PUBLIC DATA ANALYSIS OF PARENT-CHILD WELL RELATIONSHIPS ACROSS US UNCONVENTIONAL BASINS

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Abstract

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Parent-child wells are horizontal wells drilled in close proximity to each other in unconventional basins. Simulation work in the technical literature demonstrates how the depletion effects and fracture communication between parent and child wells can lead to child well underperformance. High-level, basin-wide data analysis of unconventional basins confirms this effect. However, as completion designs evolve and more state-of-the-art horizontal wells are completed in these basins, it is necessary to revisit this analysis and make adjustments and additions to the previous body of work. Specifically, initial production differences between parent and child wells need to be correlated to cumulative production differences, and more analysis regarding the effect of timing and spacing were in order. In this study, parent-child well pairs for wells completed within the last seven years in nine different unconventional basins are identified with Python code and Enverus public data obtained in November 2020. Those basins include the Bakken, Delaware, Eagle Ford, Haynesville, Marcellus/Utica, Midland, Niobrara, Powder River, and Scoop/Stack Basins. In Python, calculations are performed to create the necessary comparative metrics for analysis. Four cumulative production proxies are created and First 12 Months BOE (barrel of oil equivalent) is chosen as the appropriate metric for analysis. Basin-to-basin comparisons are conducted, and the effects of well spacing and infill timing are investigated. The study finds that as stated in the technical literature, child well performance increases with spacing and decreases with infill timing but asserts that parent produced BOE at child completion is a better indicator of child performance. Additionally, the study finds that child well productivity decreases with parent proppant loading and increases with child proppant and fluid loading. Overall, these assessments can help operators manage child well underperformance and can help them understand the effects of differing completion metrics on child well performance in different US unconventional basins.

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Public Data Analysis of Parent-Child Well Relationships Across US Unconventional Basins

While suppressed commodity prices and environmental and political concerns weigh heavily on the industry, the most pressing engineering problem for the economic viability of prospects in the oil and gas unconventional space is understanding and determining how to increase the production of infill wells, or child wells, to that of their initial, predecessor wells. Infill wells refer to horizontal shale wells drilled alongside, generally parallel to, existing horizontal wells called the parent wells. In these shale formations, the reservoir rock has extremely low permeability, so long wellbores are drilled and frac'ed at regular intervals to increase the surface area exposed to the reservoir rock. The large surface area contacting the virgin source rock created by these fractures allows these expensive wells in the low permeability medium to be economically viable.

At the outset of the shale boom, exploration and production companies typically drilled one well per 640-acre section of their newly leased land. As a stipulation of the lease terms, generally the operators were required to drill and produce each lease within a certain period of time, typically two to three years, to hold the acreage and avoid expiring the lease contract. Producing a well on a lease designates that lease Held By Production (HBP), affording operators additional time to drill other locations before returning to the section to drill more wells. Only after drilling all their expiring sections would an operator typically return to drill infill wells on previously leased acreage. However, as infield development progressed over time, problems associated with drilling the child wells began to manifest themselves. The problem that operators experienced most frequently was that the interaction between parent and child wells often decreased production and ultimately decreased recovery rates causing lower economics in both parent and child wells.

These problems occurred when the child wells' fracture network interacted with that of the parent wells. Miller et al. (2016) first noted the positive and negative effect that child wells' stimulation could have on the parent wells. The paper highlighted that child wells were beginning to constitute a higher proportion of new wells drilled, and that percentage has increased significantly since its publication. Subsequently, Lindsay et al. (2018) developed code to identify these parent-child well pairs to compare their production. The 2018 paper concluded that after normalizing to total proppant and lateral length, the parent wells outperformed the child wells 70-80% of the time, whereas longer lateral lengths and higher volumes of proppant made the child wells capable of producing similar result to the parent well on an absolute basis. This study was followed by Xu et al. (2019), which used a similar methodology as Lindsay et al. (2018) to identify parent-child well pairs. This study investigated parent-child production differences for various interval targets within the Midland and Delaware Basins and provided more granular detail regarding well traits.

These analyses are worthwhile exercises, but there are more aspects of the data that deserve inspection. For example, many wells have been completed or have recently met the production time criteria for consideration as parent-child well pairs since the two studies' publication dates. Considering completion designs have become more uniform since the publishing of those papers, this new data could provide a clearer picture of the difference in parent and child well production. This paper aims to detail the problems associated with completing infill wells, describe the available public data analysis of parent-child wells, and outline concerns with the analysis. Lastly, it will detail the reasoning, methodology and results behind the Enverus public production data analysis of ten different shale basins: the Bakken, Delaware, Eagle Ford, Haynesville, Marcellus/Utica, Midland, Niobrara, Powder River, and Scoop/Stack Basins.

Challenges with Child Wells

Many different factors influence the completion and production of a child well. An engineer's role is to determine the optimal way to complete infill wells to mitigate those risks, namely depletion and fracture communication, and maintain economic efficiencies. This section provides a high-level overview of the primary problems that cause child wells' reduced production performance.

Depletion. One significant problem with drilling infill wells is the effect of depletion on the child well's fractures. When the parent well is produced, a lower pressure area forms around the fracture network due to removing fluid from the system. Due to the decreased reservoir pressure caused by the parent well production, the rock formation stresses lower. This pressure depletion can lead to fracture asymmetry in the child well (Kumar 2020). Specifically, fracture asymmetry refers to the difference in fracture wing lengths as child well fractures grow preferentially and longer towards the parent well, which is the depletion source. Kumar et al. (2020) performed simulation work to demonstrate how this depletion and differing reservoir characteristics would affect this fracture asymmetry, and the effects are quite significant. Kumar et al. (2020) define the measure of fracture asymmetry according to the following formula:

