Spatial statistical analysis of potential impacts to landscapes and streams in LaSalle County Texas from exploration, production, and infrastructure development in the Eagle Ford Shale Play

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Abstract:

This analysis uses a GIS (ArcGIS) to identify and quantify areas of landscape and hydrologic disturbance from oil and gas (O&G) activity as a result of the Eagle Ford Shale Play (EF) in LaSalle County Texas. A combination of landscape ecology, hydrology, and spatial statistics are used to identify "hot spots" of disturbance from O&G activity. This is an exploratory examination which attempts to establish methodologies and management tools that are readily accessible to O&G operators as wells as land management entities. The methods presented in this research are an attempt at identifying important disruptions to ecosystem services from O&G activity.

Introduction:

Producing hydrocarbons from tight formation source rocks, through the advent of improved technologies in hydraulic fracturing and horizontal drilling, has become one of the most important changes in the North American petroleum industry in decades. Within the last 10 years, the practice has evolved from a novelty concept to a common method of extraction. Between 2009 and 2011, permits acquired for the Eagle Ford Play went from 50 to 600 (Driskill et al., 2012), and as of November 4, 2013, over 7,000 wells are currently producing oil and gas and over 5,000 new permits have been issued (Railroad Commission of Texas, 2013). This rapid increase in activity in south Texas is accompanied by roads, pipelines, and other infrastructure that compound disruptions to surficial geomorphic processes.

Several recent studies have found that the hydraulic fracturing process itself has had very little impact on environmental quality and most incidences of contamination occurred on the surface (GAO, 2012). Researchers in Pennsylvania have begun to analyze early trends of landcover change in the Marcellus Shale Play and preliminary results have indicated the importance of choosing the location of well pads and support infrastructure to minimize soil erosion, stream sedimentation and alteration in stream flow rates, as well as landscape fragmentation (Drohan and Brittingham, 2012; Drohan et al., 2012). Their work is preliminary, yet it shows how exploration can be done with reduced above-ground impact.

Very little, if any, research has examined the spatial and geomorphic fragmentation effects of the recent shale boom in the semi-arid/arid climates of Texas, where reduced rainfall rates could substantially lengthen landscape reclamation periods following drilling and fracturing. Above-ground issues from landscape fragmentation will most likely be important throughout the life of the play (Braun and Hanus, 2005; Bi et al., 2011).

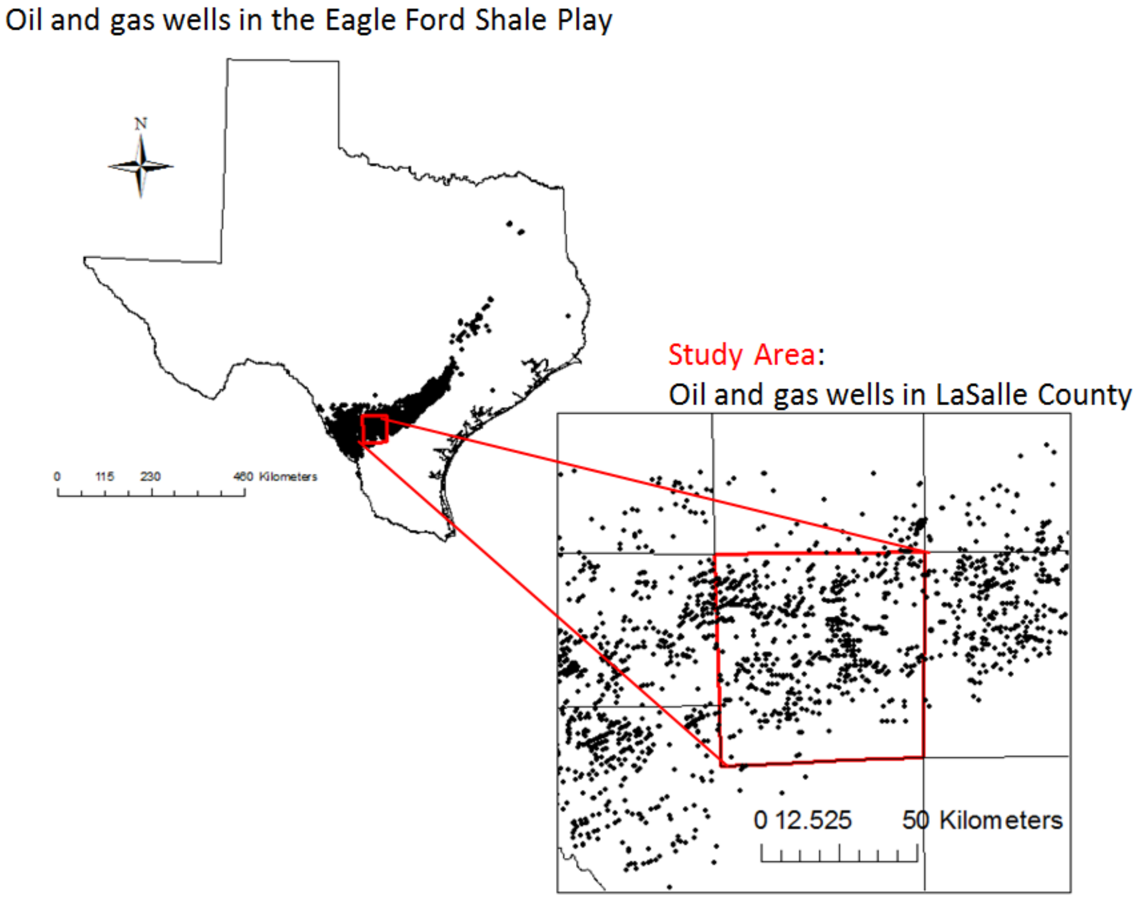
The EF spans from the southwest border counties of Webb and Maverick Counties to Leon and Madison Counties in the East. The formation lies to the south of the Edwards Plateau. The shale formation is thickest in LaSalle County and liquid rich (oil and gas condensate) sections of the play have recently been discovered in LaSalle County. As a result, the O&G activity is more concentrated in LaSalle County compared to the other 24 counties. This exploratory examination focuses in on fragmentation effects over a 12 year period (March 30, 2001 to December 11, 2012) in LaSalle County only. Landscape ecology and spatial statistical analyses are employed along with derived landscape classifications associated with disturbances to identify hot spots and trends in the alteration of landscapes and hydrology in the semi-arid climate of the EF region.

There were three main objectives to this analysis:

1. to quantify how much landscape fragmentation has occurred in LaSalle County during this 12 year period;
2. to identify the "hot spots" of core forest degradation in LaSalle County; and
3. to identify the "hot spots" of stream disruptions in LaSalle County.

Study Area:

Figure 1: LaSalle County study area



Local and Regional Importance:

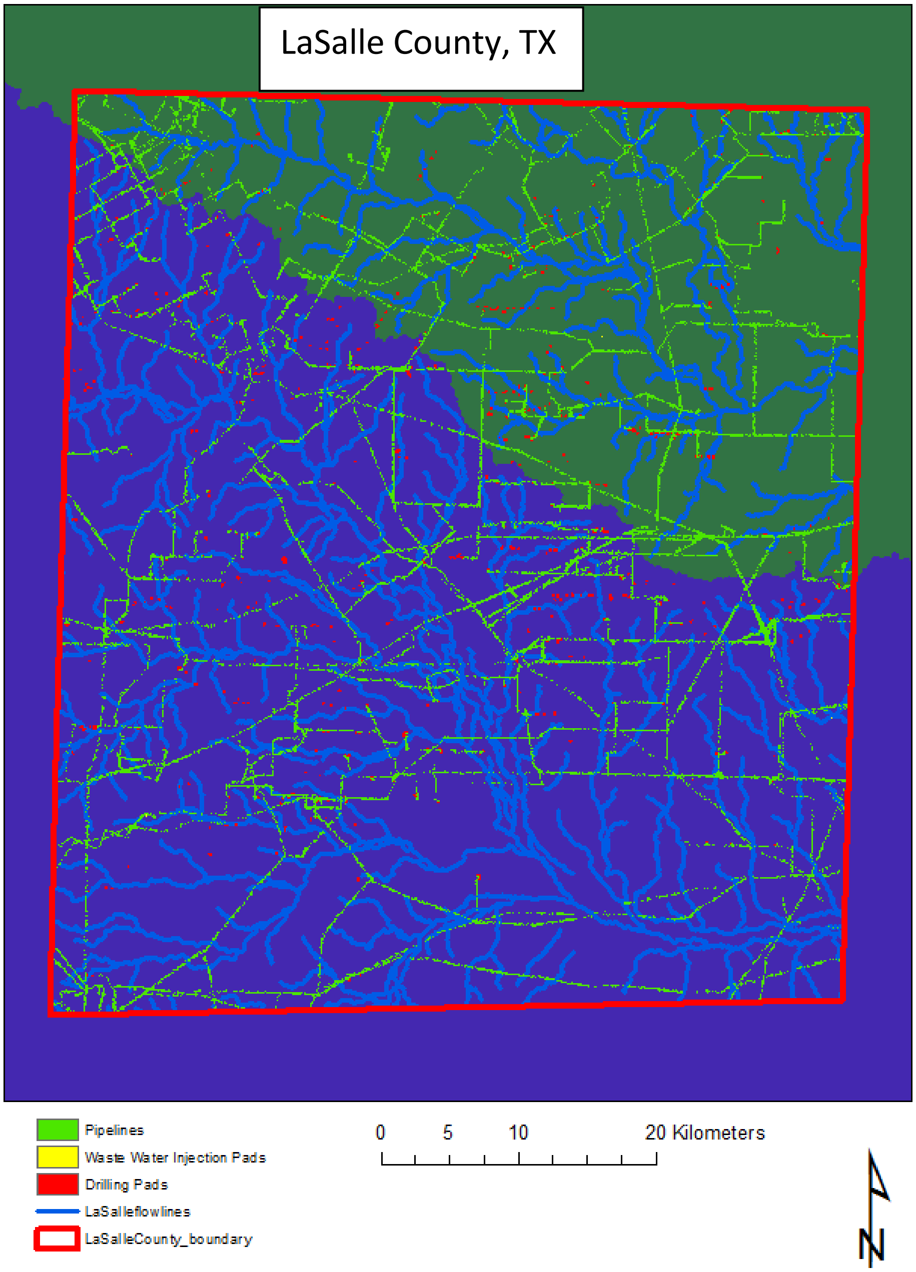
The Eagle Ford (EF) play is currently one of the most important in Texas with respect to gas and oil production. Outside of severance taxes collected on oil production, the influence of income from exploration and production has greatly relieved the financial stresses on south Texas. The EF is being targeted for extraction in three phase windows: liquids, gas condensate, and gas. Horizontal drilling became a commercially viable practice in the late 1980's, when it was successfully employed in the Austin Chalk (AC) and the Bakken Shale (King, 1993). Hill et al.

(1978) indicate that, as early as 1976, considerable interest existed in hydraulically fracturing the AC to stimulate production. The EF falls within the same footprint as the AC. Today, both horizontal drilling and hydraulic fracturing are used to extract oil and gas from the AC and the EF. Extraction of oil and gas in tight formations, however, requires the hydraulic fracturing of between 100 to 1000 times the numbers of wells needed in conventional reservoirs, depending on the source rock. Because of the larger numbers of wells needed for production from unconventional formations, the fragmentation from the EF activity will be larger than what occurred in the AC.

