the tornado occurred	1950-1954	1955-1964	1965-1974	1975-1984	1985-1994	1995-2004	2005-2009
Census the tornado was assigned to	1950	1960	1970	1980	1990	2000	2009

Table 1: Assignments of each tornado to the nearest census.

due to the rarity of these catastrophic events. Thus, F5 vulnerability changes averaged to zero in all counties.

The visualizations for the F0, F1, and F2 k-means analyses (Figs. 7-9) showed strong spatial patterns, with counties in the same cluster being located in the same region. Additionally, the F3 k-means (Fig. 10) showed some regionalization between clusters, but also showed many counties in the same clusters being widespread over the study area. In the case of F4 k-means (Fig. 11), different counties in the same cluster were widespread over the study area. In the F5 analysis (Fig. 12), Childress County, TX was the only county clustered differently than the rest.

5. DISCUSSION

A large number of factors, many perhaps not even known, contribute to the overall vulnerability of a county to a tornado. When these factors coincide, vulnerability can be either enhanced or diminished, depending on the factors themselves. Thus, a number of possibilities are proposed regarding how certain factors may coincide to produce this study's vulnerability trends. The ideas given in this section theorizing these underlying factors have not been shown scientifically. Rather, the hypotheses presented here are open for interpretation and future study.

5.1 Population and Media

Population density and media focus are two such factors this study shows may coincide. In the composite average vulnerability trend (Fig. 2), a large portion of the counties with a decrease in vulnerability are observed to occur in the central and southwestern parts of Oklahoma. These areas of decrease contain the densely populated areas of Oklahoma City and its surrounding suburbs located in Oklahoma County, Lawton in Comanche County, and Wichita Falls in Wichita County. Greater vulnerability would be expected to result in these areas from the potential of higher casualties when a tornado event occurs there. However, this is not what is seen in the cases of these three counties, meaning factors other than population density may contribute to the overall vulnerability of these regions.

These increased vulnerability trends may be attributed to a potential media coverage increase in these areas. In a community with a high population density, media presence and focus will naturally be greater. Because of higher populations, should a threat occur in the nearby area, media have a greater sense of urgency to alert those in the path of a storm. With the counties around Oklahoma, Comanche, and Wichita counties, decreased vulnerability may be explained by the proximity these neighboring counties share to highly populated areas. With metropolitan centers nearby, the likelihood a person in the surrounding areas will receive notification of a tornado threat increases, helping decrease vulnerability. The effect media coverage may have on vulnerability may also be seen by comparing the composite average vulnerability trends between Oklahoma and Texas. With more population centers in Oklahoma than in the Texas study area, the likelihood of people hearing the warning and responding is increased in Oklahoma rather than Texas.

The preceding prediction can also be shown by comparing average vulnerability trends between F-scales. In the F3 and F4 average vulnerability maps (Figs. 5 and 6), vulnerabilities decrease in the areas around Comanche and Wichita counties. The same holds true with the F2 and F4 maps (Figs. 4 and 6) in the areas around Oklahoma County as well as with the F3 average vulnerability trend in the area around Potter County, TX, which contains the large city of Amarillo. These cases point to the role the media may play in decreasing vulnerability around metropolitan areas.

Unfortunately, meteorological literature has had little focus on the changes in media coverage for disaster events between differing population densities, let alone for tornadoes. Thus, the hypotheses here are unverified and provide a case for future study.

5.2 Population Bias of Urban Areas

Even though the average vulnerability maps show a decreasing vulnerability trend within specific areas in Oklahoma and Texas, a portion of this trend may be attributed to population biases. Brotzge and Erickson (2010) analyzed tornadoes not warned on by the National Weather Service (NWS). Their study associates an increased population density with a smaller percentage of tornadoes warned on. The authors explain this decrease in tornado warnings with an increase in reports. With more people in an area, they say, the likelihood of a tornado being reported will increase. Thus, many tornadoes not warned on by the NWS are reported by the public, causing an apparent increase in the number of unwarned tornadoes as population density increases. This can play an important role in contributing to decreased vulnerability trends in Oklahoma County (Fig. 2). According to this study's population data, Oklahoma County has increased in population from 1950 to 2009. Thus, with population increases comes a greater possibility of tornado reports in these areas. In this study's vulnerability definition, the number of tornadoes indirectly relates to vulnerability. Thus, with the potential for more tornado reports as time progresses, vulnerability will naturally decline.

Though population bias may play a role in Oklahoma County, it may not hold true for all other areas. Tulsa County, containing the metropolitan area of Tulsa, OK, has also increased in population over the study period. However, Tulsa is reported in the average composite map (Fig. 2) as well as in the F1 and F2 averages (Figs. 3 and 4) as having increased vulnerability. Thus, since two areas of increased population show differing trends, the role population bias may play in vulnerability trends is unclear.