$$Asymmetry = \frac{L_2 - L_1}{L_2 + L_1} \qquad \text{(Eq. 1)}$$

In the equation, L_2 represents the length of the fracture wing extending towards the parent well's depletion area, and L_1 represents the length of the fracture wing extending away from the depleted zone. Due to the fracture's preferential growth towards the parent well, L_2 will consistently be larger than L_1. The simulation work shows that fracture asymmetry eclipses 0.5

after only four months of parent production. Put differently, an asymmetry score of 0.5 would indicate a 3:1 length ratio of the fracture wings towards the parent well. The asymmetry scores plateau at a maximum of around 0.85 as the infill timing increases. Kumar et al. ran sensitivities for the following reservoir properties, permeability, porosity, viscosity, and compressibility, but the work is best summarized when the variables combine into diffusivity:

$$Diffusivity = \frac{k}{\phi \mu c_t} \qquad \text{(Eq. 2)}$$

Using this reservoir diffusivity allowed the authors to create a color plot of fracture asymmetry for infill timing and diffusivity. This plot included general diffusivity ranges for a few common shale reservoirs, highlighting how routinely the rock properties can vary between reservoirs and how different the effects of depletion can be.

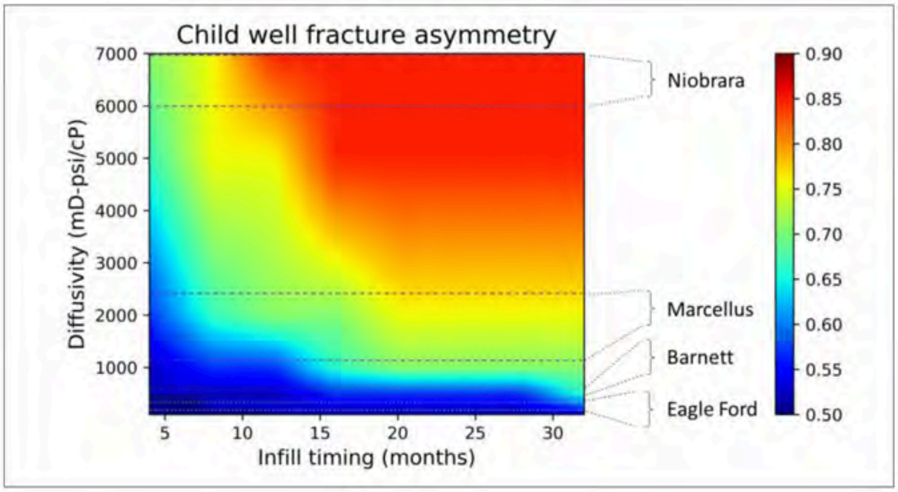


Figure 1. Fracture asymmetry for infill timing vs. diffusivity (Kumar et al. 2020)

This study simulated the fracture asymmetry to understand its impact on production. Kumar et al. (2020) focused on the production of the parent-child well pair as a whole with a baseline production assuming simultaneous completion of both the parent and child wells. Below are the results of those simulations.

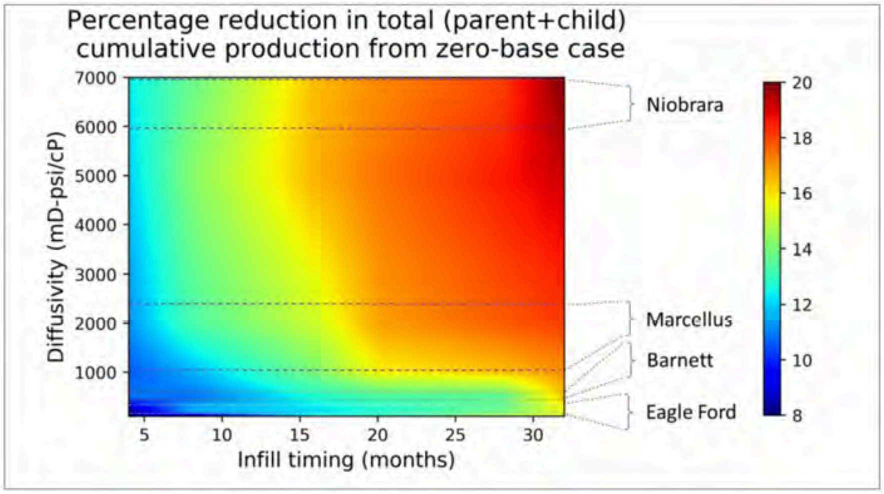


Figure 2. Total production as a function of infill timing and diffusivity (Kumar et al. 2020)

The graph clearly shows that child wells' production is affected by infill timing and that the effect can be significant. The paper does not quantify the percent difference in EUR performance between parent and child wells since their production is combined. However, typically heavily frontloaded unconventional well production suggests that much of the production loss results from the child well underperformance. Therefore, it is fair to assume that parent depletion can lead to child well underperformance of 20-30% in many cases, even more depending on the infill well timing and reservoir properties. As hypothesized, timing and the geologic properties that determine reservoir diffusivity have a material effect on the depletion interference from the parent well. Parent well depletion, and in turn, fracture asymmetry, can derail the positive economic return of a child well. This paper aims to analyze parent-child well pairs' public data to better understand this trend in practice. In the data analysis set forth, one would expect to see the effect of timing and spacing on the parent and child wells' production difference. It will be more challenging to see the effect of reservoir diffusivity because public geological data is not readily accessible. Ideally, the data will support the contention that child well underperformance is due to parent well depletion effects as simulated and predicted in Kumar et al. (2020).

Fracture Communication. Another issue associated with infill drilling is fracture communication between the existing parent fracture network and the propagating child fractures. Although much like depletion effects, the relationship to spacing characterizes fracture communication. Depletion is the pressure sink, and associated stress changes create fracture asymmetry, whereas fracture communication is the interference between fracture networks and the overlap in stimulated reservoir volume (SRV) that also causes child well underperformance. This communication is primarily a function of well spacing since it is necessary for the child well's fractures to interact with those of the parent by moving into its fracture network. Lindsay et al. (2018) describe this as the "balancing act" between single well EURs and pad-level economics. The decline in potential production due to tighter spacing manifests in the decline curves produced by Rafiee and Grover (2017).

