Who, What and Why: A Statistical and Geospatial Analysis of the Development of the Marcellus Shale in West Virginia

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Who, What and Why: A Statistical and Geospatial Analysis of the Development of the Marcellus Shale in West Virginia

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Capstone Project

Master of Science in Geographic Information Science

18 November 2015
ABSTRACT

Over the last decade, the Marcellus Shale in West Virginia has seen a rapid rise in exploitation of resources. The boom is undeniable but the reasons behind the success stories remain debatable. What factors have led to successes for operators in the Marcellus Shale in West Virginia? Statistical and spatial analysis can aid in making that determination. Statistical analysis will focus on correlating leased acreage numbers to drilled and producing well data to demonstrate the correlation between leased acres and number of wells. Spatial Analysis will be used to determine the areas with the highest prevalence of drilled and producing horizontal wells.
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INTRODUCTION

The Marcellus Formation, or Marcellus Shale as it is commonly referred to, extends through much of the Appalachian basin stretching from New York to West Virginia covering approximately 95,000 square miles.¹ Due to the proximity to the densely populated East Coast, the region is attractive for energy development despite drilling and production being challenging from an engineering and environmental perspective². Many of these challenges have only recently been overcome thanks to technological advancements in the industry.

The reason development of the Marcellus shale is so important, is that it is the most expansive shale gas play in the United States. Energy independence is very important if the United States wants to diminish our dependence on foreign oil and gas. Development of the Marcellus Shale also has the potential to bring jobs and economic prosperity to the region, another positive benefit for those living in the region. It is not just oil and gas operators that reap the economic benefits of natural gas development but also the land owners and the local economy.

This analysis is going to focus on the “frontier” of Marcellus Shale development, which is in Northwestern West Virginia near Ohio and Pennsylvania. If you examine permit data for West Virginia, you can clearly

see the core of the activity is in the Northwestern portion of the state (see figure 1, page 3). West Virginia has a long history of oil & gas drilling, with the first oil well being drilled in the state nearly 200 years ago in the 1820’s. The major difference has been the advent of horizontal drilling, which has enabled the industry to access shales in areas that were not economic to drill prior. This analysis will not look at data from vertical wells and will be limited exclusively to horizontal Marcellus wells in West Virginia.

Interest in the Marcellus Shale boom in West Virginia came about due to my current job. I am a GIS Analyst at Antero Resources, an oil & gas company that operates in the Utica & Marcellus Shales in Ohio & West Virginia, respectively. A large portion of my job is analysis of the Utica and Marcellus plays. I regularly analyze acreage position, well locations and well results of a given operator to see how they stack up to Antero and other regional operators. This analysis will initially look at all Marcellus horizontal wells in West Virginia and will then hone in on the wells and acreage position of the top ten operators in the region in regards to number of producing wells, number of wells drilled and number of acres leased. The final step will be geospatial & statistical analysis of wells and acreage totals as well as identification of statistical and spatial patterns.

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Fig 1. Horizontal Marcellus Well Activity in West Virginia
Fig 2. Horizontal Marcellus Well Locations in West Virginia by Operator.
Purpose

The purpose of this project is to determine the role and importance of the "land grab" aspect of the oil & gas industry, specifically as it applies to the development of the Marcellus Shale, by using statistics and spatial analysis. In addition to assessing the correlation between number of drilled & producing wells and the number of acres a company has leased, a spatial analysis of drilled and producing locations will help determine the areas with the highest prevalence of drilling and production activity. These areas are presumably the most desirable locations to drill from a geologic and economic perspective. The finale will be a comparison of the findings from the statistical correlation and the spatial analysis. The findings of this analysis will be valuable to companies that are currently operating in the Marcellus Shale in West Virginia or are looking to get into the Marcellus Shale by acquisition or other means. This analysis could also be valuable to the thousands of employees that are employed by companies operating in the Marcellus Shale, to help them better understand and visualize big picture spatial trends and statistical analysis.

Goals

The primary goal of this analysis is to find meaningful correlations and spatial patterns between drilled & producing wells and leased acres in relation to the development of the Marcellus Shale in West Virginia. This
analysis will also aid me professionally because the GIS analysis I do on a daily basis at work tends to be focused on small scale land acquisitions, deals and trades as well as working with geologists on Antero’s plan of development. I rarely get to examine the bigger picture of what is going on in West Virginia cohesively. My daily use and absorption of data is it bits and pieces, while this analysis looks at the big picture which will help me better understand Marcellus Shale development in West Virginia.

THESIS STATEMENT

While it may seem obvious that oil and gas companies that have leased a lot of land in the Marcellus Shale are more likely to have drilled more wells and gotten more of those drilled wells to the production phase, there is a void of academic literature with this type of analysis. There is some spatial analysis literature regarding Marcellus Shale development but it is from an environmental perspective and spatial analysis is used to demonstrate human health impacts of the industry. This analysis acknowledges that there are potentially serious environmental implications and concerns associated with development of the Marcellus Shale, but debating whether those environmental negatives do or do not outweigh the economic positives is not a goal of this study. This study is simply looking for meaningful statistical correlations and spatial patterns from what exists and will not be examining potential environmental implications.
Body of Knowledge

While there is ample literature available regarding analysis of the Marcellus Shale from geologic, engineering, environmental and financial perspectives, there is very little information from a GIS perspective or that looks at spatial analysis of well locations. Spatial analysis is a critical tool in the oil & gas industry and there is a need for more academic literature on the topic. Spatial analysis is critical to the oil & gas industry because there are many moving parts associated with the industry as well as a given gas well and it can help bring data from a multitude of fields onto one platform where it can be analyzed cohesively.

Data

There are two types of primary research resources that will be used for this study. First, is the West Virginia Department of Environmental Protection (commonly abbreviated WV-DEP) permit and well data. This is the most critical data in this assessment of the Marcellus Shale because without well data, this analysis would not be possible. This analysis will use the bottom hole location of the well for analysis rather than the horizontal well bore. This data will be used for nearly every type of analysis associated with this project.