5.3 Media, NWS, and Spatial Factors

The role of the National Weather Service and media can be further analyzed using k-means analyses. K-means compare similarity in trends, with counties in the same cluster having similar up-and-down changes in vulnerability. By mapping k-means clusters, the role the NWS may play in determining vulnerability on either a regional or local level can be determined. When comparing the F4 and F5 k-means clusters (Figs. 11 and 12), clusters are shown to be widely spread. Any deviations in vulnerability trends over time are highly localized in the F4 and F5 maps, with counties in the same cluster of the F4 map being widespread over the study area. However, when the k-means maps are analyzed for F0, F1, and F2 tornadoes (Figs. 7-9), strong spatial correlations are found. Clusters in these maps are regionalized rather than localized, with counties deviating from the majority sharing a border with each other. This may be explained by the differences in NWS warnings on weak and strong tornadoes. Brotzge and Erickson (2010) find the likelihood of a tornado being warned on increases with greater tornado intensity. Their study finds tornadoes with greater than F1 strength had nearly half the ratio of unwarned tornadoes when compared to F0 and F1 intensities. If less intense tornadoes have a diminished likelihood of being warned on, individuals over a larger area may be less informed about these events when they occur. Thus, the impacts on vulnerability of these less intense storms will be shown over a larger area, causing counties clustered together in a k-means analysis to be within the same region. On the other hand, if more intense tornadoes have a greater likelihood of being warned on by the NWS, people over a larger area may be more likely to receive notification of a warning. Thus, any deviations in trend patterns of more intense tornadoes are expected to be spread, as the F4 k-means analysis shows (Fig. 11). Rather than tornadoes impacting vulnerability over a larger region, any deviations in vulnerability trends will be due to local factors. The same holds true with the F5 k-means map (Fig. 12). Childress County, TX in this map is clustered differently than all other counties, implying factors solely within this county cause it to be clustered differently. As a way to justify these predictions, the F3 k-means can be analyzed (Fig. 10). If these hypotheses hold true, a transition should occur in the F3 analysis to bridge the gap between the regional F2 clusters and the localized F4 clusters. In the F3 k-means, a regional cluster of counties appears in the southwest portion of the study area, while localized clusters are spread throughout other regions. Since both regionalization and localization occur in the F3 k-means, this provides the necessary transition.

This study's k-means patterns may also be explained by media coverage. If the likelihood of media coverage of a tornado event can be found to increase with greater tornado intensity, k-means vulnerability analyses may appear similar as they do in this study. Greater media coverage of tornado events may lead to more people over a wider area being informed, making any changes in vulnerability trends stand out more prominently on a local level. This may also be shown by the average vulnerability trends of Tulsa. As shown in Figures 3 and 4, the vulnerability of the area in and around Tulsa County increases in F1 and F2 tornadoes. If the media does have a greater sense of urgency during more intense events, when less-intense events occur in highly populated areas, other vulnerability factors may be left open for tornadoes to exploit.

5.4 Structure Type and Population

Though the media and NWS may be used to explain vulnerability trends in certain regions of the study area, different factors should be considered in other areas. For example, on the composite average vulnerability map (Fig. 2), while the highly populated counties of Oklahoma, Comanche, and Wichita have decreased overall in vulnerability, Tulsa and Potter counties, also highly populated, overall have had vulnerability increases. The media can certainly have an influence on these areas as well. But because these areas have a visible media presence due to their high populations, other undetermined factors are likely contributing to their vulnerability trends. Structure type and population may be two factors working to produce the trends in these regions. If the highly populated areas of Tulsa and Amarillo have older structures or a greater density of mobile homes, the greater population in these areas may be left more vulnerable to harm. Southern Oklahoma may also be a region where structure type plays an important role in vulnerability. While a cluster of counties in southern Oklahoma shows decreased vulnerability in the F2 and F3 average vulnerability maps (Figs. 4 and 5), the same area increased vulnerability in the F4 average (Fig. 6). Perhaps this indicates an area with strong structure types, with the structures in this area able to withstand tornadoes of a lower intensity but not of a greater intensity.

5.5 Land Cover

When combined with other factors, land cover may be a potential factor contributing to vulnerability. As indicated in the composite average map (Fig. 2), vulnerability in northeast Oklahoma shows an overall increase. The vulnerability here has also increased to some extent in each of the four applicable F-scales (Figs. 3-6). Thus, there must be some regional factor in this area contributing to the observed vulnerability trends. Because a much greater cover of trees exists in the eastern part of Oklahoma compared to the west, land cover could be one factor adding to the vulnerability of this area, since greater land cover could lead to more people not being able to see a tornado. If land cover can help explain this region's vulnerability trends, it likely combines with other variables to produce the overall increased vulnerability trends. Ashley (2007) suggests the presence of vegetation may not be significant in increasing vulnerability in the southern U.S. If this holds true for northeast Oklahoma as well, unknown factors must be present in this area to account for the observed vulnerability increases.

6. IMPROVEMENTS AND FUTURE

Several improvements can be made to further this study. As previously mentioned, future work can focus on the role of media in contributing to vulnerability. Other hypotheses presented in this study can be tested as well. Future work can focus outside the Oklahoma and Texas study area to incorporate a larger area of the United States, giving vulnerability insights across a greater extent. Additionally, this study assumes casualties to be proportional to tornado length. A more rigorous study could look at each county's distribution of communities compared with the track of tornadoes through the county to determine casualty numbers for any tornado crossing county boundaries. Also, rather than solely using population numbers from decade census counts to determine vulnerability over five or ten year periods, population estimates for each year can be used to determine trends on a yearly basis. Finally, mathematically calculating vulnerability may not be appropriate in every situation. According to Kelman et al. (2009), an understanding of vulnerability is not always quantitative. Rather, qualitative and subjective analyses could be included in future studies. Additionally, vulnerability is contextual, with a county's vulnerability depending on each specific threat situation. Thus, a more thorough analysis can be completed accounting for vulnerability differences in the midst of different tornado events.