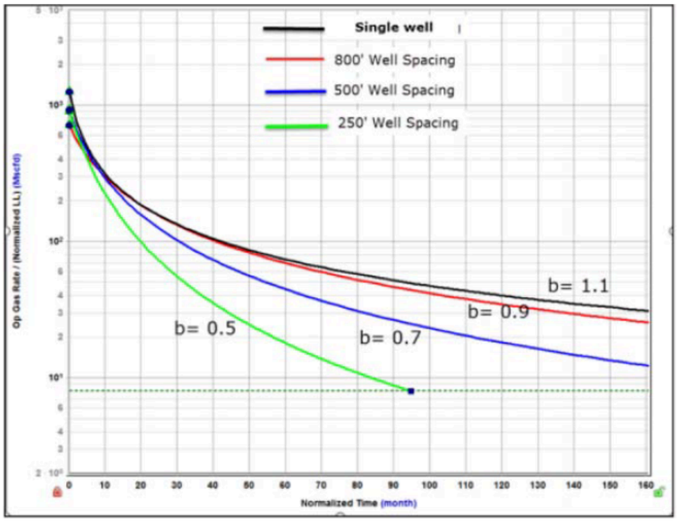


Figure 3. Decline curve results for varying well spacings (Rafiee and Grover 2017)

Kumar et al. (2020) also discuss the dilemma of well spacing and fracture interference. The researchers simulated three different fracture spacings: 660 feet, used in their depletion analysis, and two wider spacings of 754 feet and 880 feet. Again, the results indicated a reduction in both the parent and child well's total production, illustrated below.

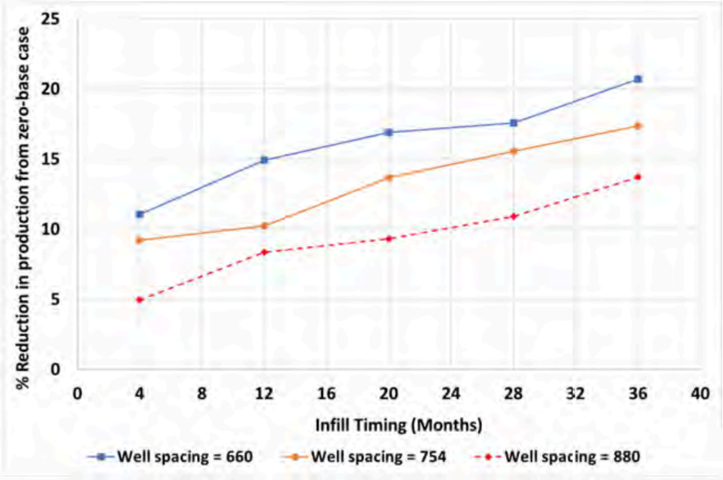


Figure 4. "Impact of well spacing on parent-child well interactions. Loss in total production increases with decrease in well spacing." (Kumar 2020)

Overall, fracture networks are more likely to overlap with closer spacing, making fracture intersection more likely. Correct spacing and infill timing can play a meaningful role in mitigating the damaging effects of fracture interference on total production. This paper will empirically investigate the impact of well spacing on parent-child well production differences.

Current Public Production Analysis

The data analysis conducted in this study was inspired primarily by the work of Lindsay et al. (2018) and Xu et al. (2019), two groups of Schlumberger researchers. Both groups took a high-level approach to analyzing and characterizing various unconventional basins by aggregating all parent-child well pairs within each basin for analysis. It is necessary to understand their methodology and results to appreciate the methodology changes and assumptions adopted in this study's approach. This section details the Lindsay et al. (2018) study, the Xu et al. (2019) study, and the subsequent changes to methodology adopted.

Lindsay et al. (2018).

The first public data analysis performed on horizontal infill well pairs was performed by Lindsay et al. (2018). They noticed the distinct lack of basin-wide parent-child production trends analyzed and documented in industry literature. They sought to obtain a better grasp of child well performance compared to parent well performance in order to understand the impact of infill drilling programs. The study analyzed public IHS well level data for eleven different unconventional basins: Bakken/Three Forks, Barnett, Bone Springs, Eagle Ford, Fayetteville, Haynesville, Marcellus, Niobrara, Wolfcamp (Midland and Delaware), and Woodford Basins. The researchers employed a statistical moving window approach to gathering well pairs. McCain et al. (1993) first employed this method, and many others have since. In this technique, the method compares each well in each basin to the wells surrounding it within a certain distance radius. The identifying point for each well was the midpoint of the well's horizontal wellbore. The method preserves each pair for analysis as long as the surrounding wells are sufficiently younger, or child wells. The study set the time difference threshold at 12 months. Thus, from the midpoint of each well, any wells within the defined radius and completed more than 12 months later would be considered child wells to the primary parent well in question. Additionally, the study required that the child well have 12 months of production history, meaning the child is one year old, and the parent is at least two years old per the study parameters. A diagram used in the paper, displayed below, allows visualizing the grouping technique.