As experience grows in the EF play, particularly the knowledge of the localized areas where gas/oil flow is higher and the wells are more profitable, well operators will concentrate their efforts into smaller areas. For example, recent research by a producer in the EF formation (Rosetta Resources, Inc.), suggests a 29% increase in production from EF wells by reducing spacing between wells from 100-acre spacing to 55-acre spacing (Hagale, 2012). With a continuous increase in producing and permitted wells, the likelihood exists for the potential of on-going and substantial above ground activity. Even with a slight increase in the number of wells drilled per pad, there is an existing potential for thousands of hectares worth of disturbance to ground surface, much of which in addition to providing ecosystem services is also hydrologically connected to surface and underground water systems, all of which are valuable assets to this southern Texas region. Given the extraordinary long-reach capabilities of today's horizontal drilling rigs, operators are able to locate multiple wells on one pad. This ultimately reduces the level of landscape disturbance, although it extends the operational lives of drilling pads, which likely hinders reclamation efforts. Given their potentially prolonged life spans, many pads may not be ready for reclamation for quite a while. However, other infrastructure such as pipelines and compressor stations will be suitable for reclamation when installation is complete (Drohan, 2012).

Above-ground conditions play a role in ecosystem services, soil quality (through the alteration of soil-processes, available soil moisture, and hydrologic capture), erosion potential, and groundwater quality (John et al., 2009; Alados et al., 2010; Robson et al., 2011; Nainggolan et al., 2012). Identifying detrimental trends early and establishing methods to identify these trends will be crucial to implementing infrastructure development guidelines.

Figure 2: Demonstrates the extent to which O&G infrastructure has a presence in LaSalle County.



The blue and green represent two subwatersheds within the Nueces River Basin.

Ecological Importance:

Researchers in PA have identified many realistic threats to streams such as increased sedimentation and Cl^- concentrations in streams from shale gas activities involved with infrastructure development and waste water treatment (Entrekin, 2011; Olmstead, 2013). Additional research efforts in PA have identified rapid increases in landscape fragmentation along with inadequate reclamation practices (Drohan and Brittingham, 2012; Drohan et al., 2012).

Semi-arid and arid climates are often more affected by disturbance to the landscape compared to more humid environments, particularly when disruptions to first order streams occur. Water scarcity along with increased reclamation periods have been shown to exacerbate anthropogenic effects on the landscape and surrounding ecology in water scarce regions. Many countries in semi-arid climates with existing water scarcity have been identified as having large shale reserves. An opportunity exists to advance ecosystem conservation measures through the lessons being learned by current research. Similar studies as those done in the Marcellus should be carried out in the less humid shale plays of the world. Levin's (1974) work observed in semi-arid fragmented landscapes that habitat subdivision was highly complicated by shrub-grass competition/facilitation and increased homogeneity in vegetation is a result of the reduction of minority cover species. John et al. (2009) concluded these disturbances on a local level can manifest themselves into changes at the regional biome level in the context of regional climate change and water stresses. Man-made impacts to ecosystems of less humid climates often take more time to express detrimental effects but they have long been noticed by researchers in ecology. Alados et al. (2010) showed paleontological evidence for species lost in semi-arid Mediterranean areas of southeastern Spain due to anthropogenic activities of previous civilizations. The species loss was directly correlated with water scarcity and the disruption of first order stream networks by the activities of man.

Methods: (bold lettering indicates ArcGIS tool used)

Forest fragmentation

Datasets that include well location coordinates, spud date, operator name, geologic province name, and many other attributes associated with each well in the EF (whether used for production or injection) were downloaded from the IHS website (Information Handling Services, Inc., 2013). This database contained well permits for the EF acquired between March 30, 2001 and December 11, 2012. Using ArcGIS, wells were plotted and overlaid onto 2012 aerial imagery obtained from the National Agricultural Imagery Program (NAIP) (USDA NAIP, 2012). A polygon layer representing the areas of disturbed land from the development of infrastructure, well pads, containment ponds, staging areas, etc., that were clearly from oil and gas activity, was obtained by manually outlining disturbed (bare ground) areas at a 1:4000 scale in **editor** mode. If any doubt existed that the disturbance was from O&G activity these disturbed areas were not included in the analysis.

GIS data for oil and gas pipelines were obtained from the Texas Railroad Commission (RRC) and projected in ArcGIS. A 90m buffer was applied to the pipelines**.** **Iso Cluster Unsupervised Classification (Spatial Analyst)** using 10 classes was performed on 10m resolution NAIP imagery of LaSalle County to produce a raster layer. The values in this new raster layer were compared to the NAIP imagery to identify were bare ground existed. The classified image raster was then reclassified (**reclassify (spatial analyst)**) into two valued groups representing disturbed and undisturbed landscapes. This raster was then resampled (**resample (Data Management)**) to 30m resolution. Using **extract by mask (Spatial Analyst)**, the 30m raster cells within the 90m pipeline buffer were extracted to obtain disturbance areas from recent pipeline installations.

The National Land Cover Dataset (NLCD) of 2001 was downloaded from the USGS Landcover Institute (Homer et. al, 2007) to establish a baseline for landscape forest cover prior to EF development. The NLCD raster image was then reclassified (**reclassify (spatial analyst)**) into two groups, disturbed and undisturbed.

Using **raster calculator (spatial analyst)** and the **con is null statement** while maintaining the same extent of the 2001 NLCD image, the disturbances from drilling pads, injection pads, and pipelines were incorporated into the 2001 NLCD reclassified image. Two 30m resolution raster images were ultimately created containing only two classes, disturbed and undisturbed. The reclassified NLCD image represented the pre EF (2001) conditions and will be referred to as preEF in further discussion. The reclassified NLCD with the incorporated disturbances from drilling pads, waste water injection pads, and pipelines represented post EF conditions (2012) and will be referred to as postEF in further discussion.

The Landscape Fragmentation Tool (LFT) v2.0 (third party ArcGIS tool) developed by the Center for Land Use Education and Research (CLEAR) (Parent and Hurd, 2012) of the University of Connecticut which is based on the work of Vogt et al. (2006) was downloaded from CLEAR. Based on previous research (Goodrich et al. 2002; Howell et al. 2007; Robson et al. 2011; and Svobodová et al. 2011), a 100 m edge distance is commonly used for analysis. In accordance with LFT recommendations of having resolution be an incremental value of the edge distance, a 90m edge was assigned. Using the methods outlined by Vogt et al (2006) LFT defines core forest (and/or shrubland) as forest pixels greater than 90 m from non-forested pixels, perforated forests contain forest pixels within 90 m of non-forested pixels, edge forests contain forest pixels along the outside edge of a core forest, and patch forests contain forest pixels that do not contain core forests. Edge forests and perforated forests both contain pixels within 90 m of a core forest; however, patch forests exist on the interior edge of a core forest while edge forests exist on the exterior edge of a core forest. Both the preEF and postEF raster images were processed with **Landscape Fragmentation Tool** (LFT) to represent forested conditions previous to EF development (preEF LFT) and post (postEF LFT) forest conditions 12 years into O&G extraction from the EF.

Comparison of pre EF and post EF forest conditions

PreEF LFT and postEF LFT were converted to polygons using the **raster to polygon tool**. A comparison of the total area of the 6 forest classes in preEF LFT and postEF LFT was made. The total change in each class was obtained by calculating the total area of each class before and after EF development. Graphing these changes provides an overall picture of the forest fragmentation occurring in LaSalle County due to resource extraction of the EF.

Stream fragmentation

The NHDPlus v2.0 flowlines were downloaded from Horizon Systems Corporation (NHDPlus v2, 2013). These polylines were converted to raster form using the **polygon to raster** tool. All first order streams where selected (**select by attributes**) and extracted (**export data**) in order to identify disruptions to first order streams. Additionally all stream networks were reclassified (**reclassify (spatial analyst)**) to an equal value in order to identify disruptions to all streams. These two rasters were then individually added (**raster calculator (spatial analyst)**) to the raster layer which represents all disturbances from O&G infrastructure development in LaSalle County. The result was two raster layers which were reclassified (**reclassify (spatial analyst)**) to have a value of 1, which represents where infrastructure and streams meet, and a value of 0, where there is no intersection of streams with infrastructure. One layer represents the intersection of first order streams with infrastructure development and the other layer represents the intersection of all stream networks with infrastructure development.

Spatial statistical analysis of GIS data

It is known that fragmentation in the EF is not solely the result of O&G alone. Many other factors are contributing to landscape fragmentation and the examination of all fragmentation sources in LaSalle County is beyond the scope of this study.

Recent research demonstrates how spatial statistics can be used to track and identify trends in area loss of geographic and geologic features. Roberts et al. (2000) analyzed forest fragmentation to track changes in connecting corridors between forested regions Caledon, Ontario. Chen et al. (2012) used spatial statistics to map changes in thermokarst lakes over time in the Yukon. Estiri (2013) tracked urban sprawl with spatial statistics. Chas-Amil et al. (2013) used spatial statistics to map the incidences of forest fire in relation to the wildland-urban interface.

Zonal statistics (spatial analyst) was used to determine the percentage decrease of all core forest categories by overlaying the preEF LFT polygon with the raster layer that represents drilling pads, injection pads, and pipelines disturbance. When the raster layer that represented disturbance from pipelines, drilling pads, and injection pads intersected a core forest polygon an area of 900 m^2 (30mx30m resolution raster) was subtracted from the preEF area polygons for each raster cell that intersected. A percentage decrease for each core forest polygon was calculated. Similarly, the two raster layers which represent intersection of O&G infrastructure with 1st order or any stream network were each assigned a percentage of area loss in accordance with the aforementioned methods described using **zonal statistics** to obtain a percentage loss of area.

The spatial statistics involved with this analysis include both global and local statistics. The global statistics used to asses spatial autocorrelation were Moran's I (Moran, 1950) (**Spatial Autocorrelation (Global Moran's I)**) and Getis-Ord General G statistic (Getis and Ord, 1992) (**High/Low Clustering (Getis-Ord General G) (Spatial Statistics)**). The local statistics used to identify areas of potentially intense ecosystem disruption were Local Indicators of Spatial Association (LISA) (Anselin, 1995) (**Cluster and Outlier Analysis (Anselin Local Morans I) (Spatial Statistics)**) and Getis-Ord Gi* Hot Spot Analysis (Getis and Ord, 1992) (**Hot Spot Analysis (Getis-Ord Gi*) (Spatial Statistics)**). All of these statistics both global and local were weighted by a variable based on the percent decrease in core forest area from an intersect of O&G disturbance with core forest, or of the percent decrease in 1st order stream areas from an intersect of O&G disturbance with 1st order streams, or of the percent decrease in all stream network areas from an intersect of O&G disturbance with all stream networks. In order to examine the effects of scale both global and local spatial statistics were calculated using three distances of neighborhood measurement conceptualizations of measurement. The three fixed distance conceptualizations of 8482m (5.2 miles), 10000m (6.2 miles), and 16093m (10 miles) were used for the global and local statistical analyses. All statistical tests were executed using row standardization.

Results:

Quantitative analyses

Figure 3: Pipeline infrastructure had the greatest overall amount of disturbance area compared to drilling pads or waste water injection pads.