7. CONCLUSION

This study analyzes changes in vulnerability on a county basis. Previous studies on vulnerability have been wide ranging, with the context of vulnerability changing between studies. Thus, this study proposes a definition of vulnerability to encompass all factors contributing to the vulnerability of a spatial region. Results show strong spatial patterns in vulnerability trends between regions. When analyzing the average change in vulnerability, groupings of increase and decrease appear around large metropolitan areas compositely and in each F-scale. K-means analysis reveals a decrease in F-scale is associated with regionalization patterns of counties in the same cluster. Reasons for these patterns are not clear and are likely due to the presence of many undetermined factors.

8. ACKNOWLEDGEMENTS

This work was prepared by the authors with funding provided by National Science Foundation Grant No. ATM-0648566. The statements, findings, conclusions, and recommendations stated in this study are solely those of the authors and do not necessarily reflect the views of the National Science Foundation.

The authors wish to thank those who assisted in forming a definition of spatial vulnerability: Dr. Harold Brooks, Ms. Daphne LaDue, and many of those affiliated with the Center for Spatial Analysis.

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10. APPENDIX

Average Vulnerability Trends – Figures 2–6:

In these maps, the darker shade (red-orange) represents an overall vulnerability increase and lighter shade (light green) represents an overall vulnerability decrease. Counties in white had no overall change in vulnerability.