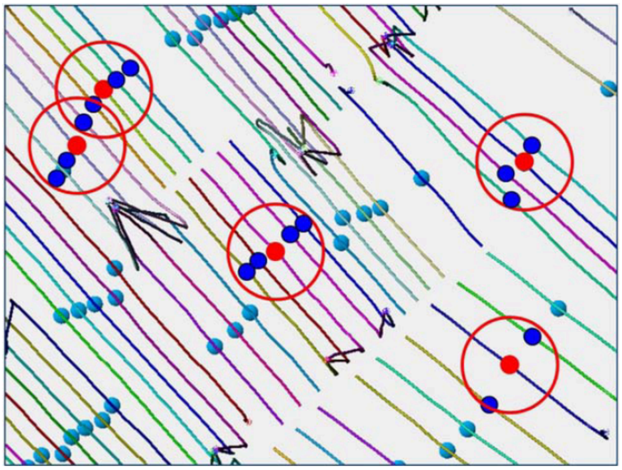


Figure 5. Parent-child well pairs using the moving window approach (Lindsay et al.2018)

The researchers explain that by aggregating all wells for the basin, the aspiration was to understand the basin on a high level, rather than scrutinize well pairs because there would be significant scatter. The analysis involved calculating the best 12-month volume (B12) for each well and comparing the parent well and child well's best 12-month volumes. The volume used for the study was a barrel of oil equivalent (BOE) with 1 BOE equaling 1 barrel of oil or 6 Mcf of gas. The study aggregated the results of each pair by ranges of spacing. The wells were grouped according to distances, below 1000 feet, and then in 500-foot intervals increasing to 2,500 feet. For example, for parent-child well pairs in the Eagle Ford with under 1,000-foot spacing, child wells had higher best 12-month production volumes 51% of the time. They also showed results for best 12-month production volume normalized by total proppant in pounds and lateral length in feet. In general, the study analysis indicated child wells were better around 50% of the time on an absolute basis but were worse 60-80% of the time per the normalized basis.

Additionally, the researchers produced a graph for each basin that displayed the difference in time between the parent and child completion versus the percent difference between normalized parent and child best 12-month production volume. These graphs confirmed that the parent wells outperformed on a normalized basis. The data also revealed that the smaller the time difference between the parent and child completion, the more likely for the normalized child well to outperform the normalized parent well.

Xu et al. (2019).

A similar parent-child study was conducted the following year by Xu et al. (2019), which was completed by much of the same group from Schlumberger. This study utilized the same moving window approach as Lindsay et al. (2018), but it furnished new metrics and further analysis, specifically on changing completion designs over time. Furthermore, it added a section displaying the impact of increasing proppant per lateral foot values on peak production and Estimated Ultimate Recovery (EUR). The study focused on the Permian Basin, performing separate analyses for the Midland and Delaware Basins' primary target formations. This paper had similar inclusion criteria for parent-child well pairs. "A radius of 2,000-ft spacing and at least a 1-year production history gap between the parent and child wells were used" (Xu et al. 2019). The study did not discuss production techniques and assumed stationarity for geological and reservoir properties. Again, the researchers used IHS public data, retrieved in October 2018. The Xu et al. paper used BOE as its production measurement with 1 BOE equaling 1 barrel of oil or 6 Mcf of gas and used the best 12-month production (B12) measurement. Unlike the Lindsay et al. (2018), Xu et al. (2019) only considered parent-child well pairs that landed in the same target interval. The paper displays a scatter plot of total proppant in pounds versus horizontal length with data points sized by B12 production. They conclude that total proppant increases with lateral length, that total proppant has increased steadily, and that production increases with an increase in total proppant and lateral length. The following graph also corroborates these trends.

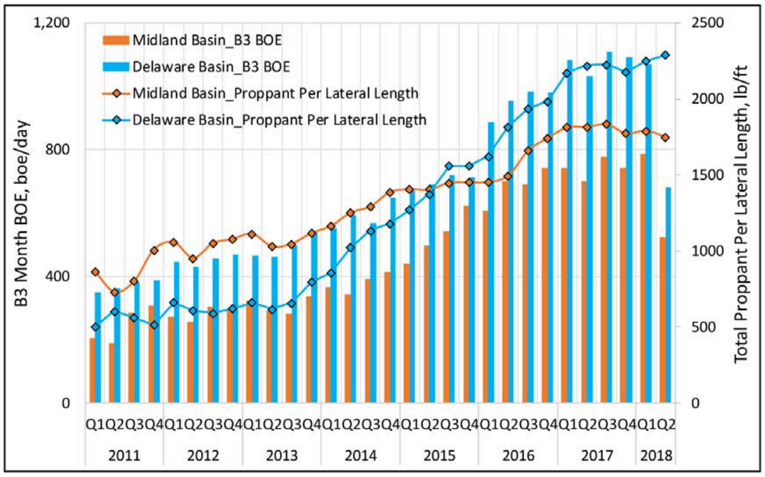


Figure 6. Trend plot for proppant per lateral length and best 3-month BOE in Midland and Delaware Basins (Xu et al. 2019)

From the graph above, there appears to be a clear correlation between proppant per foot and best 3-month BOE production average. Following a type-curve analysis on all the wells, it also becomes clear that the increase in 30-year EUR over time correlates closely with the increase in proppant per foot. However, these results do not reveal anything about parent-child well relationships as the study grouped them for this analysis. This section shows how increasing sand proppant totals significantly improved the economics of these shale basins. The study then progresses to its infill well analysis and starts by highlighting completion changes over time. Compared to parent wells completed early in these basins' development, completion of the child wells employed much larger proppant packages. In the Midland basin, many of the target formations showed child wells completed with 20-30% more proppant per foot than parent wells drilled before 2015 or 2016. In the Delaware Basin, completion of the child wells employed proppant per foot values anywhere from 30-50% over their parent wells. The study notes that around 2015 or 2016, the parent wells utilized larger packages, and the gap closed significantly. This paper will dedicate some analysis specifically to the period post-2016 in consideration of the completion jobs of parent wells and their child wells are much closer in completion proppant totals. The author proposes that studying parent and child wells with similar completion packages is the ideal way to perform parent-child analysis.

The Xu study then proceeds to the results of production. While the Lindsay et al. (2018) study focused on comparing the B12 values of each parent-child well pair, this study places a predominant focus on best 1-month (B1) values, both absolute and normalized. On an absolute production basis, the parent wells outpace the child wells around 65-70% of the time for well spacing below 800 feet; however, for spacings larger than 800 feet, the parent wells outperform the child wells generally no more than 50% of the time. On a normalized basis, the parent wells outperform approximately 80% of the time. This information does not provide meaningful insight into the cumulative value of the wells. With the estimation assumptions involved in allocating public data, it is dangerous to utilize only one month of oil production data to judge a well. Flowback procedures significantly influence peak production; therefore, if the study does not ensure that parent and child wells have the same operator (since the operator likely has standard choke procedures), one month of production is insufficient data to provide conclusions.