The second type of primary data to be used is the number of acres each company is claiming to have leased in the Marcellus Shale in West
Virginia. There is no way to determine the accuracy of this number, as precise acreage position is highly secretive and confidential. Companies do typically give a total figure of the number of acres they have leased in a given play in their investor presentations, so company websites are an important source of acreage data. While it's impossible to determine if this number is accurate, this is the only acreage number that is available and it is unlikely that a company would lie substantially about this number to prospective investors.

**Table 1. Operator websites and leased acreage numbers**

<table>
<thead>
<tr>
<th>Company</th>
<th>Website</th>
<th>Leased Marcellus Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antero Resources</td>
<td><a href="http://www.anteroresources.com">www.anteroresources.com</a></td>
<td>395,000</td>
</tr>
<tr>
<td>Chesapeake Energy</td>
<td><a href="http://www.chk.com">www.chk.com</a></td>
<td>N/A*</td>
</tr>
<tr>
<td>Consol Energy (CNX)</td>
<td><a href="http://www.consolenergy.com">www.consolenergy.com</a></td>
<td>230,000</td>
</tr>
<tr>
<td>EQT Corporation</td>
<td><a href="http://www.eqt.com">www.eqt.com</a></td>
<td>90,000</td>
</tr>
<tr>
<td>Gastar</td>
<td><a href="http://www.gastar.com">www.gastar.com</a></td>
<td>31,400</td>
</tr>
<tr>
<td>Jay-Bee</td>
<td><a href="http://www.jaybeeoil.com">www.jaybeeoil.com</a></td>
<td>30,000</td>
</tr>
<tr>
<td>Magnum Hunter (Triad)</td>
<td><a href="http://www.magnumhunterresources.com">www.magnumhunterresources.com</a></td>
<td>97,000</td>
</tr>
<tr>
<td>Noble Energy</td>
<td><a href="http://www.nobleenergy.com">www.nobleenergy.com</a></td>
<td>350,000</td>
</tr>
<tr>
<td>PDC Energy</td>
<td><a href="http://www.pdce.com">www.pdce.com</a></td>
<td>125,000</td>
</tr>
<tr>
<td>Southwestern Energy</td>
<td><a href="http://www.swn.com">www.swn.com</a></td>
<td>413,000*</td>
</tr>
<tr>
<td>Stone Energy</td>
<td><a href="http://www.stoneenergy.com/appalachia">www.stoneenergy.com/appalachia</a></td>
<td>90,000</td>
</tr>
<tr>
<td>XTO Energy</td>
<td><a href="http://www.xtoenergy.com">www.xtoenergy.com</a></td>
<td>170,000</td>
</tr>
</tbody>
</table>

*Southwestern acquired Chesapeake's Marcellus Acreage in WV

Secondary sources will be limited to websites and scholarly articles about the development of the Marcellus Shale. These sources will not be used for analysis as intensively as the primary sources. These sources are more to help gather background information, help gain differing perspectives.
(geologic, engineering, finance, etc.) and to assess why the Marcellus Shale boom has occurred.

Permit data that has been filed with the WV-DEP is the most crucial data for this analysis. This is public information that anyone can access. There are many companies that compile this data and sell it in a format that is conducive for GIS users. I will be using permit data that has been compiled by a company called "Rig Data". The data is updated as new permits are filed or as permitted wells are drilled, completed, etc.

Academic literature that is relevant to this topic is important for background information about the oil and gas industry. Google scholar was helpful for locating relevant academic articles, although there is an obvious lack of academic literature related directly to geospatial analysis of the development of the Marcellus Shale. There is ample literature available regarding the development of the Marcellus Shale from varying perspectives.

Analysis will largely focus on answering "who, what & why" in regards to development of the Marcellus Shale. The "who" aspect of this analysis will be determining the top 10 companies in regards to number of drilled wells, number of producing wells and number of acres leased. This portion of the analysis will identify the location of all producing and drilled horizontal Marcellus wells in West Virginia. Acreage position is considered to be proprietary, so while it is impossible to know the exact location of each
company's leases; it is possible to correlate the total number of acres a company claims to have leased. Correlating the number of acres leased to their number of drilled or producing wells to determine if there is a positive or negative correlation between the number of acres a company has leased and the number of wells they have permitted or are producing.

Analysis of "what" will largely be dependent upon literature review. "What" is an analysis of what factors lead to the Marcellus shale boom that we have seen over the last 10 years. This will largely focus on technological advances that have made horizontal drilling not only possible but also economically feasible. Literature analysis will largely look at articles with a geologic, engineering or economic focus on the history of the development of the Marcellus Shale. Examination of what has led to the Marcellus shale being such a significant play, in addition to why and how it has become so economically important and how it will lead to furthering energy security in the United States.

Point Analysis techniques will also be employed to determine if there are any notable spatial point patterns. Kernel density and point density will be used to determine statistically significant spatial clusters with further examination of the well operators in these clusters.

The final step will be to identify which companies have been most successful and why. This analysis will involve determining not only who the
major players are but what has led to their success. These variables will be measured and analyzed using statistics. There will be an assessment of the level of correlation between wells and leases. Visual displays of the statistics in scatterplot form will be critical as well. Maps of drilled wells and producing wells are critical to understanding the spatial and statistical patterns associated with the development of the Marcellus Shale in West Virginia.