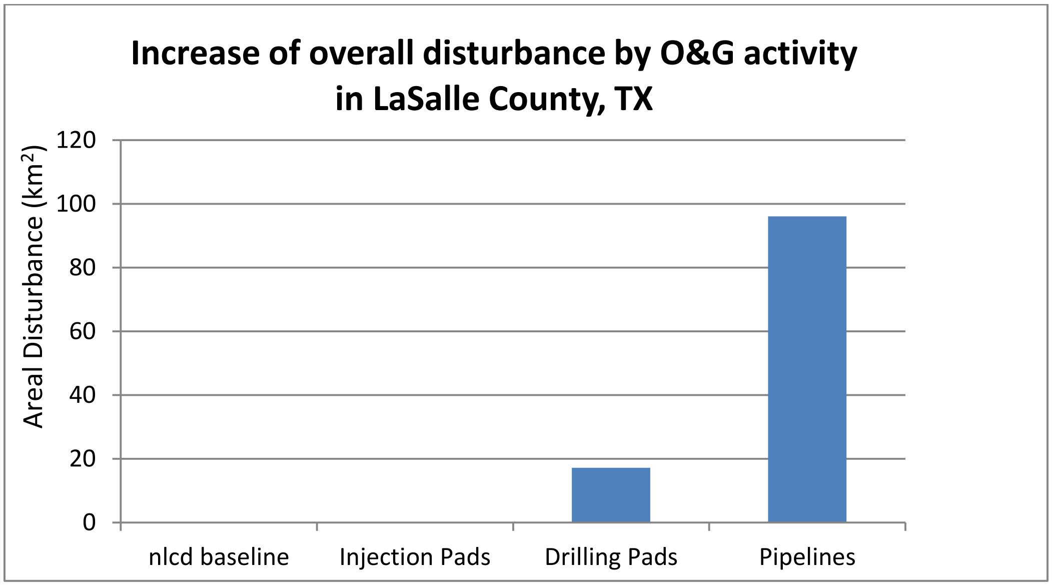


Figure 4: Direct intersection of O&G infrastructure with stream networks

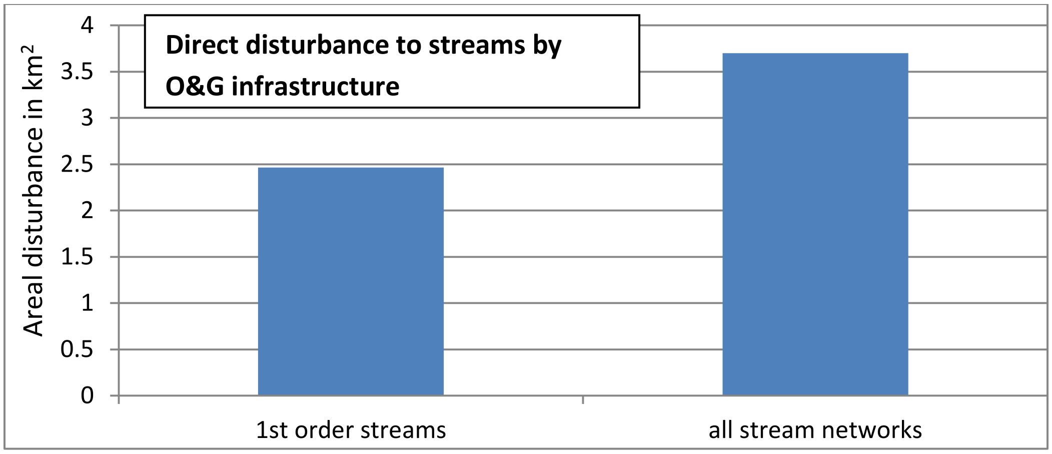


Figure 5: LaSalle County undisturbed landscape classes pre Eagle Ford development

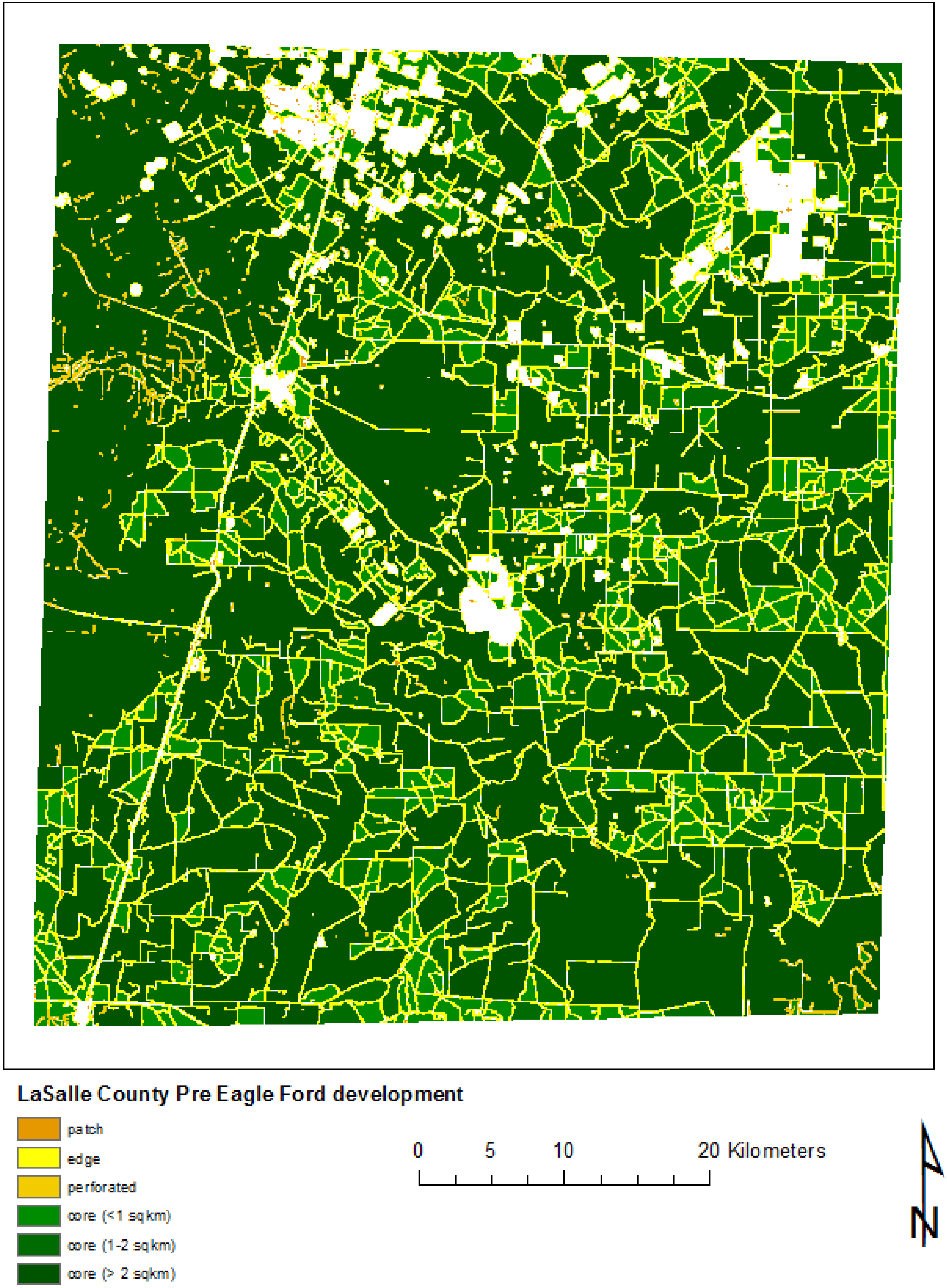


Figure 6: LaSalle County undisturbed landscape classes after 12 years of Eagle Ford development

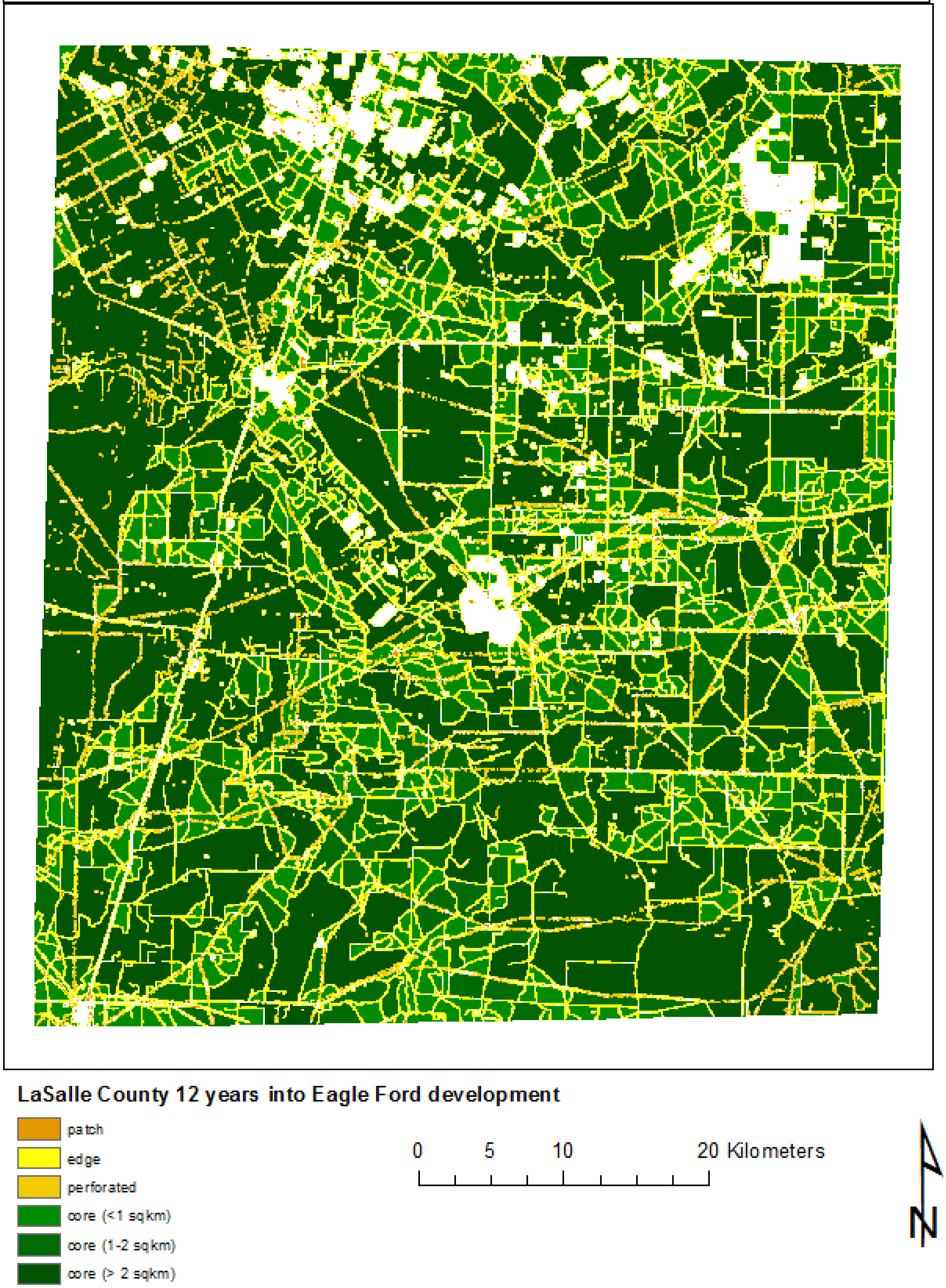


Figure 7: Pipeline infrastructure also contributed to the greatest amount of undisturbed land class changes.