Another issue pertains to normalizing peak production by proppant totals. This method does not provide valuable information because the study data indicates that parent completion jobs used much less proppant. The parent wells had the benefit of a virgin reservoir but pumped significantly less proppant, whereas child wells used larger volumes of proppant to overcome the effects of depletion and fracture communication. Normalizing by proppant totals would only make sense in a parent to parent or child to child comparison when reservoir conditions are similar. Since the normalization is between parent wells and child wells, the normalized results obscure conclusions about the cumulative value of the wells, which is undesirable for analysis purposes.

Finally, the study analyzes a proxy they developed for production decline rate: B1/B12, or best 1-month BOE divided by best 12-month BOE. This section provided the most compelling results of the study. Xu et al. (2019) created a cumulative distribution plot of the best 1-month production difference between parent and child wells. Since peak production can significantly affect the decline rate, they compared only the parent-child well pairs in the middle 40-60th percentile of the best 1-month production difference. This chart, displayed below, indicates that the child wells of pairs spaced more closely together are more likely to have more significant declines than their counterparts, specifically in the Midland Basin. However, as the well spacing increases, the parent wells are increasingly likely to have a higher decline rate, demonstrating that child wells are less likely to be impacted by the depletion effects as spacing increases. One might expect an even probability for large spacings due to decreased depletion effects; however, larger parent declines suggest that increased proppant loading improves decline profiles, yet, at closer spacings, the depletion effects are simply too much to overcome.

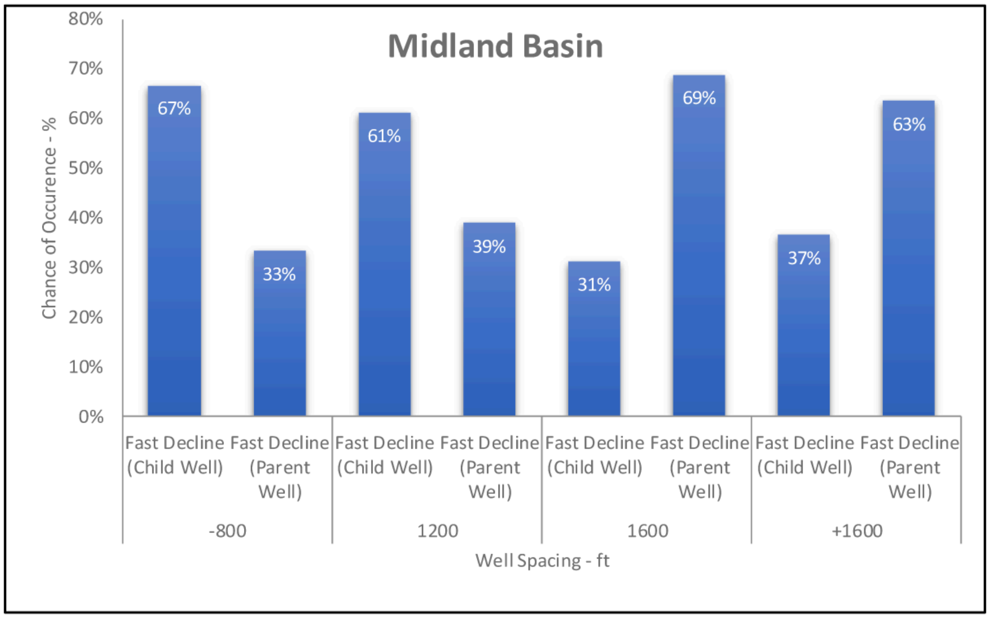


Figure 7. “Delaware Basin P40 – P60 child and parent well B1/B12 decline grouped by well spacing.” (Xu et al. 2019)

In the Delaware basin, parent wells consistently display more rapid decline rates than the child wells, but this basin also received a more pronounced average increase in proppant loading than the Midland Basin. Perhaps this trend is caused by the effects of completion design changes.

Xu et al. (2019) empirically demonstrates many of the production trends that would be expected from parent-child well pairs and qualitatively highlights the industry completion trends that have contributed to the Midland and Delaware Basin's explosive growth. Specifically, their data that emphasizes the difference in parent-child decline rates with spacing is especially interesting as it confirms many suspicions regarding the effect of fracture communication. This study aims to build off the findings of Xu et al. (2019) to uncover additional empirical trends.

Concerns with Methodology and Adjustments Made

After examining the two studies detailed above, it becomes apparent that there is more to investigate in the data, and significantly more data has become available in the years since the studies cited were published. Notably, the earlier studies were not insignificant, and this study is not likely to void the results. This study aims to improve on the work done previously and address details that raise concerns. The preceding section included a number of details regarding these issues and concerns; however, this study aims to present an analysis and more explicit illustration of these issues and concerns and their resolution.

12-Month Completion Date Difference. One criterion of a parent-child pair in the Lindsay and Xu studies was that child wells were required to be completed more than 12 months after the parent. As we learned in the Kumar et al. (2020) study, depletion effects and fracture asymmetry can begin to affect the child well's completion as early as four months, with fracture asymmetry even more pronounced by 12 months. However, after 12 months, the increase in fracture asymmetry appears less pronounced in formations that do not have high diffusivities;

thus, gathering infill data points within that 12-month timeline is an important task. This study postulates that including those data points in the analysis is the most likely way to distinguish the impact of infill time difference impacting child wells. Additionally, operators supporting a robust development plan to mitigate the risks associated with infill drilling routinely complete child wells within that 12-month threshold, and this study maintains that including those data points in the data set is essential. This analysis employs a three-months difference in completion dates as a cut off for including a well pair. Including this limit avoids incorporating well pairs that are a part of the same pad or completed simultaneously, which would not be considered parent and child wells. On the other hand, including additional well pairs completed with shorter time differences allows a view of the effects of depletion over time.