LITERATURE REVIEW

The U.S. government's Energy Information Association (EIA) is an excellent resource for information on the Marcellus Shale boom. According to the EIA, the advent of the technologies needed to develop the Marcellus Shale coincides with the advent of horizontal drilling and hydraulic fracturing. The technology was necessary not only to develop shale in the Eastern U.S. but to make it economically viable as well. Even though the process is becoming more economical, drilling in the Marcellus Shale is still an expensive endeavor, with the average well costing $3-5 million, just for the completion stages. The EIA, also notes the significance of when the shale boom began noting that while there has been shale production since the 1990's, it didn't become a "game changer" in the U.S. natural gas market until approximately 2006. This shows the significance of producing Marcellus wells in the last 10 years. The EIA also demonstrates the significance of the

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Marcellus Shale in regards to on-shore natural gas production in the lower 48 U.S. states by showing figures for recoverable shale gas resources remaining in U.S. shale plays. The EIA estimates that there are 410 trillion cubic feet (Tcf) of natural gas in the Marcellus Shale alone. Kargbo, et al estimates that recoverable reserves could be as high as 489 Tcf though. With estimated reserves between 750 and 1,744 trillion cubic feet of shale gas in the lower-48 of the United States, the Marcellus Shale represents approximately 28-55% of the U.S.'s potential shale gas production in the lower-48 states, making it an extremely significant shale play. This is why development of the Marcellus Shale is so important to the United States; it represents a large portion of the available natural gas reserves in the United States. Analysis of successful exploration, drilling and production methods can only lead to more educated decision making and more effective means of drilling and producing.

Kargbo, et al focus on the importance and challenges associated with developing the Marcellus Shale. The Marcellus Shale is nearly 1 mile below the earth's surface and it is largely captured within the pores of the shale, which are tiny, have limited permeability and are connected poorly. Kargbo, et al are quick to point out that while the Marcellus Shale has nearly unlimited potential, there are many obstacles that make development

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particularly tricky in regards to exploration, drilling, water resources, hydraulic fracturing and health & environmental issues. A lot of these issues are related to the depth of the Marcellus Shale. As drill pipe extends deeper, drilling costs go up, the likelihood of challenges goes up, the life of the drill bit is shortened by the increase in rock hardness, placement of casing becomes more difficult as does the removal of drill cuttings, which are just a few of the issues associated with drilling the Marcellus Shale.\(^9\) There are also potential geo-hazards such as disruption of subsurface hydrology, the potential of triggering small earthquakes, and severe ground subsidence.\(^10\) 2-10 million gallons of water are required to complete a single horizontal deep well, and due to the costs of transporting water, it is typically obtained from local sources like a stream.\(^11\) This causes concerns for those communities particularly under drought conditions. There are also major environmental and health concerns associated with development of the Marcellus Shale. Potential environmental issues associated with disposal of wastewater, air pollution and potentially elevated concentrations of radium are a few of the potential issues operators are faced with.\(^12\)

The list of potential challenges associated with developing the Marcellus Shale may seem daunting, but the potential reserves have led to possible solutions and innovations for overcoming the challenges associated

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\(^9\) Ibid.
\(^10\) Ibid.
\(^12\) Ibid.
with developing the Marcellus Shale. In regards to drilling, horizontal drilling is currently used but some companies are starting to do multilateral drilling because it "is known to be more effective than horizontal drilling as it enables drainage of the multiple target zones, enlarges recoverable reserves, and increases productivity."\(^{13}\) To eliminate air pollution from the large volume of diesel trucks that are needed to transport water, many companies are building a network of pipes to transport fluids, which helps eliminate the need for water trucks.\(^{14}\) Hydraulic fracturing, or "fracking", is a hot topic right now. Alternatives to hydraulic fracturing, as well as development of more environmentally friendly hydrofracture fluid, are being explored by many of the operators in the Marcellus Shale.\(^{15}\) Another potential solution is recycling the fluid used for hydraulic fracturing (also called flowback water) and/or to treat the water on-site.\(^{16}\) Other options for disposing of wastewater are being explored as well. Re-injecting the wastewater back into the earth is a common method of disposing of the water, but doing so at shallow depths can contaminate the drinking water. Another alternative that is being explored in the Marcellus Shale, is injecting this waste water into formations deeper than the Marcellus because they are not used as aquifers.\(^{17}\)

\(^{13}\) Kargbo et al, "Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities", 5682.
\(^{14}\) Ibid.
\(^{15}\) Ibid.
\(^{16}\) Ibid.
\(^{17}\) Ibid.
While this analysis is confined to West Virginia, analyzing data from other states can help determine factors that could become important in West Virginia. The best state for analysis would clearly be its neighbor to the north, Pennsylvania, largely due to the fact that one of Pennsylvania's core regions for Marcellus development is very near West Virginia's Marcellus core. Of particular interest would be Pennsylvania's business model for the industry. For example, in an attempt to generate more tax revenue from the oil & gas industry, Pennsylvania's governor proposed a severance tax of natural gas production. Considine's, et al study determined that this would result in a 30% decline in drilling activity in Pennsylvania, which would cause negative economic impacts. He found that for every dollar the industry spent in the state of Pennsylvania, $1.94 of economic output was generated. West Virginia opted to increase severance tax, which Considine argues is the reason Marcellus development in Pennsylvania has exploded while West Virginia's gains were more modest. He proposes that the higher levels of drilling in Pennsylvania are due to lower taxes and a more favorable business climate. This could potentially be a very valuable lesson for the state of West Virginia and could provide a business model to increase tax revenue without passing the taxation directly onto drillers and producers which causes a negative economic reaction. Considine says it quite simply:

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19 Ibid.
"...if you tax something you get less. In this case, you get less drilling and gas development." These strategies and policies that encourage growth of the Marcellus gas industry in Pennsylvania will likely lead to growth in West Virginia as well.