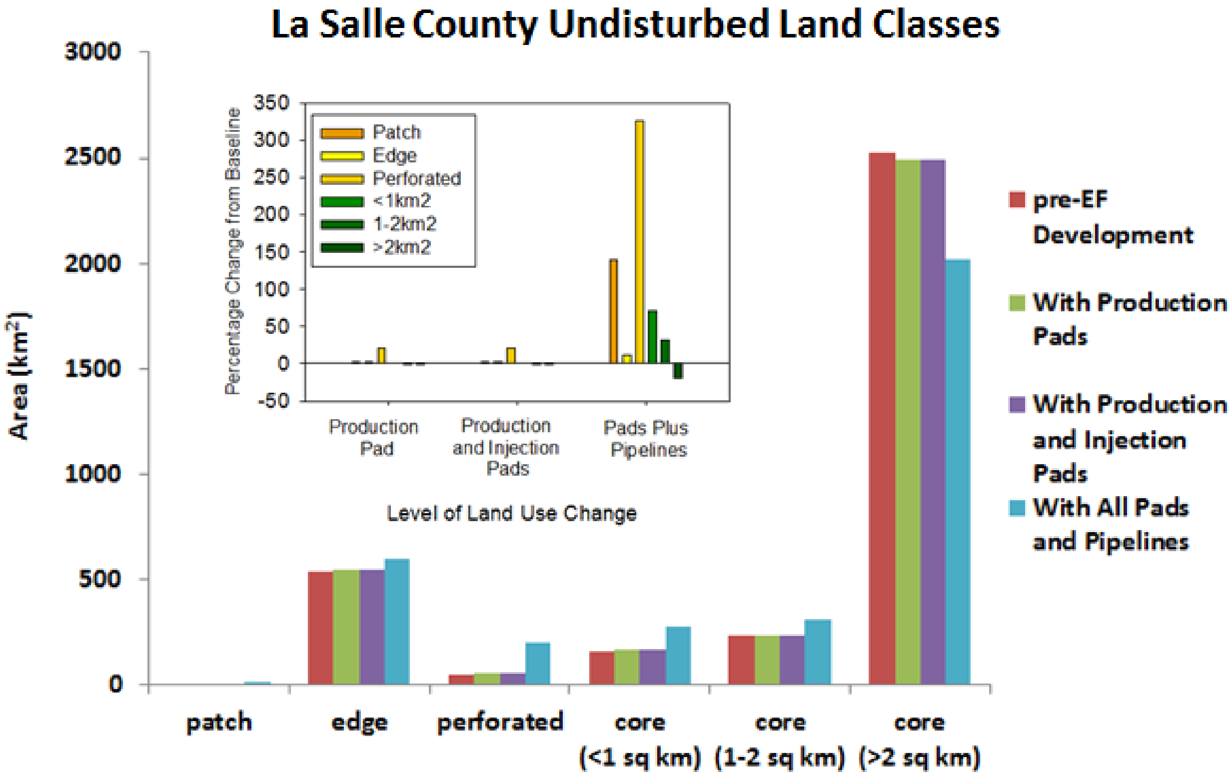
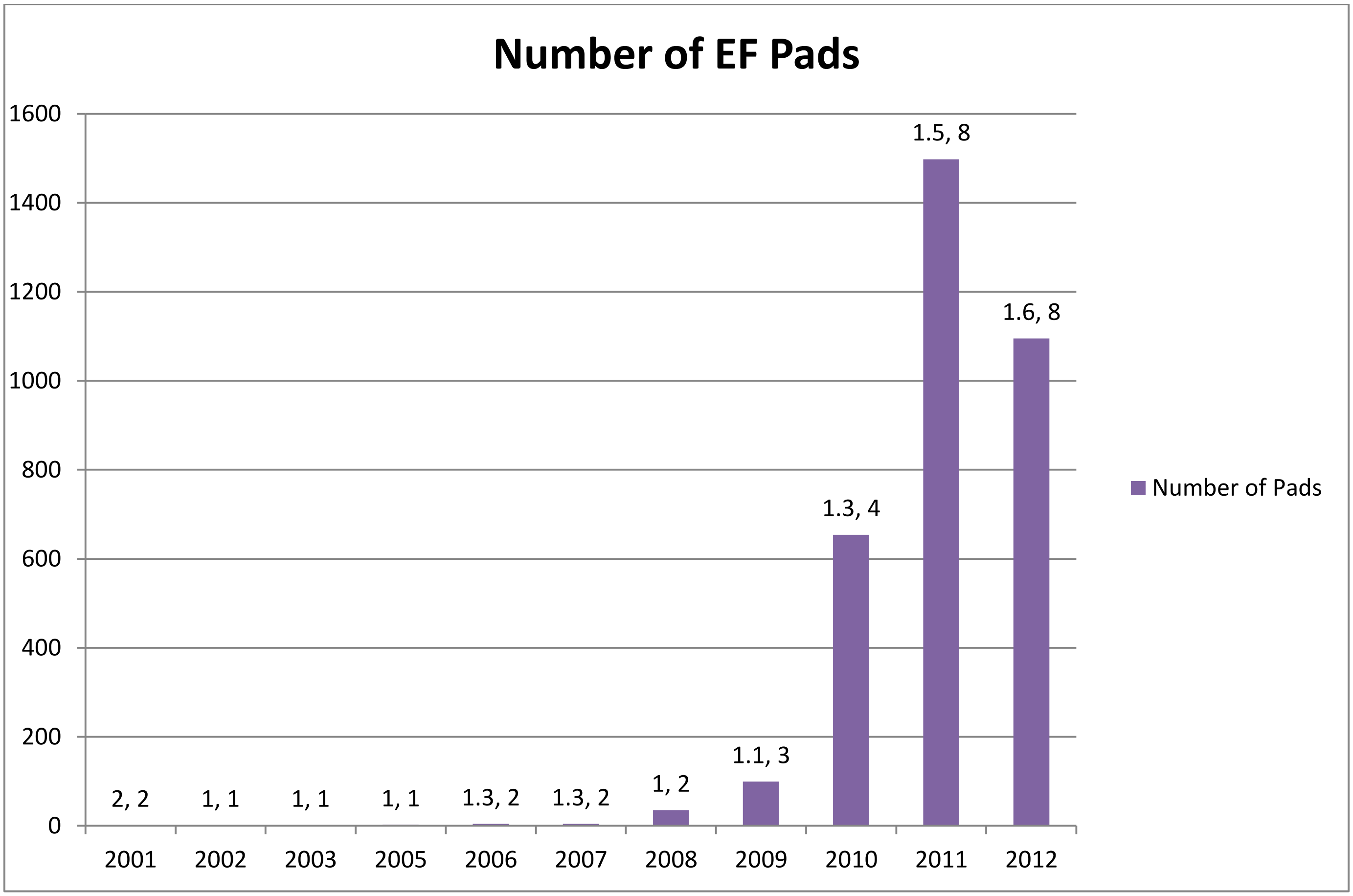


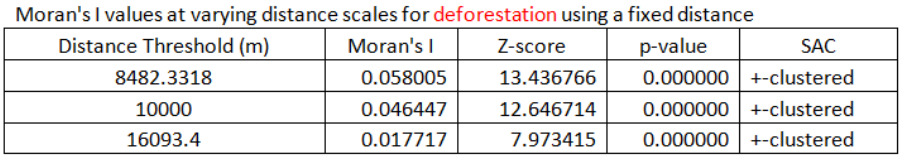
Figure 8: The number of wells per pad over time has increased only slightly.



Above each bar are the mean wells per pad and the maximum wells per pad, respectively

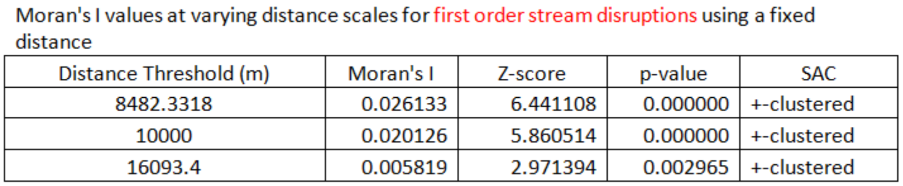
Spatial statistical analyses

Table 1: **Moran's I** global statistic indicates positive spatial autocorrelation at all distance conceptualizations with deforestation, first order stream disruptions, and all stream network disruptions.



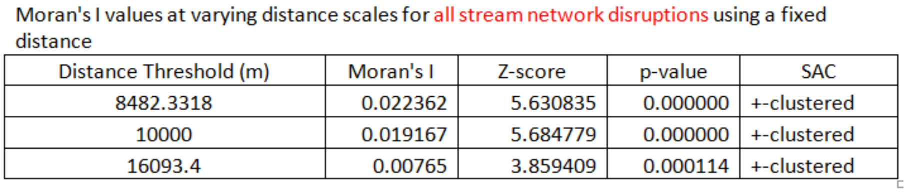
Moran's I values at varying distance scales for deforestation using a fixed distance

Distance Threshold (m)	Moran's I	Z-score	p-value	SAC
8482.3318	0.058005	13.436766	0.000000	+-clustered
10000	0.046447	12.646714	0.000000	+-clustered
16093.4	0.017717	7.973415	0.000000	+-clustered



Moran's I values at varying distance scales for first order stream disruptions using a fixed distance

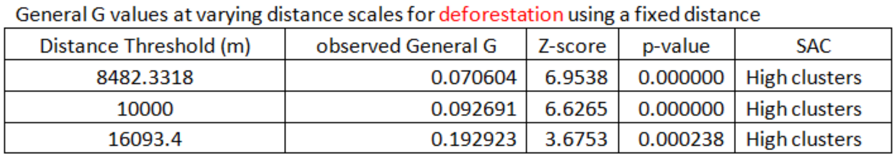
Distance Threshold (m)	Moran's I	Z-score	p-value	SAC
8482.3318	0.026133	6.441108	0.000000	+-clustered
10000	0.020126	5.860514	0.000000	+-clustered
16093.4	0.005819	2.971394	0.002965	+-clustered



Moran's I values at varying distance scales for all stream network disruptions using a fixed distance

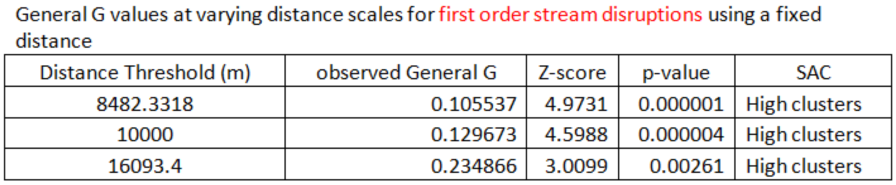
Distance Threshold (m)	Moran's I	Z-score	p-value	SAC
8482.3318	0.022362	5.630835	0.000000	+-clustered
10000	0.019167	5.684779	0.000000	+-clustered
16093.4	0.00765	3.859409	0.000114	+-clustered

Table 2: **General G** statistic indicates that more high clustering is occurring than low clustering with deforestation, first order stream disruptions, and all stream network disruptions.