Percent Difference in Production Not Provided. The studies cited conducted much of the analysis on a binary format. The data aggregated the answer to the question: was the parent well or child well more productive during their best 12-months of production? There are undoubtedly important takeaways from this form of analysis, and it is a strong starting point. However, this study proposes that it is important to provide quantitative differences in production between the parent and child wells. Including a percent difference in production is especially important if the parent-child well pairs have large time differences between completion jobs since the magnitude of the production difference is often considerable and varies widely in that scenario. The question becomes how much worse the child well performs versus the parent wells rather than merely which well performed better.

The previous studies certainly had many well pairs that had a large time difference and did not provide enough quantitative analysis of the impact of infill timing. This study concluded that metrics like the percent change in production between the parent and child well should be used more often in the analysis and that aggregation of data should avoid percentage of wells that outperformed. This numerical approach will allow comparison of the magnitude of the production differences between parent and child well and compare the production results to simulations in order to gain a more concrete understanding of the relationship between simulation results and reality. Lastly, by using percent differences in parent-child well production data, a correlation develops between the initial production results and the cumulative results, a correlation not referenced in the existing literature. These correlations can display this initial production metric's effectiveness as an analytical tool and will be discussed further in the following section.

12 Months of Child Production Data/No Correlation of Initial Production Results to Cumulative Results. The studies outlined included only child wells with 12 months of production to show B12 comparative calculations. This 12-month criterion was selected arbitrarily and was not backed up with any data correlating it to cumulative performance. This production length requirement, coupled with the 12-month completion date difference requirement, implies that all parent wells had at least 24 months of production, and many were likely older. As mentioned earlier, the well pairs completed since 2017 appear to be the most consistent in the total amount of proppant pumped per lateral foot; therefore, suggesting as many new wells as possible must be included. The newer parent-child wells are probably more similar in completion design, resulting in our analysis reflecting a more consistent comparison. The fact that the length of time of initial production time is chosen arbitrarily calls into question its usefulness as a metric for implying overall production differences between two wells. This study will conduct analysis to produce that correlation and prove the effectiveness of a production proxy.

This study also requires fewer months between parent and child completions, thereby increasing the number of well pair data points. Employing this technique helps accumulate supplemental data points to quantitatively demonstrate the difference between initial production and cumulative production for the wells. For example, Xu et al. explain that “B1 BOE production was compared because it represented the best single-month production the well could attain, which can be a good reference for the production potential” (2019). This study completed a more rigorous evaluation of cumulative “production potential.” This study created four production proxies to discover the necessary months of production wells required to generate a meaningful comparison. The study then compared those to the cumulative production difference in well pairs calculated when the parent well had the same number of months as the child well exhibits currently.

Generating decline curves is the ideal way to perform this analysis; however, it was not possible with the tools available derived from public data sources. A discussion of this methodology appears in greater depth in later sections. After performing this analysis, the study expects to provide a clearer idea of what number of months of production is vital to predict the cumulative production difference between infill well pairs and expects to have an improved idea of that prediction’s accuracy. Lastly, the study includes comparably more data points by shortening the number of months required for child inclusion.

Spacing Metric Based on Midpoints. The spacing measurements in both of the studies were simply the 3D distance between the parent and child wells’ midpoints. This technique works properly if the wells’ layout is relatively uniform and parallel, starting at the edge of a square section and drilled to the end. In reality and practice, many of these horizontals are not drilled perfectly parallel to each other, nor are they the same lateral length. These differences in the trajectory result in distances between well midpoints that do not represent the average distance between wells. The example below shows how an error like this could occur. In this case, the two considerably extended wells and any of the shorter wells would register a spacing much larger than they actually are in actuality.

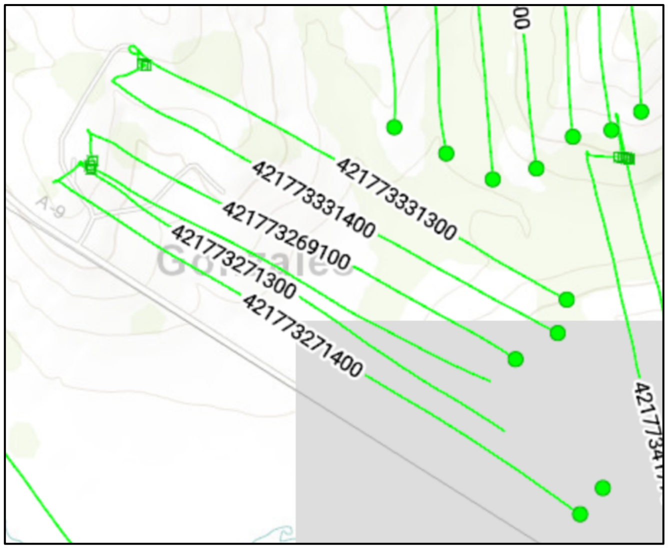


Figure 8. Example of non-uniform well trajectory

A mathematical technique involving projections must be employed to correct for this error and calculate the shortest distance to the opposite well path at each end of the well. Since the analysis aggregates well pairs within spacing intervals smaller than the those in the previous studies, obtaining accurate distances for the well pairs is a crucial element to the analysis.

Production Data Normalization. Both earlier studies used total proppant in pounds as a normalization metric for well production. For example, Xu et al. explained that “B1 BOE normalized by the total proppant and lateral length was also studied to understand the completion impact” (2019). However, this study contends a linear relationship between the mass of proppant used and well production as this metric would imply. A review of the literature failed to find support for this claim, nor does Lindsay et al. (2018) reference any support for using proppant totals for normalization either.