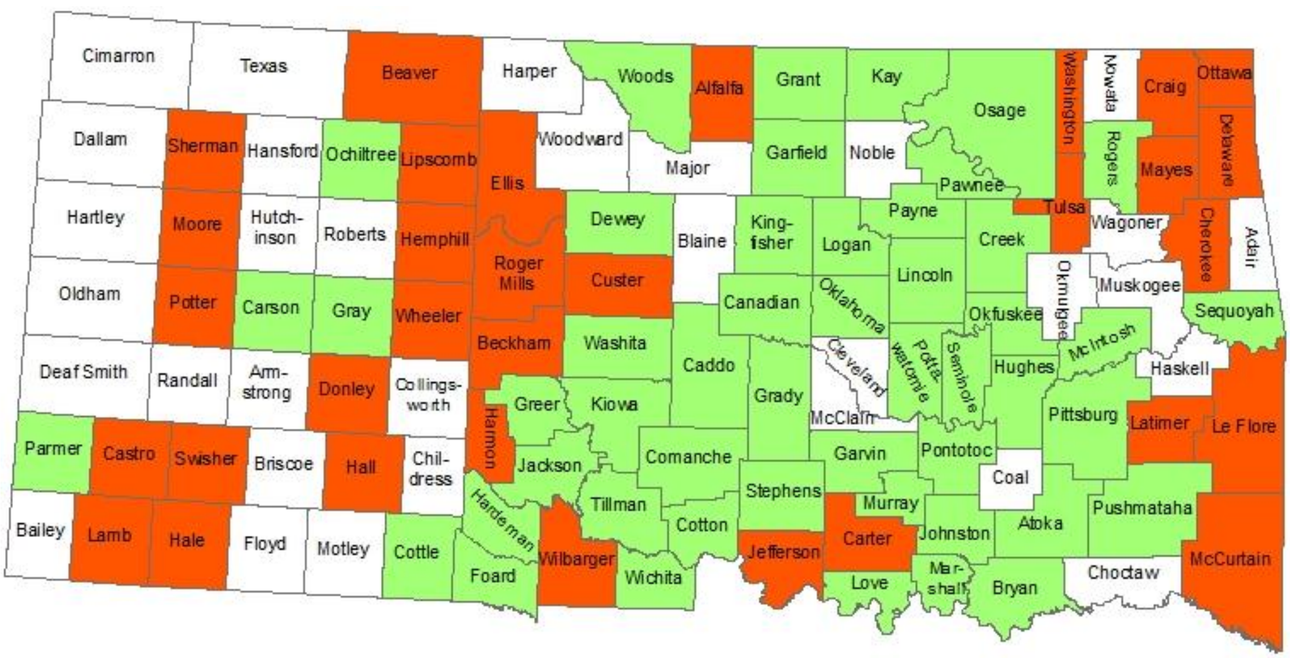

Fig. 2 – Composite average vulnerability trends

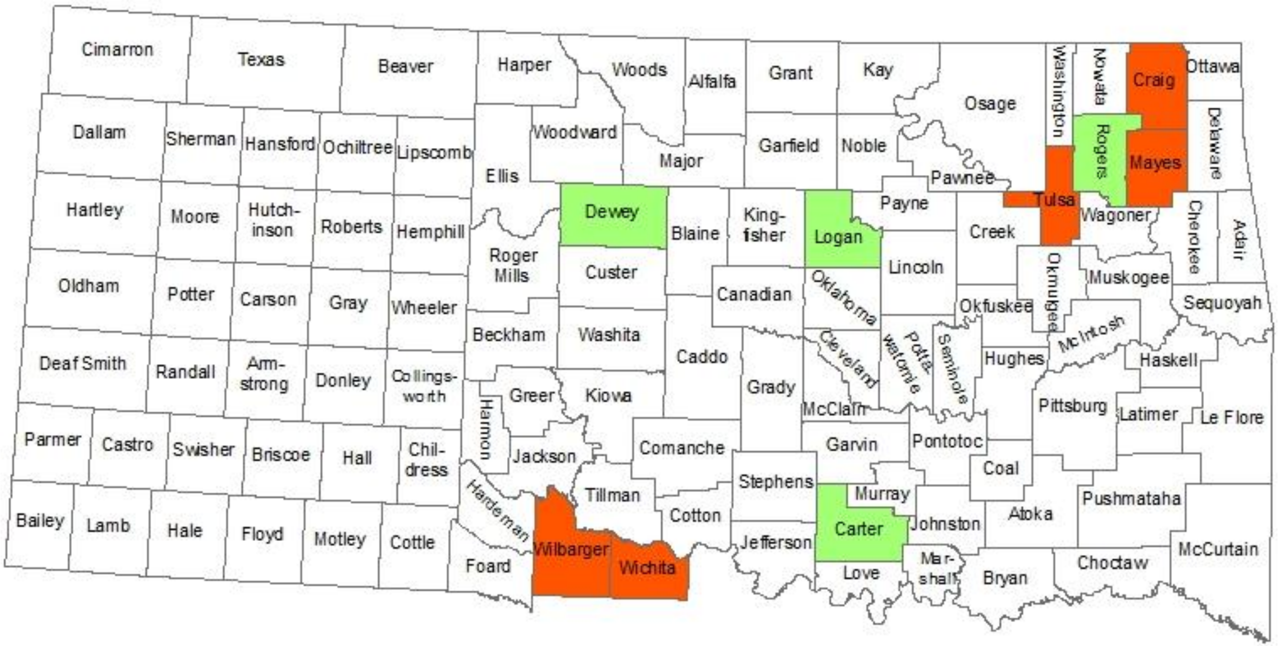

Fig. 3 – F1 average vulnerability trends

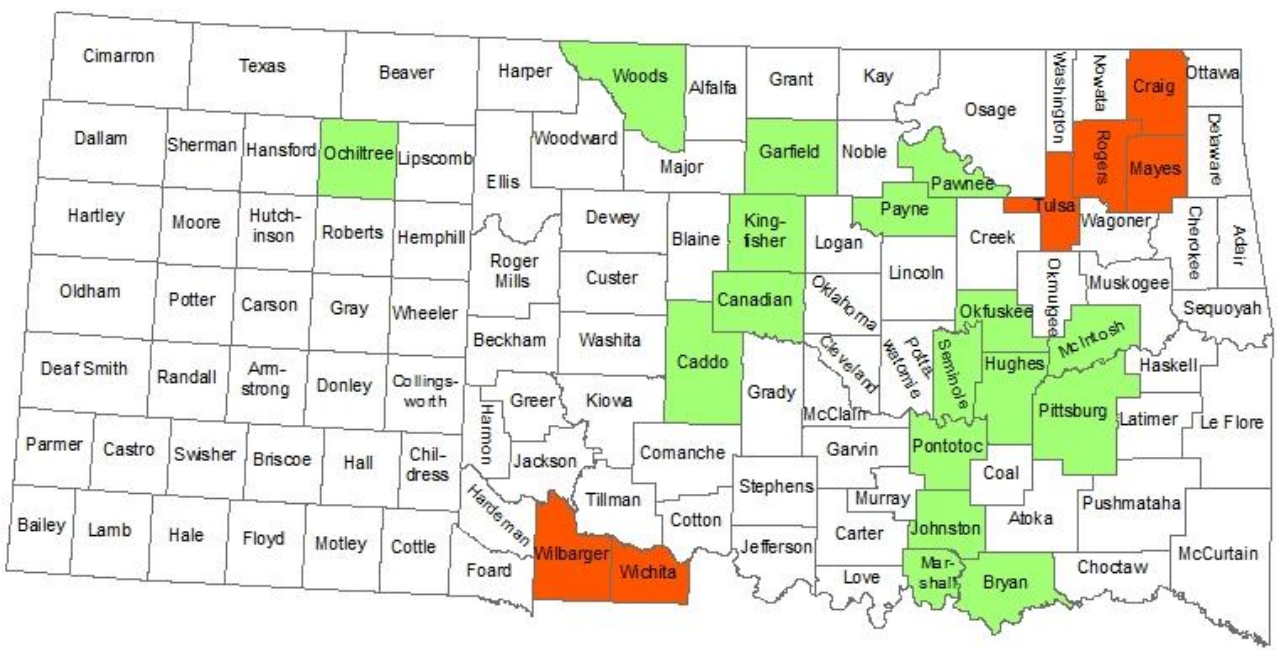

Fig. 4 – F2 average vulnerability trends

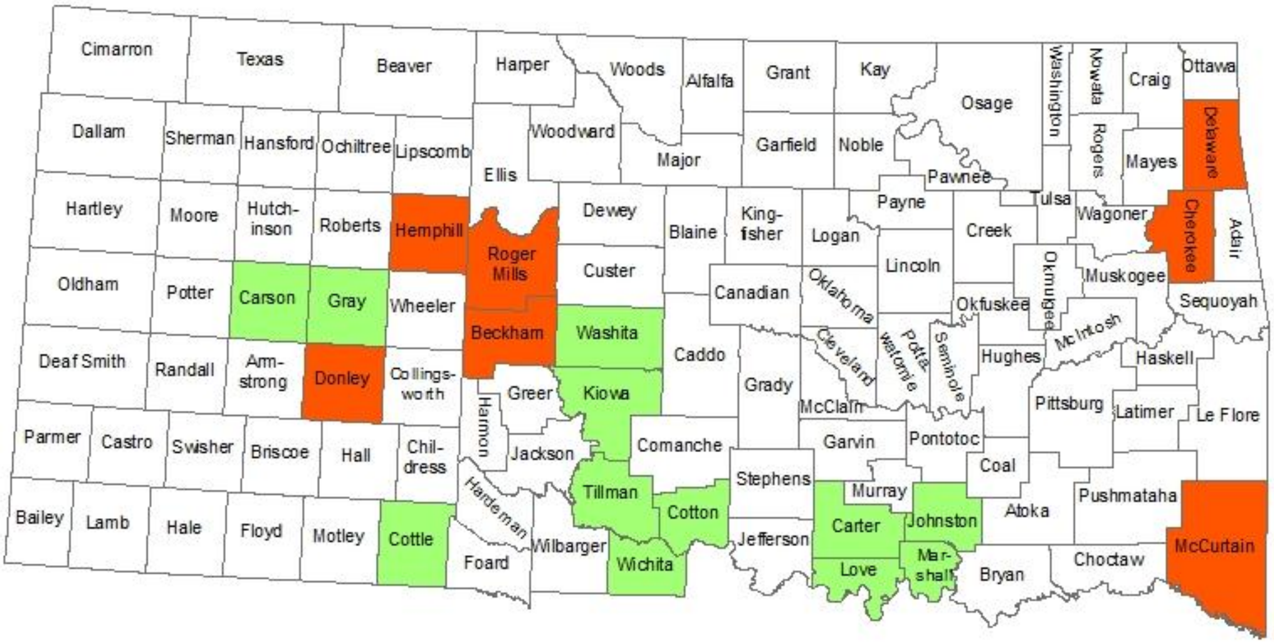