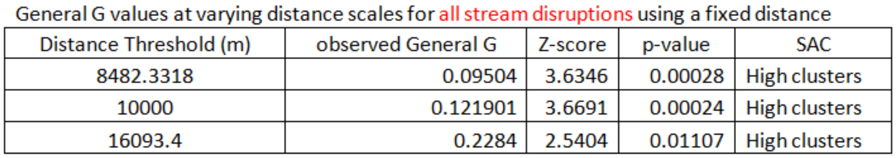
General G values at varying distance scales for deforestation using a fixed distance

Distance Threshold (m)	observed General G	Z-score	p-value	SAC
8482.3318	0.070604	6.9538	0.000000	High clusters
10000	0.092691	6.6265	0.000000	High clusters
16093.4	0.192923	3.6753	0.000238	High clusters



General G values at varying distance scales for first order stream disruptions using a fixed distance

Distance Threshold (m)	observed General G	Z-score	p-value	SAC
8482.3318	0.105537	4.9731	0.000001	High clusters
10000	0.129673	4.5988	0.000004	High clusters
16093.4	0.234866	3.0099	0.00261	High clusters



General G values at varying distance scales for all stream disruptions using a fixed distance

Distance Threshold (m)	observed General G	Z-score	p-value	SAC
8482.3318	0.09504	3.6346	0.00028	High clusters
10000	0.121901	3.6691	0.00024	High clusters
16093.4	0.2284	2.5404	0.01107	High clusters

Figure 9: LISA-Local Indicators of Spatial Association

Clustering weighted by percent decrease of core forest based on minimum distance of 8482m.

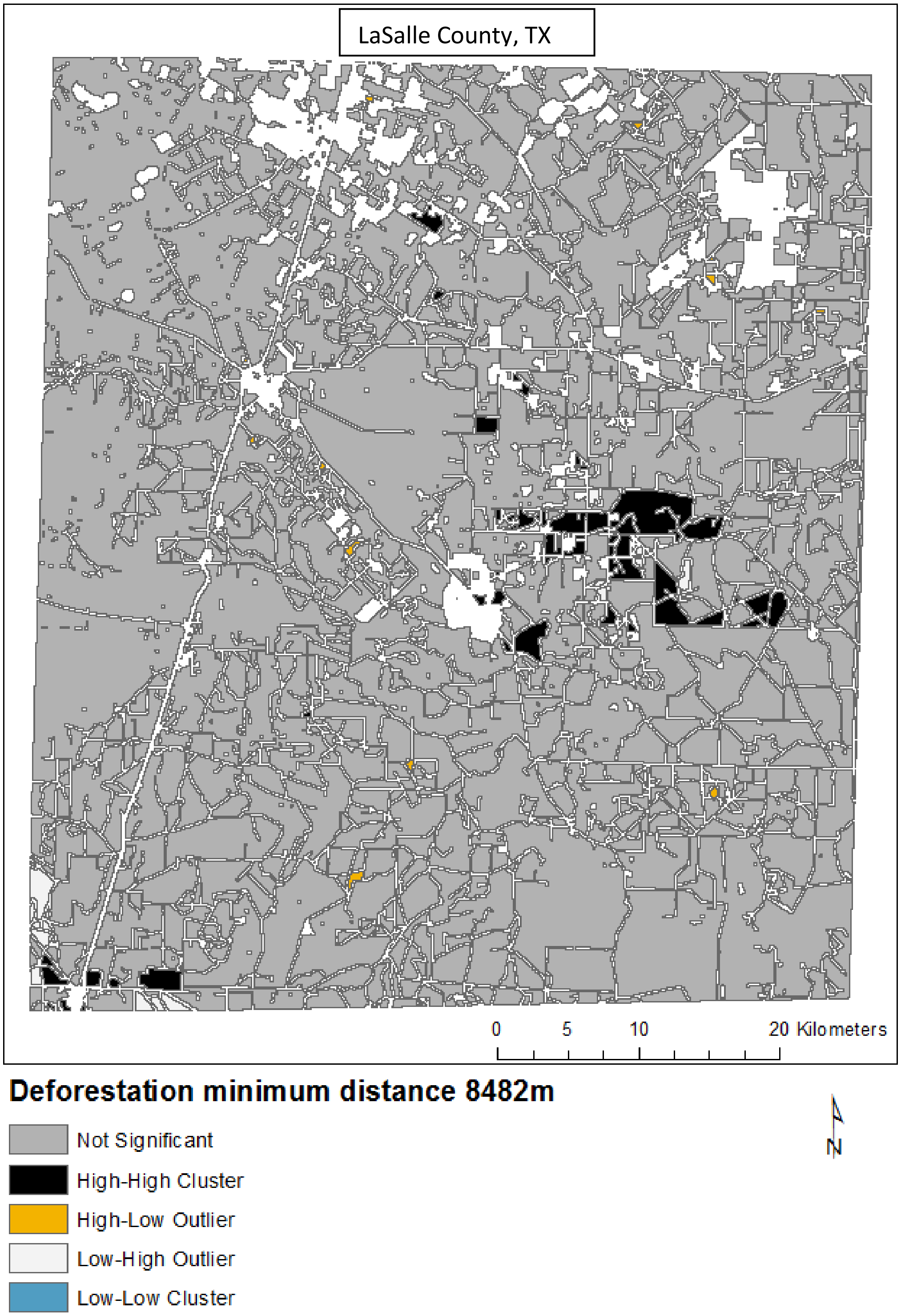


Figure 10: Deforestation hot spots and cold spots

Clustering weighted by percent decrease of core forest based on minimum distance of 8482m.

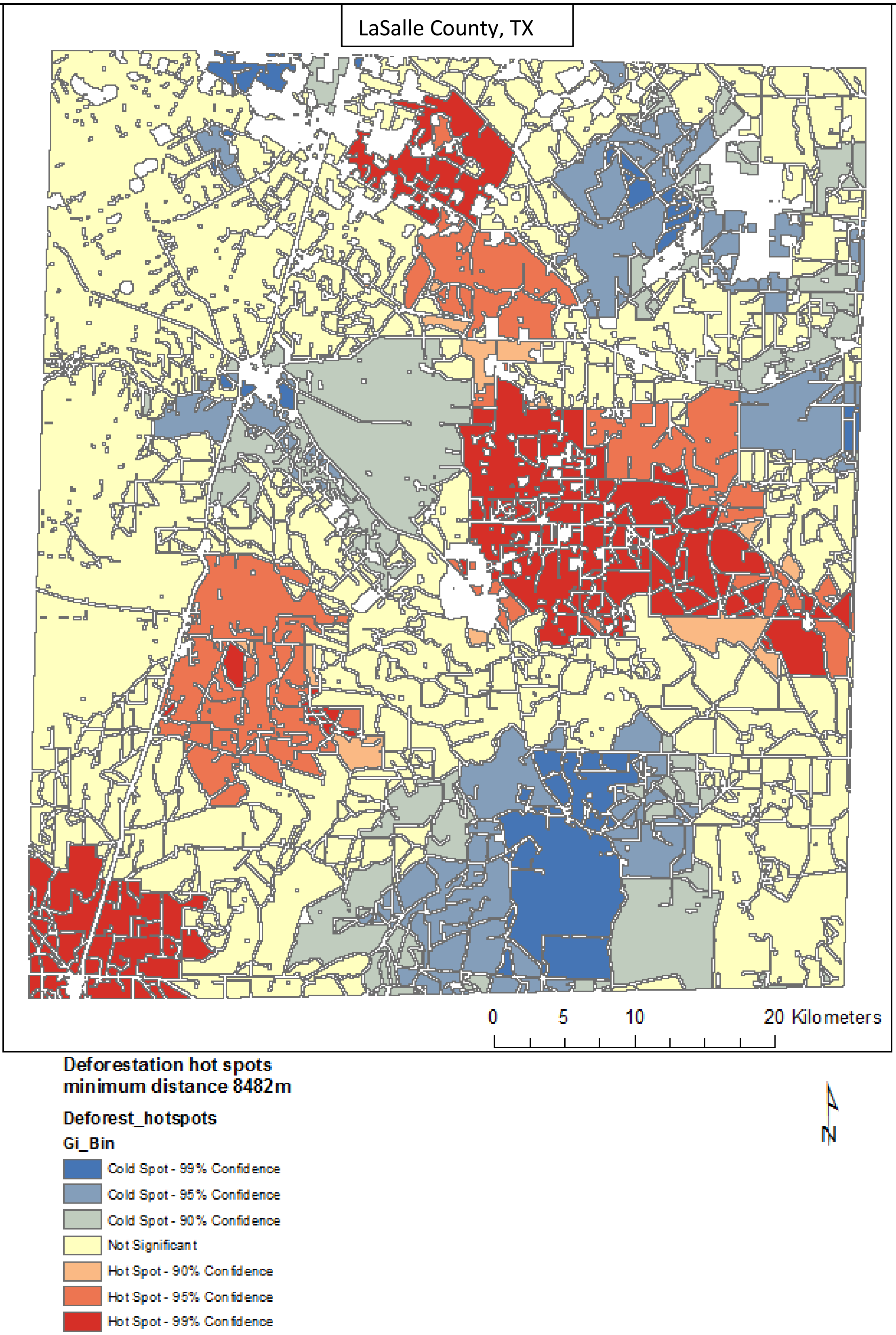


Figure 11: LISA-Local Indicators of Spatial Association

Clustering weighted by percent decrease of 1st order stream area based on minimum distance of 8482m.