While there are no existing academic articles that examine the growth of the Marcellus Shale from the geospatial and statistical perspective of this study, but there are articles that examine sociodemographic geospatial patterns in areas experiencing development related to the Marcellus boom. While the goals of those studies are far different from goal of this study, these articles still hold value because they are assessing geospatial patterns related to the development of the Marcellus Shale, albeit from a very different perspective. Huang and Ogneva-Himmelberger used geospatial techniques to evaluate environmental and human health impacts related to Marcellus Shale Development in Pennsylvania, Ohio and West Virginia. Their methods are noteworthy as they are somewhat similar to my geospatial and statistical methods. Huang and Ogneva-Himmelberger used a t-test to find statistically significant differences between rural populations living near wells and those not living near wells in addition to using Local Indicators of Spatial Autocorrelation (LISA) to find spatial clusters of areas that have both high well density and high proportions of vulnerable...

populations\textsuperscript{22}. While a t-test will not be used for this test, similar statistical methods will be used, namely the correlation coefficient in excel.

**DESIGN AND IMPLEMENTATION**

The methodology associated with this project is largely statistical in nature. The first part of the analysis is strictly statistical, examining the correlation between the number of wells a given company has drilled and producing and the number of acres they have leased. This statistical analysis is aided with maps that show the location of wells used for the correlation.

The second portion of this analysis will utilize spatial analysis, which is also statistical in nature as the kernel density and point density tools utilize spatial statistics. Maps produced from the kernel density and point density analysis provide a visual aid associated with these spatial analysis techniques. The final step will be to compare and analyze the findings of the statistical and spatial analyses to determine if there are any notable or distinctive patterns.

**Statistical Analysis**

The first step of this process was assessing the attributes of the well data from RigData. Then, definition queries were performed to remove vertical wells and wells that are outside of West Virginia from the data set because this study is limited to horizontal wells in West Virginia. The

\textsuperscript{22} Ibid.
statuses of these wells were closely examined after the definition queries were performed. This data set includes "wells" that have been permitted but have not yet been drilled, so differentiating between the two is a critical step. This is important because a permitted "well" has not been drilled and does not actually exist, except for on paper. The operator has simply obtained permission from the WV-DEP to drill a well at that specific location and they could easily change or abandon their plans at this stage. Additionally, differentiating between wells that are drilled and wells that are drilled and producing is the next step. Another critical determination is evaluating the different companies that operate the wells and how many wells each company has drilled and producing. Abandoned wells are not counted in the well total because these are hypothetical wells that are considered “abandoned” because a permit was filed with the WV-DEP to drill the well, but the plan was abandoned before any drilling occurred. Dry wells, on the other hand, are included in drilled well totals but not producing well totals because the well was drilled but it was found to be dry after it was drilled thus no production.

General knowledge about current happenings in the Marcellus Shale was another critical piece for an accurate assessment of the data. Chesapeake has been a major player in the Marcellus Shale in recent years but they recently sold all their acreage and operations in West Virginia to another major player in the Marcellus Shale, Southwestern. Many of the
wells are still attributed as being operated by Chesapeake but it is well known that Chesapeake has sold all assets in the region to Southwestern.\textsuperscript{23} These wells are included in this analysis as being drilled by Southwestern because Southwestern now owns the wells, but the well may have actually been drilled and started producing while owned by Chesapeake. Chesapeake has sold all assets in the area of this analysis to Southwestern.

At this point, the first two overall maps were made to show all the well locations on a map, even including locations that are permitted, abandoned, etc. First, displaying the wells by type (see figure 1 on page 3) and then displaying the wells by operator (see figure 2 on page 4). As of September 2015, there are 2,800 horizontal well locations in West Virginia that are associated with 38 companies with permitted locations. Of the 2,800 existing locations; 1,753 have been drilled by 32 operators and there are 31 operators that have 1,386 producing wells.

Excel was critical for evaluation because it is the best tool for organizing and analyzing the different sets of numbers. Well counts were compiled for both drilled and producing wells in ArcGIS, and then the top ten companies were noted for each in Excel as well as noting the company and number of wells they have drilled and producing. The top ten companies for number of drilled and producing wells were similar but not identical. The

Next step was to examine the websites and investor presentations for the companies on my top ten lists to determine the number of acres each company claims to have leased in the Marcellus in West Virginia (see table 1 on page 8).

Once these numbers were input into Excel, it was very easy to analyze them. I was immediately able to determine that the top ten drillers and producers account for a huge portion of the drilling and production activity in West Virginia. The top ten horizontal drillers in West Virginia account for nearly 87% of the drilling activity and the top ten producers account for nearly 97% of the producing horizontal wells in West Virginia. Even though there are 38 companies with locations in the Marcellus Shale in West Virginia, the top 26% of those companies account for most of the drilling and nearly all of the producing wells. It was also very easy to determine what percentage of the leased acreage each company accounts for in regards to leased acres for the top ten drillers and producers (see table 2 and 3 on page 22).

The next step was the correlation analysis between drilled wells and acres leased as well as producing wells and acres leased. By using Excel’s CORREL function, it was easy to determine the correlation coefficient between two variables. The correlation coefficient is between 1 and -1 with 1 being a total positive correlation, 0 being no correlation and -1 being a total negative correlation. See tables 2 and 3 on page 22 for results.
There is a moderately positive correlation between both drilled wells & leased acres and producing wells & leased acres, with the correlation between producing wells & leased acres being slightly more positive than the correlation between drilled wells & leased acres. This demonstrates that the number of acres a given company has leased correlates positively with the number of wells they have drilled or producing. This also demonstrates a bigger overall trend, the more land a company is able to lease, the more likely they are to drill more wells and have more producing wells than companies that have leased lesser amounts of land. Leasing large quantities of land is therefore a critical step to being successful in the Marcellus Shale. This also demonstrates the importance of the "land grab" aspect of the industry and shows how it is a variable that leads to successful development in a new shale play.