Fig. 5 – F3 average vulnerability trends

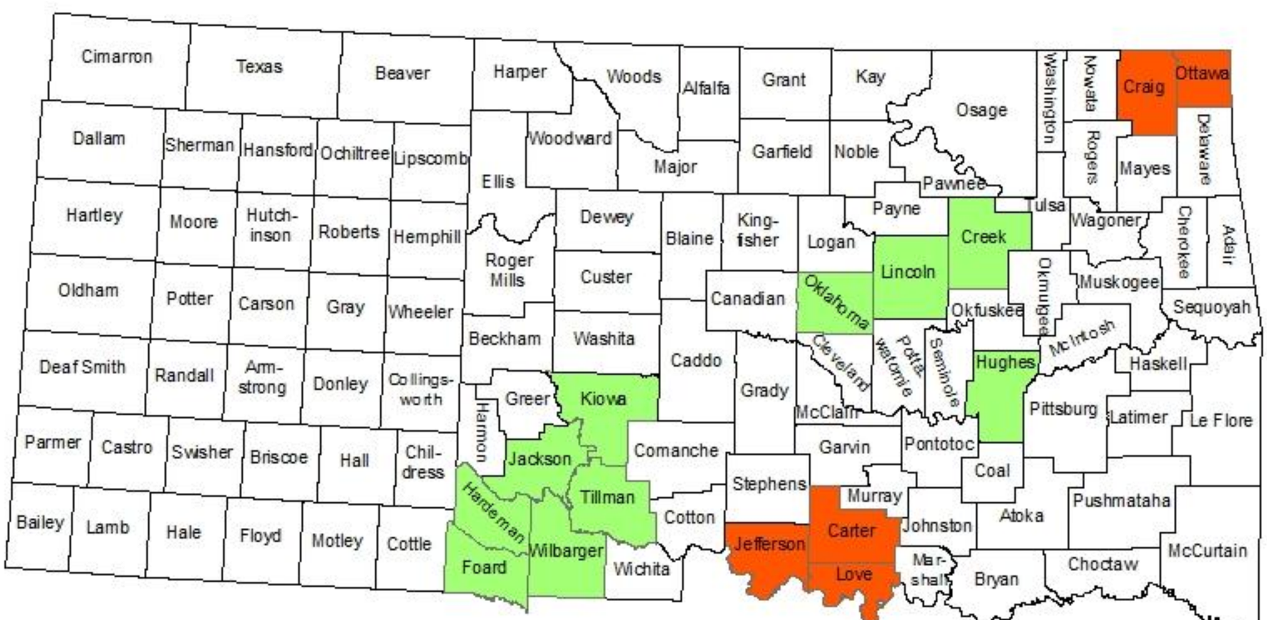

Fig. 6 – F4 average vulnerability trends

K-Means Clustering – Figures 7–12:
In these maps, counties with the same coloring are a part of the same cluster. Counties in the same cluster show similar changes in vulnerability over the seven time periods.