On the other hand, Xu et al. (2019) discuss proppant loading at length. It highlights that an increase in proppant loading has contributed to an increase in production volumes and that parent and child wells have begun to have more similar proppant loadings, given the homogeneity between recent vintages of parent and child completion designs. However, their analysis does not support its use as a normalizing metric either, since there is no evidence to prove that the relationship is linear. There are also other reasons to be skeptical of proppant as a normalizing feature. The completion of many of the well pairs considered in the studies occurred when completion designs were evolving rapidly and could be dramatically different between the parent and child wells in some cases. It is certain that, on a macro level, total proppant per foot increases have coincided with production increases, as seen in *Figure 6*, but they have also coincided with other completion technique advances such as extreme limited entry and optimized stage spacing. Also, the proppant effectiveness is more complicated than total mass, so again, the study disagrees with its use as a normalizing metric. This study avoids using it altogether.

Additionally, in both studies, more prominently in Lindsay et al. (2018), production was either normalized by lateral length and total proppant together or not normalized at all. Although this study does not use proppant totals, normalization by lateral length is a valid and industry standard methodology for well analysis. Yuan et al. (2017) employ simulation work to determine that production performance increases near linearly with lateral length. For wells with high initial rates and longer laterals, this trend can deviate slightly to a polynomial fit with a decreasing marginal production benefit with lateral length, but generally, the decrease is slight. This sudy’s analysis employs normalizing production by only lateral length, a procedure not performed in the previous two studies.

Filtering Wells Not Drilled by the Same Operator. Just as this study uses parent-child well pairs completed within a shorter time difference to encourage similar completion designs and procedures, this study also filters out and removes wells not drilled by the same operator. This decision provides the highest probability that the completion procedures and the choke schedule are similar. When using initial production proxies with minimal production months to estimate cumulative production differences, flowback procedures can play a sizable role in determining initial production rates. This selection parameter did not exclude many data points since by definition the same operator drills most child wells on the same lease.

Data Analysis

Given the considerations discussed in the previous section, a discussion of the code, methodology, and results of this project's different analyses follows in this section. After careful consideration, the First 12 Months BOE was chosen as the optimal production proxy for future analysis. The study investigates spacing, timing, and several completion factors using boxplots and production heatmaps of the First 12 Months BOE to compare the basins.

Methodology

The code, written in Python, organizes well data and identifies parent-child well pairs. Python is a popular among engineers particularly in performing numerical analysis. The first step of the process was to read in the individual well headers data and well production data for each horizontal well in the basin. As previously mentioned, retrieval of this data from Enverus took place in November of 2020. Enverus, formerly DrillingInfo, is the world's largest upstream data and analytics company. The data provided from Enverus included all horizontal wells within each basin completed within the last seven years. Seven years was required to provide enough data for analysis, especially the proxy correlation, which required older wells for calibration. The study selected seven years because, according to *Figure 6,* 2013 was roughly when horizontal wells started to employ larger completion packages. Subsequently, data cleaning measures ensured that the data was ready for ensuing calculations. Those measures included eliminating a small number of infinite values, converting latitude and longitude coordinates to cartesian coordinates, and converting date data to a form adequate for Python. Afterward, total proppant and total fluid metrics were identified in the production data and appended to the well header data for later calculations.

With the base data ready to be utilized, the study created four production proxies for cumulative production with a range of months of production included for well performance evaluation. These four proxies included between three and fourteen months of production data. The study ultimately adopted the First 12 Months as the production proxy for all subsequent production analysis. The explanation of these production proxies follows.

All production metrics were normalized by lateral length since a well’s lateral length is a key driver of production performance. Since parent-child wells are typically similar in lateral length and normalizing by lateral length is a typical industry practice, all production analysis employed normalized data. Specifically, the study used Enverus’s ‘DI Lateral Length’ metric to normalize the data. Lateral length is typically reported by gross perforated interval. In the cases when that data does not exist, a simple horizontal length is typically used. The gross perforated interval is typically a more accurate measure of the well’s stimulated length and is less likely to contain errors due to misreporting of well trajectories.

Finally, the parent-child well pairs are identified within 1,500 feet using a KD Tree. This method arranges the data by 2D, areal proximity for efficient filtering to wells within the desired radius. With a list of pairs available, well pairs that do not meet the remaining parent-child inclusion requirements are excluded, and comparative metrics are calculated for the remaining parent-child well pairs. Those additional exclusion criteria include

1. a maximum 200-foot distance in the vertical direction in order to bound the wells, and exclude horizontal from entirely different targets,
2. a requirement of at least three months of production to avoid including permitted, uncompleted or non-produced wells,
3. a requirement that the parent and child operator must be the same operator to minimize flowback differences,
4. a requirement that both the parent's completion date and first production date must be three months older than the child to avoid co-completed wells, and
5. a requirement that the parent must have at least three or more months of production than the child well for the same reason.

The code then calculates metrics for use in subsequent analysis. Those metrics include production proxy percent change, cumulative production percent change, completion time difference, spacing, parent production at the time of child completion, and other metrics. Discussion of these metrics as appropriate follows in the next sections.

Limitations

In this study, several limitations exist, inherent to this type of data analysis and specific to this project. These limitations are listed below:

- The study used Enverus public data for all analyses. Public data is prone to reporting errors. Additionally, production values are frequently reported by section, requiring the total production to be allocated to each well by way of estimation.

- Some basins did not have enough parent-child well pairs that met the selection criteria to conduct meaningful analysis. Consequently, the study excluded the Woodford Basin, and the lack of Haynesville and Powder River Basins data points frequently made analysis difficult.
- Geological data was unavailable for this analysis. Reservoir geology plays a large role in parent-child fracture interactions and production depletion effects and can cause significant data variability.
- Decline curve analysis and EUR calculations were unavailable for this analysis. This data would be necessary for any NPV calculations.
- Production methods were largely not accounted for in the analysis.
    - The study excluded parent-child well pairs with different operators to control for flowback procedures and artificial lift techniques. Otherwise, this study included no discussion of artificial lift.
    - The study accounted for shut-ins only if they resulted in a calendar month with no production history.
- A proxy to account for partial first months of production was unsuccessful. The following section discusses the attempt, but the study otherwise ignores this data limitation.
- This study does not identify co-completed child wells, which might be possible with more information. Instead, this study uses the moving window average discussed in the methodology section.