Figures 3 and 4 on pages 24 and 25 show the locations of drilled and producing Marcellus horizontal wells in West Virginia with the wells symbolized by operator. You can see that several operators have "clusters" of wells in one or a few areas. For example, Southwestern predominately drills and operates in the Northern panhandle of West Virginia while Antero is slightly south of there in Doddridge and Western Harrison counties. While a statistical analysis of the correlation coefficient is sufficient, visualizing the data on a map gives the analysis a visual and spatial dimension.
### Table 2. Drilled Marcellus Wells to Leased Acres Correlation

<table>
<thead>
<tr>
<th>Operator</th>
<th># Drilled</th>
<th>% of Total</th>
<th>Top 10 %</th>
<th>Leased Ac</th>
<th>Top 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antero</td>
<td>399</td>
<td>22.76%</td>
<td>26.22%</td>
<td>395,000</td>
<td>20.83%</td>
</tr>
<tr>
<td>EQT</td>
<td>324</td>
<td>18.48%</td>
<td>21.29%</td>
<td>90,000</td>
<td>4.75%</td>
</tr>
<tr>
<td>CHK/SWN*</td>
<td>281</td>
<td>16.03%</td>
<td>18.46%</td>
<td>413,000</td>
<td>21.78%</td>
</tr>
<tr>
<td>Noble</td>
<td>122</td>
<td>6.96%</td>
<td>8.02%</td>
<td>350,000</td>
<td>18.46%</td>
</tr>
<tr>
<td>Consol</td>
<td>109</td>
<td>6.22%</td>
<td>7.16%</td>
<td>230,000</td>
<td>12.13%</td>
</tr>
<tr>
<td>Stone</td>
<td>87</td>
<td>4.96%</td>
<td>5.72%</td>
<td>90,000</td>
<td>4.75%</td>
</tr>
<tr>
<td>Gastar</td>
<td>75</td>
<td>4.28%</td>
<td>4.93%</td>
<td>31,400</td>
<td>1.66%</td>
</tr>
<tr>
<td>XTO</td>
<td>43</td>
<td>2.45%</td>
<td>2.83%</td>
<td>170,000</td>
<td>8.96%</td>
</tr>
<tr>
<td>Triad Hunter</td>
<td>42</td>
<td>2.40%</td>
<td>2.76%</td>
<td>97,000</td>
<td>5.11%</td>
</tr>
<tr>
<td>Jay-Bee</td>
<td>40</td>
<td>2.28%</td>
<td>2.63%</td>
<td>30,000</td>
<td>1.58%</td>
</tr>
<tr>
<td><strong>Top 10 Total</strong></td>
<td>1522</td>
<td>86.82%</td>
<td>100.00%</td>
<td>1,896,400</td>
<td>100.00%</td>
</tr>
<tr>
<td>Other Operators</td>
<td>231</td>
<td>13.18%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Marcellus Total</td>
<td>1753</td>
<td>100.00%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Wells to Leased Acres Correlation:** 0.59348

*Southwestern (SWN) recently acquired all Chesapeake (CHK) acreage and wells in WV*

### Table 3. Producing Marcellus Wells to Leased Acres Correlation

<table>
<thead>
<tr>
<th>Operator</th>
<th># Producing</th>
<th>% of Total</th>
<th>Top 10 %</th>
<th>Leased Ac</th>
<th>Top 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antero</td>
<td>386</td>
<td>27.85%</td>
<td>28.78%</td>
<td>395,000</td>
<td>20.02%</td>
</tr>
<tr>
<td>CHK/SWN*</td>
<td>239</td>
<td>17.24%</td>
<td>17.82%</td>
<td>413,000</td>
<td>20.93%</td>
</tr>
<tr>
<td>EQT</td>
<td>226</td>
<td>16.31%</td>
<td>16.85%</td>
<td>90,000</td>
<td>4.56%</td>
</tr>
<tr>
<td>Consol</td>
<td>180</td>
<td>12.99%</td>
<td>13.42%</td>
<td>230,000</td>
<td>11.66%</td>
</tr>
<tr>
<td>Stone</td>
<td>79</td>
<td>5.70%</td>
<td>5.89%</td>
<td>90,000</td>
<td>4.56%</td>
</tr>
<tr>
<td>Gastar</td>
<td>66</td>
<td>4.76%</td>
<td>4.92%</td>
<td>31,400</td>
<td>1.59%</td>
</tr>
<tr>
<td>Noble</td>
<td>60</td>
<td>4.33%</td>
<td>4.47%</td>
<td>350,000</td>
<td>17.74%</td>
</tr>
<tr>
<td>Triad Hunter</td>
<td>39</td>
<td>2.81%</td>
<td>2.91%</td>
<td>79,000</td>
<td>4.00%</td>
</tr>
<tr>
<td>XTO</td>
<td>39</td>
<td>2.81%</td>
<td>2.91%</td>
<td>170,000</td>
<td>8.61%</td>
</tr>
<tr>
<td>PDC</td>
<td>27</td>
<td>1.95%</td>
<td>2.01%</td>
<td>125,000</td>
<td>6.33%</td>
</tr>
<tr>
<td><strong>Top 10 Total</strong></td>
<td>1341</td>
<td>96.75%</td>
<td>100.00%</td>
<td>1,973,400</td>
<td>100.00%</td>
</tr>
<tr>
<td>Other Operators</td>
<td>45</td>
<td>3.25%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Marcellus Total</td>
<td>1386</td>
<td>100.00%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Wells to Leased Acres Correlation:** 0.602923

*Southwestern (SWN) recently acquired all Chesapeake (CHK) acreage and wells in WV*
Fig 3. Drilled Marcellus Wells in West Virginia by Operator
Fig 4. Producing Marcellus Wells in West Virginia by Operator

![Map showing producing Marcellus Wells in West Virginia by Operator.](image-url)
**Spatial Analysis - Kernel Density**