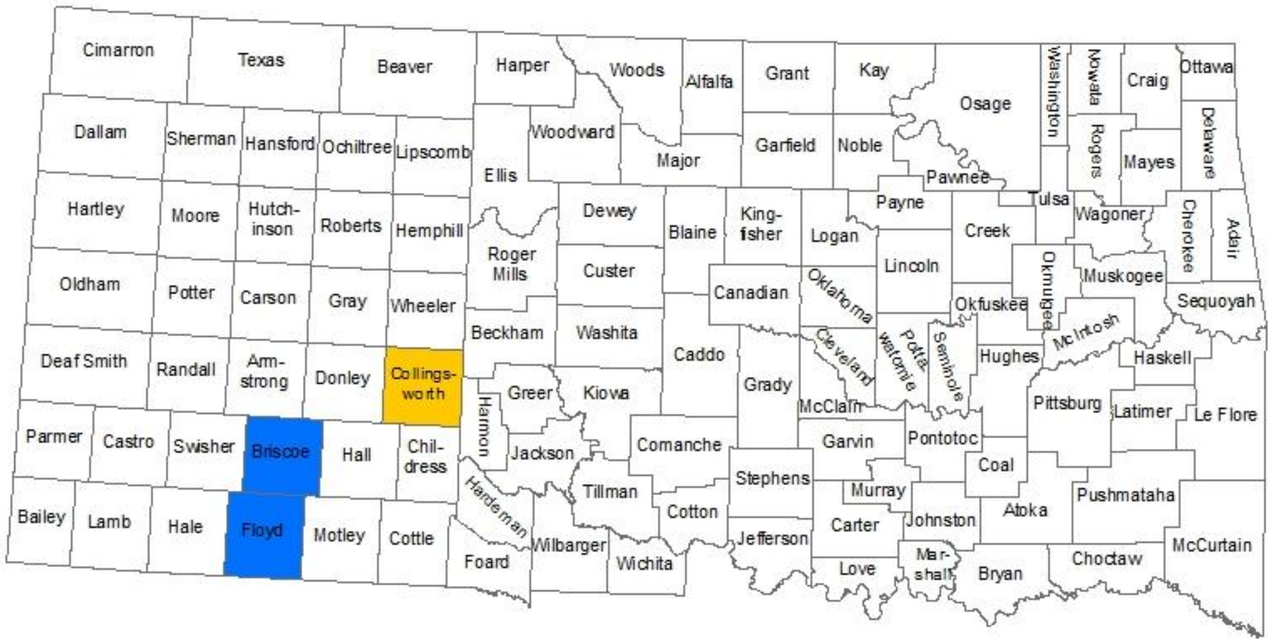

Fig. 7 – F0 K-means clusters

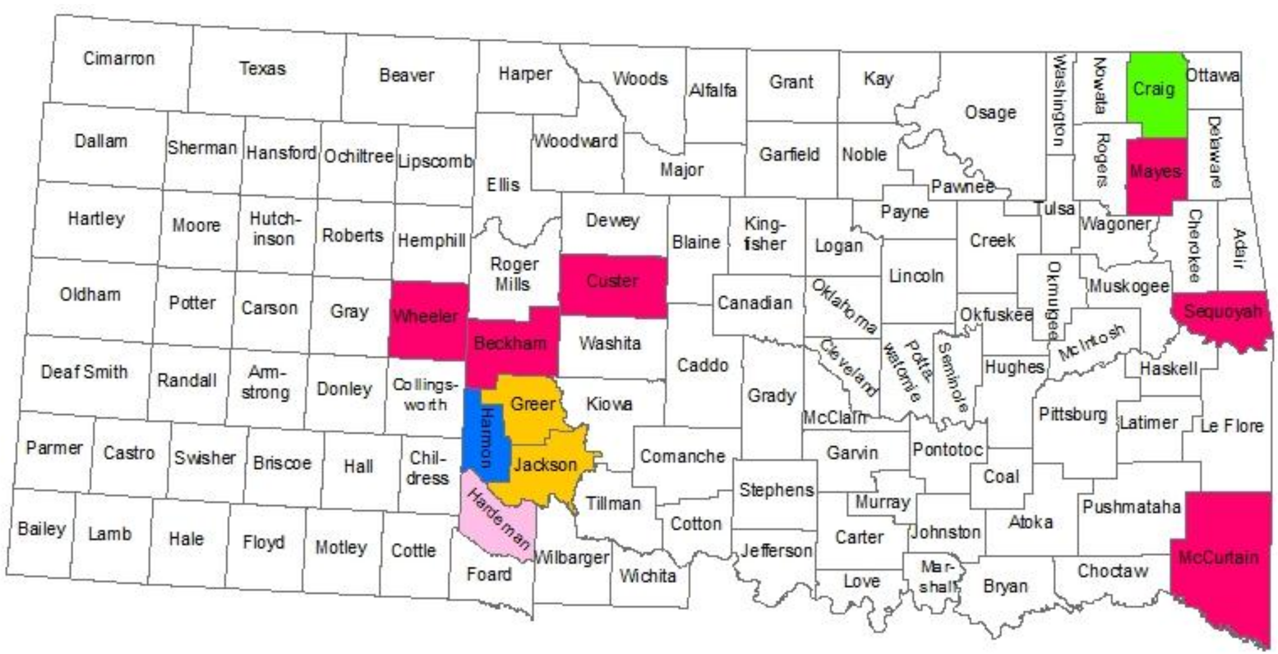

Fig. 8 – F1 K-means clusters