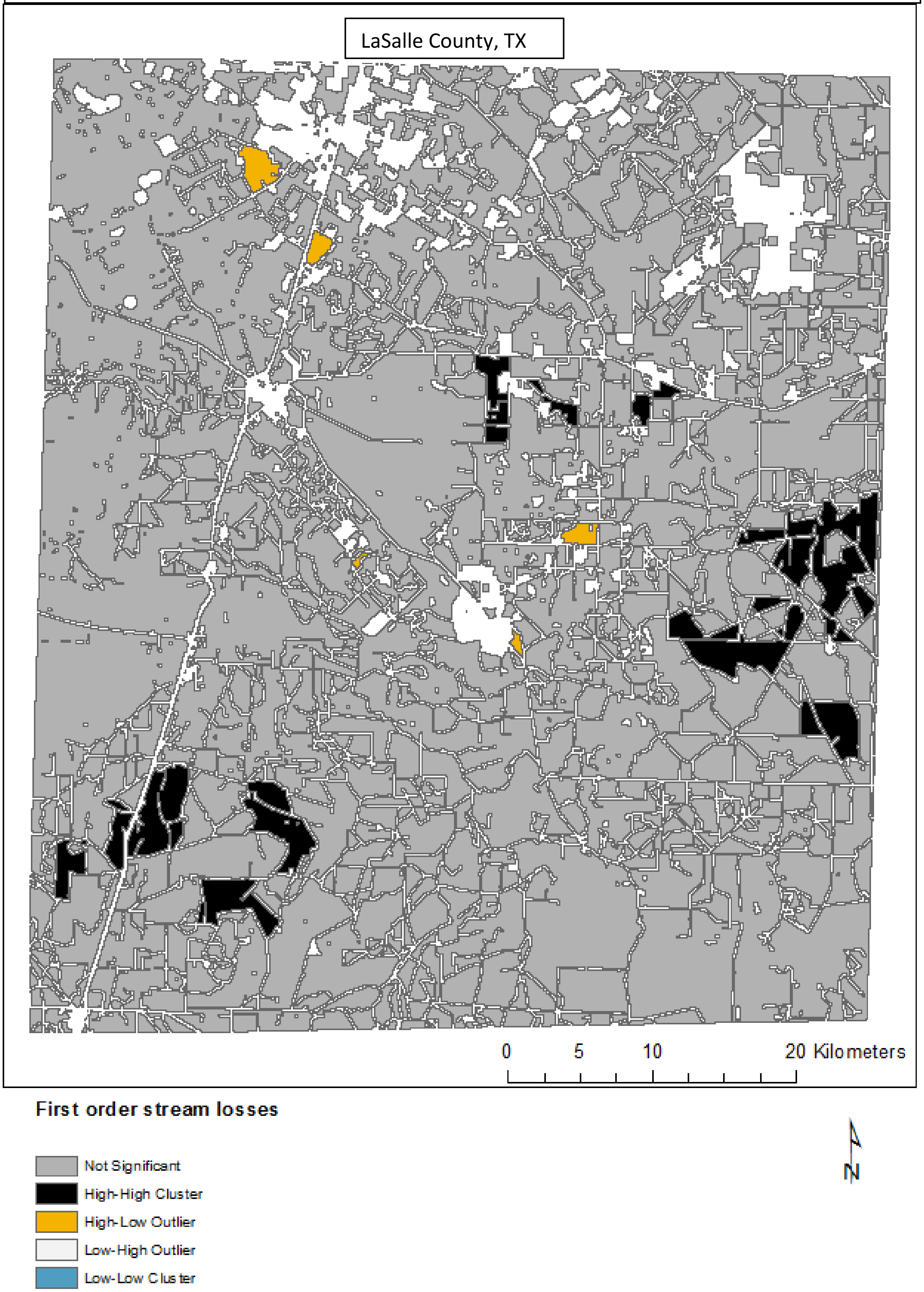


Figure 12: First order stream hot spots and cold spots

Clustering weighted by percent decrease of first order stream area based on minimum distance of 8482m.

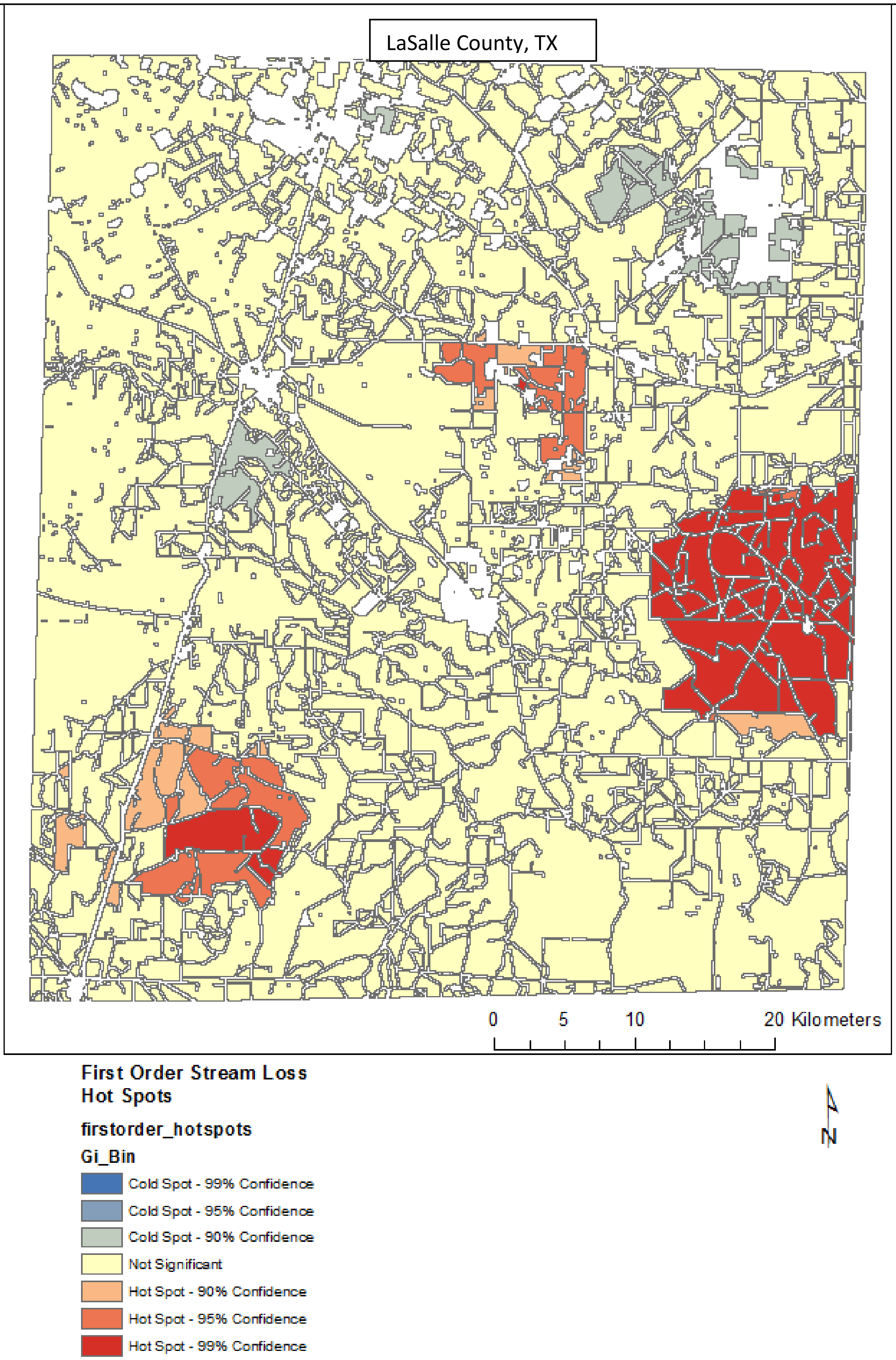


Figure 13: LISA-Local Indicators of Spatial Association

Clustering weighted by percent decrease of all stream network area based on minimum distance of 8482m.

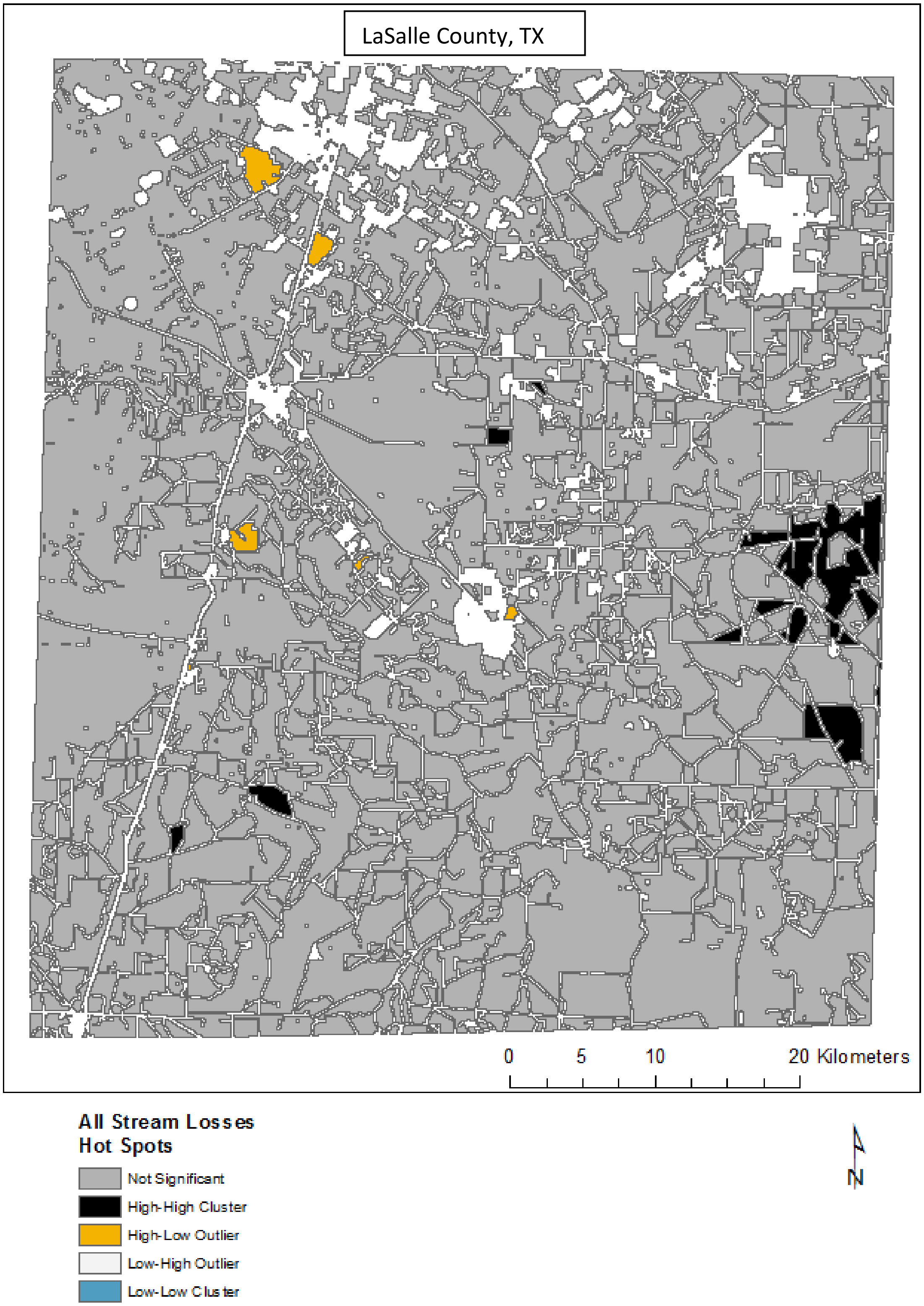


Figure 14: All stream losses hot spots and cold spots

Clustering weighted by percent decrease of all stream network area based on minimum distance of 8482m.