The Kernel Density tool is a spatial analysis tool, available in ArcGIS with the Spatial Analyst extension. It is based on the quadratic kernel function and can be used to calculate density of point or line features, this analysis will be looking at point features which are bottom-hole locations. For point features, Kernel Density calculates the density of points around each output raster cell and a smooth, curved surface is fitted over each point.\(^2\) The surface value is highest at the location of a point and decreases with distance from the point, until it reaches zero at the search radius distance from the point; the search radius can only be circular.\(^2\) The population field value for the point equals the volume under the surface. For this analysis, the default, none, was used which actually calculates as one. The density is then calculated by adding the values of all the kernel surfaces where they overlay the raster cell center.\(^2\)

The algorithm used to determine the default search, or bandwidth, is:\(^2\):

1. Calculate the mean center of the input points. If a population field other than none was selected, this, and all the following calculations, will be weighted by the values in that field.
2. Calculate the distance from the (weighted) mean center for all points.
3. Calculate the (weighted) median of these distances, \(D_m\).
4. Calculate the (weighted) Standard Distance, \(SD\).
5. Apply the following formula to calculate the bandwidth:

\[
SearchRadius = 0.9 \times \min \left( SD, \left( \frac{1}{\sqrt{\ln(2) \times D_m}} \right)^{0.2} \right)
\]


\(^2\) Ibid.

\(^2\) Ibid.
Where:

- SD is the standard distance
- \( D_m \) is the median distance
- \( n \) is the number of points if no population field is used, or if a population field is supplied, \( n \) is the sum of the population field values

For this analysis, I chose to use the defaults associated with the Kernel Density tool, except for the output cell size. The default was approximately 6588, but I changed it to 100. The larger the number used the more pixelated and less generalized the product while smaller numbers produce a layer that is more generalized and aesthetically pleasing. The Kernel Density inputs were the same for both drilled and producing wells and they are listed below in Figure 5.

Fig 5. Chosen specifications for Spatial Analyst's Kernel Density Tool
Once the Kernel Density tool has produced a raster, it needs to be clipped to the state of West Virginia and the results need to be classified. The first step is to clip the raster produced by the Kernel Density tool, so the raster is limited to the extents of the state of West Virginia. This process is necessary for all rasters created for the project and will be repeated for each. To clip the raster, the “clip” tool in ArcToolbox will be used. It can be found under Data Management Tools > Raster > Raster Processing > Clip. The input is the raster produced by the Kernel Density tool and the Output Extent is the shapefile of the state of West Virginia, additionally the “Use Input Features for Clipping Geometry” box must be selected. See inputs below, in figure 6. This will produce a raster that is limited to the extents of the state of West Virginia.

Fig 6. Clip tool inputs that will be used for all rasters in this analysis
The next step is to classify the clipped raster. The Natural Breaks (Jenks) method of classification using 10 classes was utilized. The breaks and standard deviation are detailed below in figures 7 and 8. A color palate centered around the primary colors was used where red shows a high density of wells and blue shows no or very few wells. The Kernel Density values in the legend were set to only display 5 decimal points.

Fig 7. Classification of Kernel Density of Drilled Horizontal Wells in WV

Fig 8. Classification of Kernel Density of Producing Horizontal Wells in WV
Fig 9. Kernel Density of Drilled Horizontal Marcellus Wells in West Virginia
Fig 10. Kernel Density of Producing Horizontal Marcellus Wells in West Virginia
**Spatial Analysis – Point Density**

The Point Density Tool is also available in the Spatial Analyst extension to ArcGIS. It calculates the density around each raster cell by first defining a neighborhood around each raster cell; the number of points that fall within the neighborhood is summed and divided by the neighborhood’s area. From a statistical standpoint, the function of this tool is simpler than the Kernel Density tool. Defaults were used, except for changing the output cell size to 100, exactly like the Kernel Density analysis. Adjusting the population field from the default of none to a number, would cause a point to be counted as many times you input, but the default keeps the point count as one for one. The default neighborhood radius was used because increasing the radius does not change the calculated density values very much but it does result in a more generalized output raster. Since defaults were used for the Kernel Density analysis, the same was done for Point Density. The area units used for both Kernel Density and Point Density analysis was the default, square miles. This is chosen based on the linear unit of the projection of the map, which in this case is NAD 1927 UTM Zone 17N, where the unit is US foot so the default is miles. If you were using a projection based on meters, the default would be kilometers. See figure 11 for Point Density tool specifications.

---


29 Ibid.
Fig 11. Specifications for Spatial Analyst’s Point Density Tool

Much like the Kernel Density analysis, the rasters were clipped to the state of WV then classified using the Natural Breaks (Jenks) method of classification using 10 classes. The breaks and standard deviation are detailed below in figures 12 and 13. The same color palette was used and the values in the legend were set to only display 5 decimal points.

Fig 12. Classification of Point Density of Drilled Horizontal Wells
The results of the point density analysis were similar to the kernel density results but were also far from being identical. The point density results (see figures 14 and 15 on pages 34 and 35 respectively) put far more of an emphasis on Doddridge and Wetzel counties and less of an emphasis on Harrison and Marshall Counties than the Kernel Density analysis did. The results between the two analysis techniques are similar in the fact that the differences between the drilled and producing well maps for each analysis are fairly similar. Essentially, even though the data for producing wells and drilled wells is slightly different, the resultant rasters produced by the point density tool are similar and the rasters produced by the kernel density tool are similar despite the data being slightly different. The rasters produced by the point density tool appear far less generalized than the rasters produced by kernel density tool, despite using the default inputs for both aside from the output cell size, which was set at 100 for both.
Fig 14. Point Density Map of Drilled Horizontal Wells in West Virginia
Fig 15. Point Density of Producing Marcellus Wells in West Virginia
**RESULTS**

The statistical analysis of the correlation between leased acres and number of drilled and producing wells demonstrates a moderate to strong positive correlation between the number of acres a company has leased and the number of wells they have. The correlation results, which were 0.59348 for drilled wells and 0.60292 for producing wells, are similar for both drilled and producing wells. This demonstrates the importance of the land grab aspect of the industry. The companies with the largest amounts of leased acres also had the most drilled and producing wells. This places an importance on acquiring land as a premise to being a top operator in the Marcellus Shale in West Virginia. To better visualize the positive correlation, see figures 16 and 17 for scatterplot diagrams showing the general trend of companies with more leased acreage also having more wells.