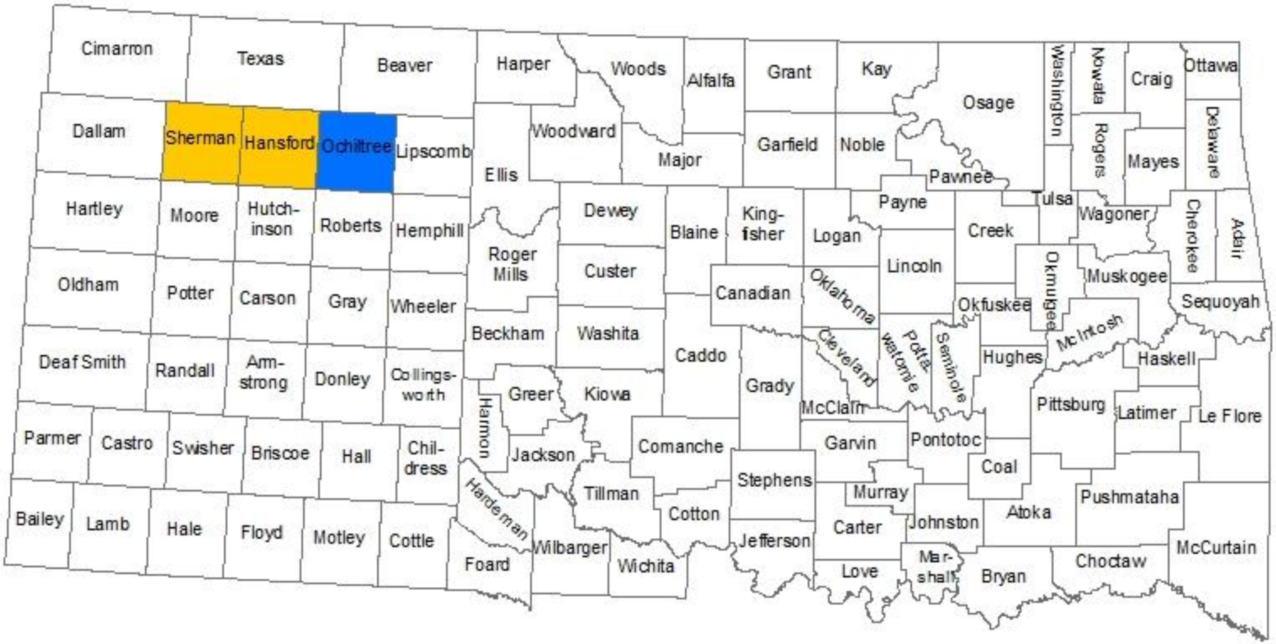

Fig. 9 – F2 K-means clusters

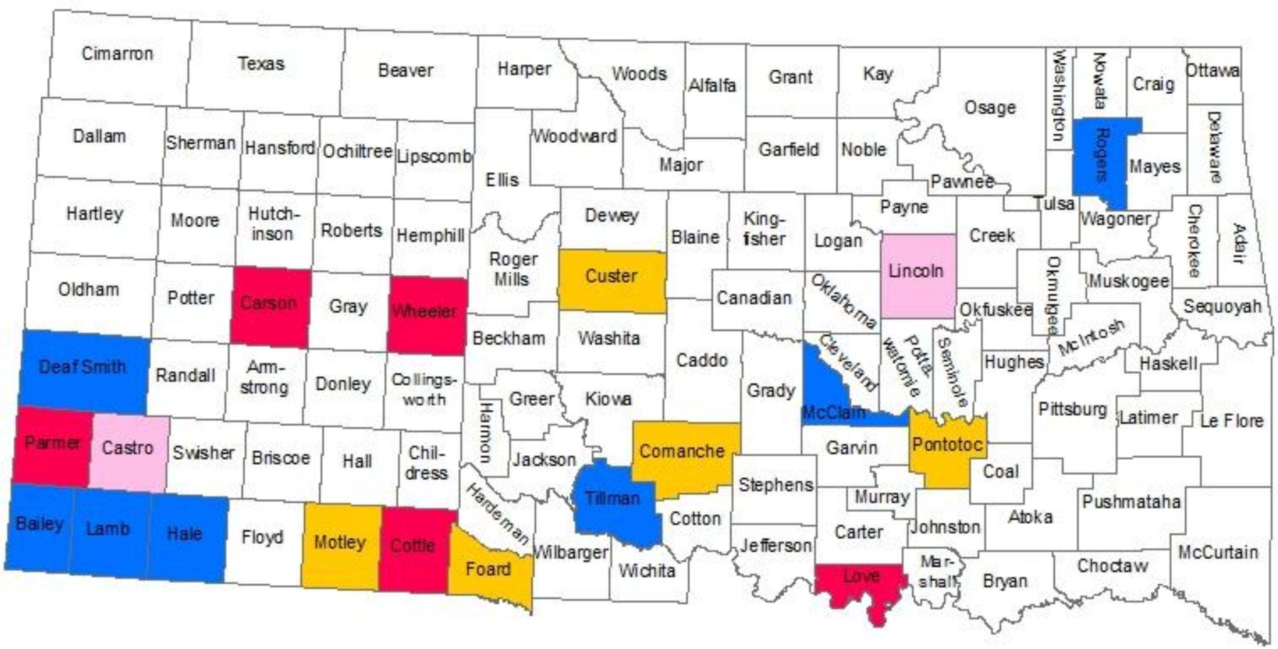

Fig. 10 – F3 K-means clusters