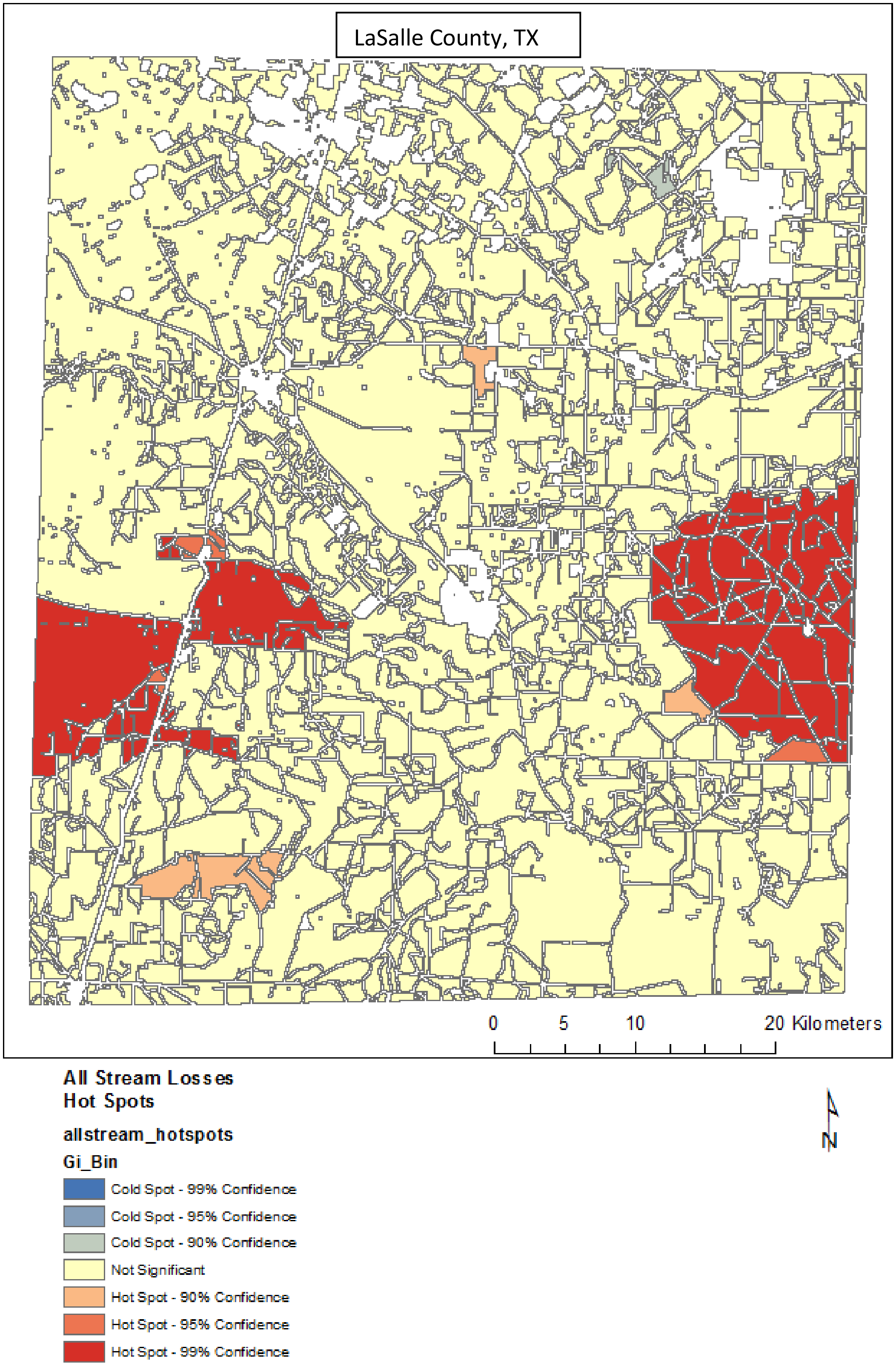


Figure 15: Bivariate cluster map of deforestation and first order stream loss.

Clustering weighted by percent deforestation versus percent of 1st order stream loss based on minimum distance of 8482m.

High-Low relationships indicate a high amount of deforestation while its neighbors have a Low amount of first order stream loss. High-High indicates the target polygon has high amount of deforestation while its neighbors have a high amount of first order stream area loss. This relationship is maintained for all other types as well.

LaSalle County, TX

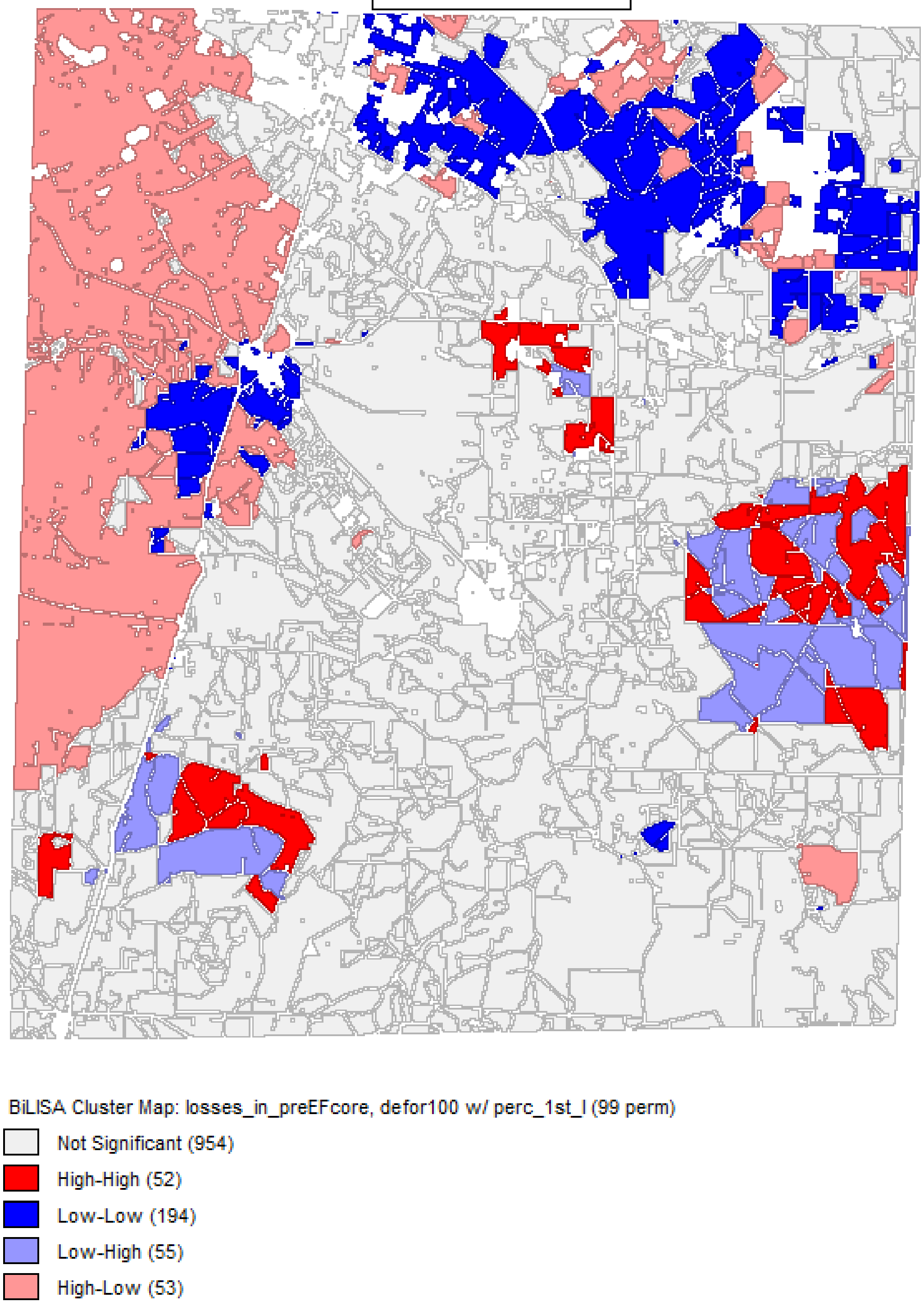


Figure 16: Bivariate LISA significance map for figure 15.

Losses in core forests with losses in first order streams.

LaSalle County, TX

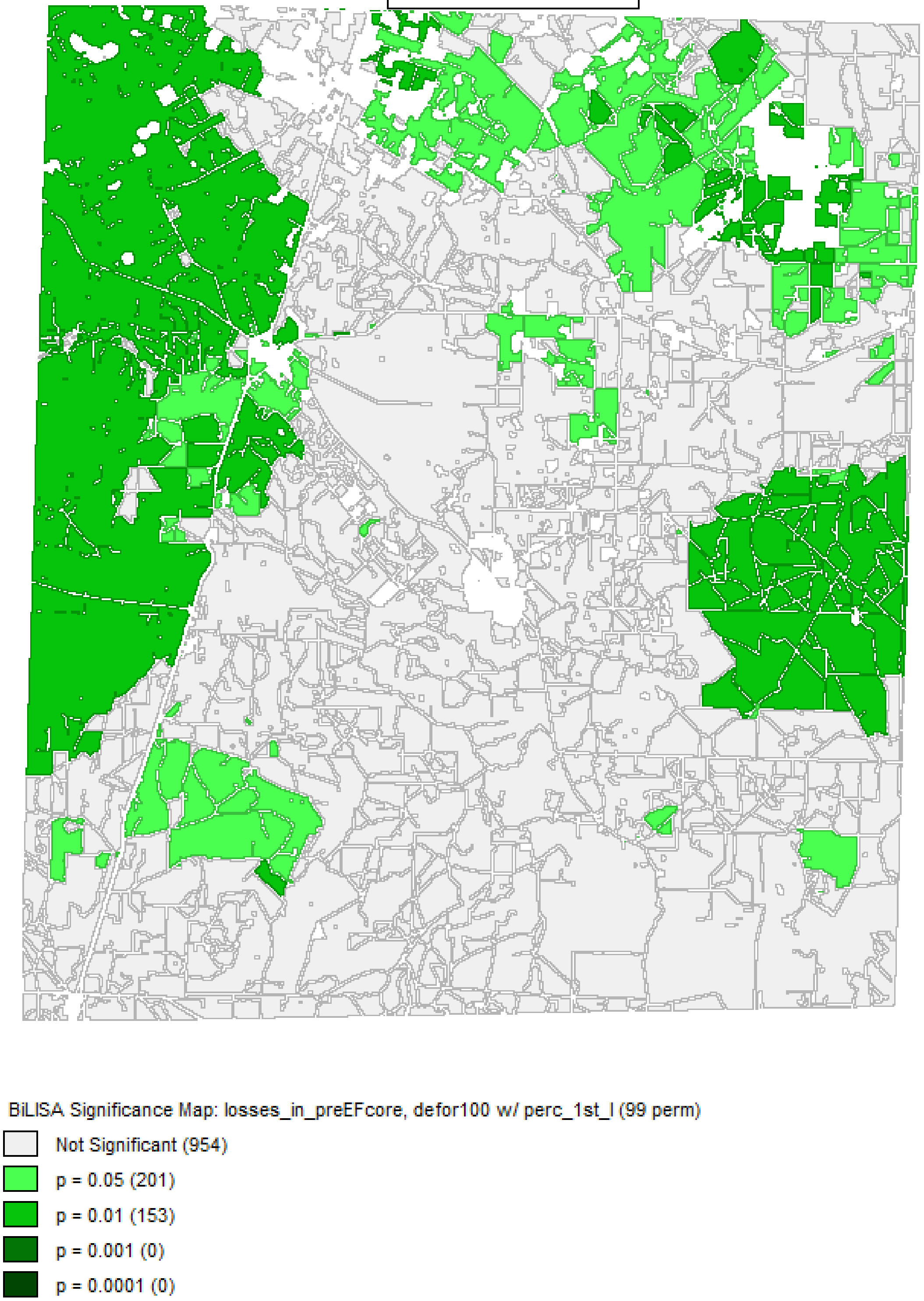


Figure 17: Bivariate cluster map of deforestation and all stream network area loss.