![Drilled Wells/Acres Leased](image)

**Fig 16. Scatterplot of Drilled Wells to Leased Acres**
A positive correlation like this also demonstrates the importance of having money to lease land. You are more likely to be successful if you have a lot of land, therefore you need to have the money upfront to buy or acquire leases. While a moderate to strong positive correlation certainly does not mean that leasing lots of land will ensure drilling success, the more land you have the more opportunities you have to drill and the more opportunities you have to get wells to the production phase.

The spatial analysis reiterates the areas of geospatial interest for drilling the Marcellus Shale in West Virginia. While having a large number of leased acres is clearly beneficial, if the acreage leased is not economical for drilling or production, the acreage is not beneficial to gains for the company. The spatial analyses demonstrate the areas with the highest densities of drilled and producing wells, which are also most likely the areas that are...
most desirable for oil and gas drilling and production. The point and spatial analyses show the areas with the greatest and least drilling activity. To better analyze the areas with the most drilled and producing wells, I chose to further examine the wells that are within the top two classifications for point density and kernel density. This is to examine the differences between the two spatial analysis methods, the differences between drilled and producing wells and to analyze which companies are operating these wells and if they are the same companies that are also the top 10 drillers and producers. See Fig 21 and 22 for a breakdown of the wells within the top two classifications.

**Table 4. Drilled Wells Analysis**

<table>
<thead>
<tr>
<th></th>
<th>Drilled Wells</th>
<th>Producing Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Density</td>
<td>Kernel Density</td>
</tr>
<tr>
<td>AEP</td>
<td>35</td>
<td>23</td>
</tr>
<tr>
<td>Antero</td>
<td>146</td>
<td>71</td>
</tr>
<tr>
<td>Consol</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>EQT</td>
<td>88</td>
<td>199</td>
</tr>
<tr>
<td>Gastar</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>Noble</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PDC</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>Stone</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>SWN</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Triad</td>
<td>N/A</td>
<td>16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>295</strong></td>
<td><strong>357</strong></td>
</tr>
<tr>
<td># of wells, non-top 10 operators</td>
<td>43</td>
<td>32</td>
</tr>
<tr>
<td># of wells, top 10 operators</td>
<td>252</td>
<td>325</td>
</tr>
<tr>
<td>% of wells, top 10 operators</td>
<td>85.42%</td>
<td>91.04%</td>
</tr>
</tbody>
</table>

**Table 5. Producing Wells Analysis**

<table>
<thead>
<tr>
<th></th>
<th>Drilled Wells</th>
<th>Producing Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Density</td>
<td>Kernel Density</td>
</tr>
<tr>
<td>AEP</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Antero</td>
<td>178</td>
<td>185</td>
</tr>
<tr>
<td>Consol</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>EQT</td>
<td>46</td>
<td>124</td>
</tr>
<tr>
<td>Gastar</td>
<td>N/A</td>
<td>42</td>
</tr>
<tr>
<td>PDC</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>Statoil</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>Stone</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>SWN</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>Triad</td>
<td>N/A</td>
<td>16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>266</strong></td>
<td><strong>406</strong></td>
</tr>
<tr>
<td># of wells, non-top 10 operators</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td># of wells, top 10 operators</td>
<td>249</td>
<td>395</td>
</tr>
<tr>
<td>% of wells, top 10 operators</td>
<td>93.61%</td>
<td>97.29%</td>
</tr>
</tbody>
</table>
Several concluding points can be made after analyzing the drilled and producing wells in the top two classifications for point and kernel density. My initial observation after doing a well count for each of the four analyses was that the number of wells included in the top two classifications is much larger for Kernel Density than for Point Density, despite using identical inputs. This is simply a demonstration in the difference in the methods of the tools, rather than something noteworthy about the data. The most significant finding seems to be the companies that predominately operate in these "hot spots". While there are 38 companies with locations in the Marcellus, the companies with wells in the top two classification areas are predominately the same companies that are on my top ten lists for number of drilled and producing wells. If you look at the bottom line of table 4 and 5, you will see that the percentage of wells operated by top ten drillers and producers account for 85-97% of the wells in the top two classifications. That shows that the areas most ideal for drilling are dominated by the biggest companies in the area. You will also notice that Antero and EQT are the biggest players in these areas as well. For every type of analysis and well status, those two companies account for a minimum of 75% of the drilling & production in these "hot spots" of activity (see table 6). This is noteworthy, because Antero is the number 1 driller and producer and EQT is the number 2 driller and number 3 producer. Essentially, the companies that
are the most successful overall are also the companies that are most
dominate in areas with the highest density of drilled and producing wells.

Table 6. Percentage of well operated by Antero & EQT in "Hot Spots"

<table>
<thead>
<tr>
<th></th>
<th>Drilled Wells</th>
<th>Producing Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Density</td>
<td>Kernel Density</td>
</tr>
<tr>
<td>Antero</td>
<td>49.49%</td>
<td>19.89%</td>
</tr>
<tr>
<td>EQT</td>
<td>29.83%</td>
<td>55.74%</td>
</tr>
<tr>
<td>Total =</td>
<td>79.32%</td>
<td>75.63%</td>
</tr>
</tbody>
</table>

**DISCUSSION**

In conclusion, to be successful in a new shale play, leasing large
quantities of land is the best way to start because it is directly correlated
with drilling more wells and getting more wells into the production phase.
Additionally, the companies that have been able to saturate the areas that
are presumably most ideal for drilling and production tend to also be the top
drillers and producers in the region, based on spatial analysis of the areas
with the highest well densities. While success stories related to the
development of the Marcellus Shale are varied, it’s clear that leasing lots of
land gives an operator an immediate advantage but the money needs to be
available, presumably obtained from prior operations in other plays, from
investors or both. Additionally, it seems that the most dominant companies
in the area also dominate the "best" areas or the areas with the highest density of wells. This could easily be explained by the fact that if a company is able to lease a large block of land, they can more easily develop the area, than if the same block of land was leased to multiple companies with smaller chunks of land here and there attempting to develop the area. This demonstrates that purchasing large blocks of land is probably a better development tactic than leasing the same amount of acres in small, discontiguous blocks of land.