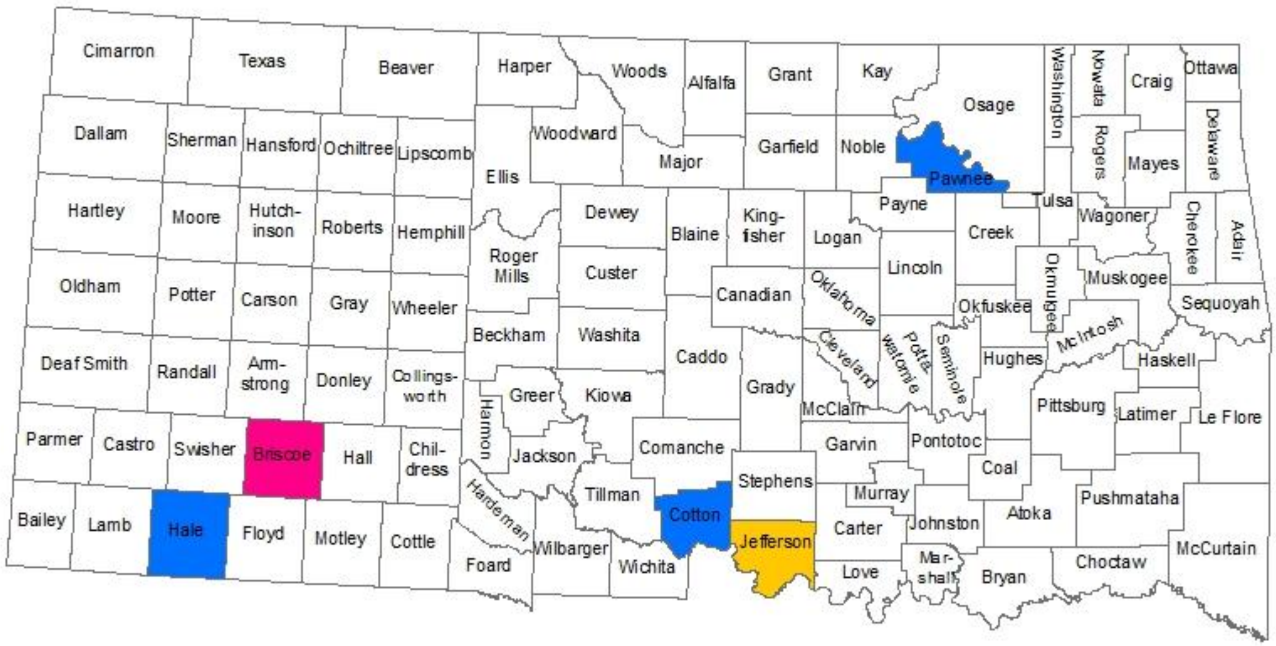

Fig. 11 – F4 K-means clusters

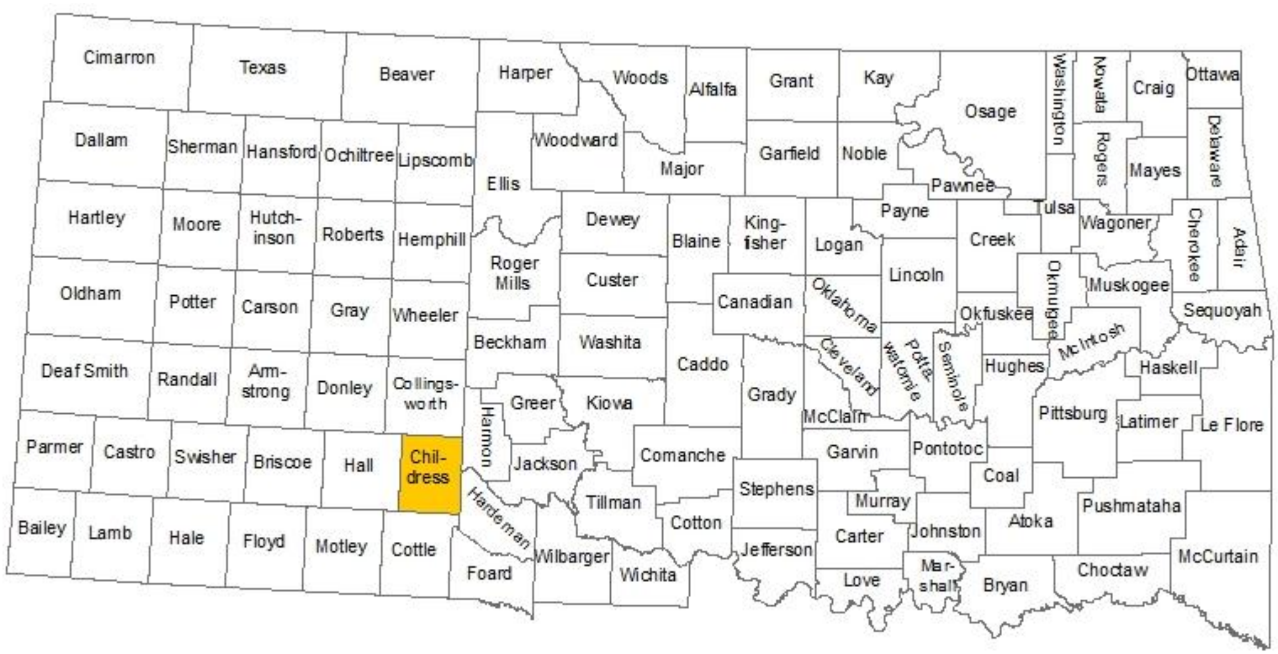

Fig. 12 – F5 K-means clusters