Clustering weighted by percent deforestation versus percent of all stream network area loss based on minimum distance of 8482m.

Relationships are:

Deforestation-loss of stream area

LaSalle County, TX

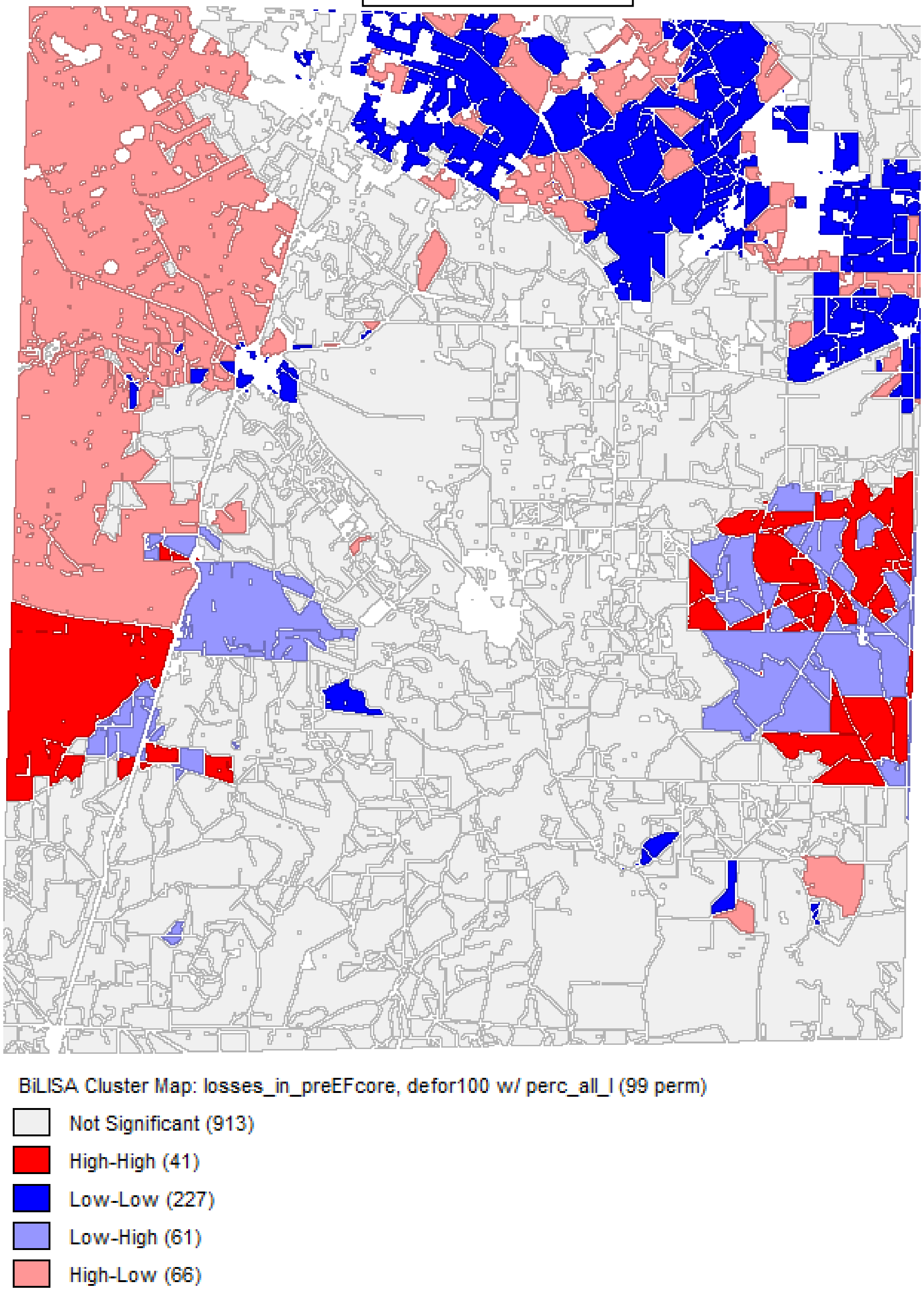
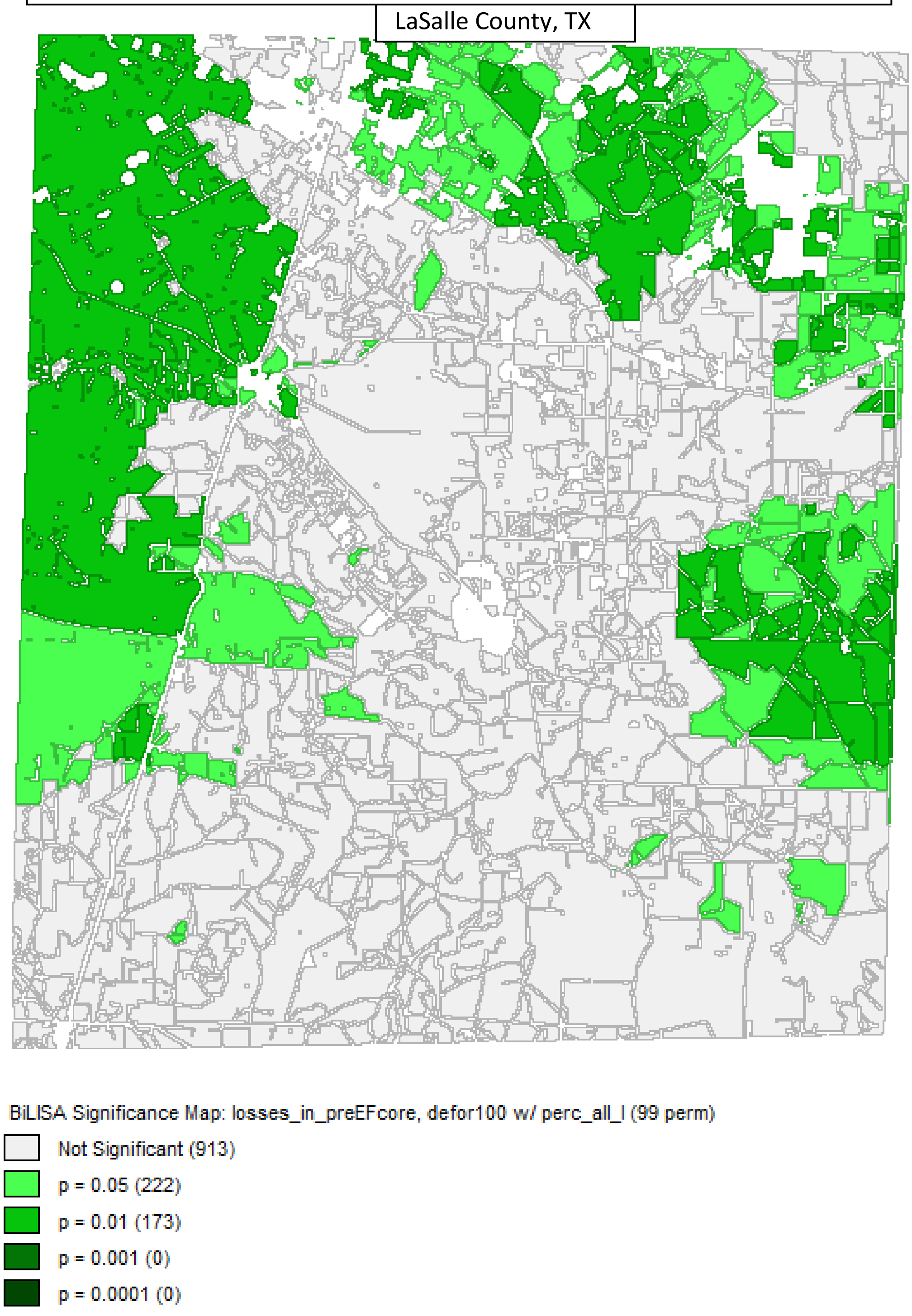


Figure 18: Bivariate LISA significance map for figure 17.

Losses in core forests with loss in area of all stream networks.



Discussion:

The objectives of this project were to quantify disturbance to vegetated land cover (classified as core forests) and stream networks from O&G activity in LaSalle County, Texas. Because of the ecological importance of first order streams in semi-arid climates recognized in the literature (Levin, 1974; John et al., 2009; Alados et al., 2011) a separate analysis was also undertaken on disturbance from O&G activity which directly intersects only first order streams.

Disturbance was assessed by identifying where bare ground existed in the 2012 NAIP imagery. Pipeline disturbance exceeded the other disturbances with an estimated 96 km^2 of bare ground existing as a result of the installation of pipeline infrastructure. An estimated 17 km^2 of disturbance was the result of drilling pad installation and an estimated 0.04 km^2 was the result of waste water injection pad installation (Figure 3). An area of 2.5 km^2 of O&G infrastructure directly intersected first order streams while an area of 3.7 km^2 directly intersected all stream networks (Figure 4).

A total of 32 km^2 of core forest was lost due to O&G infrastructure this is slightly less than 1% of the total land area in LaSalle County, TX. Despite reports of increasing densities of wells installed on drilling pads in other shale plays (i.e. Marcellus and Barnett Shale Plays) in the U.S., there has not been a significant increase in the number of wells installed on drilling pads in the Eagle Ford Shale Play. Increasing the density of wells on pads will allow other supporting infrastructure such as roadways, pipelines, and electrical service to be more centrally located and resulting in fewer disturbances to ecosystem services.

LaSalle County is situated in the heart of West Texas ranch land. As a result many unpaved roads exist. Because of the difficulty involved with identifying whether unpaved roads were installed because of O&G activity, unpaved roads were not considered in this analysis. Future work will involve developing a method to identify unpaved roads that are installed solely to serve the O&G industry.

The use of spatial statistics provides a method for identifying where ecosystem disruptions are most likely to occur. Particularly the use of local spatial statistics will provide a means for mapping likely hot spots and highly concentrated disturbances to ecosystems. Identifying these hot spots may be a useful technique to identify where to conduct field work such as monitoring streams for pollutants or assessing disruptions to soil development. Further work will include determining ecologically appropriate distance metrics for identifying neighborhoods in the analyses with spatial statistics. Additionally, further work will include the use of geographically weighted regression (GWR) to identify the influence of certain practices on ecosystem degradation. For instance, GWR could be used to map the influence of well density on drilling pads with the loss of core forests or disruptions to stream networks.

Conclusion:

The overall results of this analysis indicate that spatial statistics may prove to be a useful land management tool for O&G operators and other land management entities. Spatial statistics allow for much flexibility in how variables are weighted. Specific methods could be developed to protect threatened species, track invasive pests, and monitor environmental variables of interest. Many possibilities exist to develop methods using spatial statistics to identify potential ecosystem degradations.

Approximately, 1% of the total area of LaSalle County has been disrupted by O&G infrastructure (drilling pads, injection pads, and pipelines). If disturbances from new electrical installations and roadways were included, the total area of disruption would easily exceed 1% of the total land area of LaSalle County. The shale boom in the Eagle Ford has also brought with it an economic boom in the region. This has created a need for increased housing, retail stores, restaurants, etc. which will also lead to landscape and hydrologic fragmentation.

In conclusion, this analysis resulted in the quantification of areal landscape and hydrologic fragmentation in LaSalle County. The use of spatial statistical analyses allowed for the ability to map the concentrated areas of these disturbances.

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