**AREAS FOR FURTHER RESEARCH**

There are several different types of analysis that could help further my research, namely other types of spatial analysis. The WV-DEP well data obtained from RigData has numerous other attributes that were not examined in this analysis but could easily have value for other types of analysis. That is the best area to further research related to spatial analysis and spatial patterns. In regards to production results, further analysis could be done in regards to production volume of wells and economic output of a well.

**Line Density Analysis**

The Point Density Tool can also be used to analyze line density. I used point density to analyze the bottom hole locations of wells, but I could have gone another way with this analysis and looked at the horizontal well bores,
which are lines. It would be interesting to see if there are any differences between the point analysis of bottom hole locations and the line analysis of the corresponding horizontal wellbores.

**Hot Spot Analysis**

Hot Spot Analysis is an ArcGIS tool in the spatial statistics toolbox. It is used to identify statistically significant clusters of high values, called hot spots, and low values called, cold spots, using Getis-Ord Gi statistic. It creates an output feature class with a z-score and p-value for each feature. The z-score and p-values indicate whether the spatial clustering is more prominent than you would expect in a random distribution. The further the z-score is from zero, the more intense the clustering is. A z-score of zero indicates no obvious spatial clustering. This tool could be used as an additional method to identify significant spatial clusters of high values. The resultant raster of hot spots could be used to compare against the results from the point density and kernel density analyses to further assess significant spatial patterns and clusters.\(^\text{30}\)

**Time Analysis**

Time, or the "when" aspect of the Marcellus Shale boom, is another variable that could be investigated further to better understand the role time played in success stories. Were the companies that drilled and completed the

first horizontal wells also the companies who have been the most successful? Initially, I hoped to examine this variable as well but chose not to because of discrepancies in the data. The well data I acquired from RigData is attributed with permit data, spud date (date drilling starts) and completion date. While most wells I examined were attributed with this data, not all were. Most wells had at least one date attributed but the analysis would not be complete unless every well was attributed with at least one of those dates that I could then use for analysis. It is possible that these dates would be available through the WV-DEP, but that would involve a fair amount of leg work. The date I would be more interested in analyzing would be the SPUD date, or date drilling commenced. It would be interesting to create an animation in ArcGIS based on this date with well locations symbolized by operator.

Horizontal drilling of the Marcellus Shale has only been occurring for approximately 10 years, so an animation that shows wells drilled at 3-6 month interval over the last 10 years would be quite interesting. Examining the timing when wells were drilled in comparison to spatial and statistical patterns for drilled wells would be interesting.

**Big Picture Analysis and Other States**

It would be interesting to do this same study for the Marcellus Shale as whole, doing the same analysis but for the entire play. Or do additional case studies on other states experiencing Marcellus Shale development, such as Pennsylvania and New York.
REFERENCES


Corporate Website Sources for Leased Acreage Numbers

Antero Resources - www.anteroresources.com

Chesapeake Energy - www.chk.com

Consol Energy (CNX) - www.consolenergy.com

EQT Corporation - www.eqt.com

Gastar - www.gastar.com

Jay-Bee - www.jaybeeoil.com

Magnum Hunter (Triad) - www.magnumhunterresources.com/

Noble Energy - www.nobleenergy.com

PDC Energy - www.pdce.com

Southwestern Energy - www.swn.com

Stone Energy - www.stoneenergy.com/appalachia

XTO Energy - www.xtoenergy.com
APPENDICES

Dictionary of Terms and Acronyms

Bottom Hole Location: The subsurface point at the greatest measured penetration of a well or a well branch.

Casing: A large pipe that is assembled and inserted into a recently drilled section of a borehole, typically held into place with cement.

Correlation coefficient: A coefficient that illustrates a quantitative measure of correlation and dependence; a statistical relationship between two or more random variables or data values.

Drill bit: What cuts into the rock while drilling for oil and gas.

Drill Cuttings: Broken bits of solid materials removed from a borehole.

EIA: United States Energy Information Administration

Flowback Water: Flowback is a water-based solution that flows back to the surface during and after the completion of hydraulic fracturing.

Horizontal drilling: The process of drilling non-vertical wells.

Hot Spot Analysis: A spatial statistics tool that identifies clusters of values that are higher in magnitude than you would find my random chance.

Hydraulic Fracturing: A well-stimulation technique in which rock is fractured by a pressurized liquid.

Kernel Density: In statistics it is a non-parametric way to estimate the probability density function of a random variable.

LISA: Indicators of Spatial Association; Statistics that evaluate the existence of clusters in the spatial arrangement of a given variable.

Marcellus Shale: A marine sedimentary rock found in eastern North America, it extends throughout much of the Appalachian Basin and the shale contains largely untapped natural gas reserves.

Point Density: Geospatial tool that calculate a magnitude per unit area from point features that fall within a neighborhood around each cell.
**Shale Play**: The term "play" is used in the oil and gas industry to refer to a geographic area which has been targeted for exploration due to favorable geoseismic survey results, well logs or production results. An area comes into play when it is generally recognized that there is an economic quantity of oil or gas to be found.

**SPUD**: The process of beginning to drill a well.

**TCF**: Trillion Cubic feet; common unit of measurement in the oil & gas industry for volumes of gas.

**Well Completion**: The process of making the well ready for injection or production.

**W V-DEP**: West Virginia Department of Environmental Protection