Production Proxies

The first goal of the analysis is to correlate the initial well pair production results to the well pair cumulative results and evaluate each basin’s data. The study created four production proxies to achieve this goal. These proxies were named “From Peak,” “First Months,” “First Months with Mask,” and “First Month Fraction.” Explanation of the names follows in this section. The study designed these proxies to determine the fewest initial months of production required to select the most accurate cumulative production representation. The fewer months required in the production proxy allow for the inclusion of many more recently completed wells in the data set. This balancing act between using more months of production in a production proxy to improve accuracy and using fewer months to include more parent-child well pairs in the data set is the fundamental problem of this exercise.

Evaluation of each proxy requires five steps. First, well pairs with child wells that did not have 24 months of production were excluded. This criterion avoids child wells with cumulative productions barely longer than the proxy itself. The goal of choosing a proxy is to utilize older data to prove its viability for newer data. Second, the study must calculate proxies for a range of months of production for each well. The study stipulates a range of three to fourteen months for each proxy. Third, on identifying a parent-child well pair, the study compares the proxy of the child well to the proxy of the parent well, returning a percent change. For example, a child well that produced 50% more oil than the parent well in a given timeframe would have a percent change of 50%. A child well that produced 50% less oil would have a percent change of -50%. The formula for percent change is detailed below.

$$Percent\ Change = \left(\frac{Child\ Well\ Production}{Parent\ Well\ Production} - 1\right) * 100 \qquad \text{(Eq. 3)}$$

Fourth, the study compares the child well’s cumulative production to the parent well’s cumulative production. However, the parent and child wells do not have the same number of months of production. Therefore, the child well’s cumulative production was compared to the parent well’s production when the parent well had been producing for the same number of months. Calculating an EUR using a decline curve would have been the optimal method of comparing the ultimate production of two wells; however, that was impossible with the tools and resources available. Instead, the study compares the cumulative productions of each the well pair to return a percent change. Fifth, the study compares the percent change of each proxy for each month to the percent change of the cumulative production to determine each proxy's accuracy. The more months of production included in the proxies, the more accurate they were likely to be, but this results in excluding the more newly completed well pairs by virtue of their short production history.

This process requires an understanding of the calculation of these proxies and the cumulative production difference between parent and child wells before investigating the proxies' results. To help illustrate this point, the graph below displays the production curves of two wells representing what might occur in the case of a child outperforming a parent.

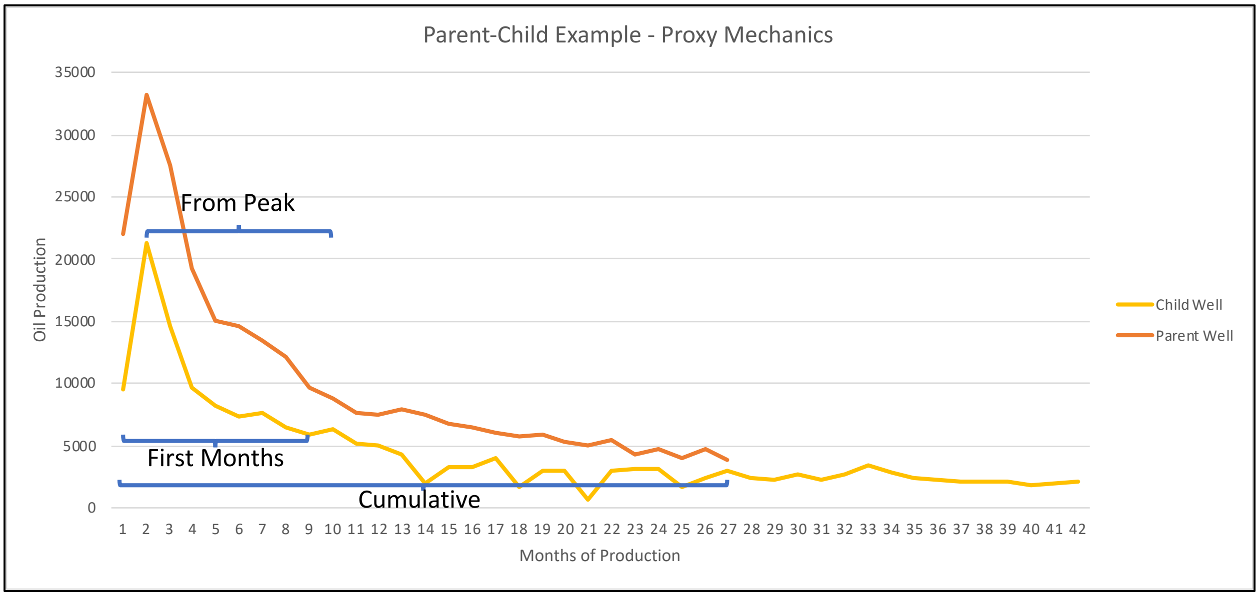


Figure 9. Representative parent-child curves with proxy annotation

One proxy calculates oil and BOE production for 3 to 14 months of production past the peak month of oil production. Labeled in *Figure 9* as the "From Peak" proxy, the proxy happens to include nine months of production data. The proxy's idea was that early well production would be dominated by various operator choke management strategies and would be more erratic. Once reaching a peak production, the declines might be more similar and more predictive of cumulative production difference. This idea proved not to be the case. The next proxy used the first 3 to 14 months of production. It is labeled "First Months" in *Figure 9.* The idea was that production is greatest at the beginning of a well's life. A proxy should include all of this early production because it will make the greatest impact on the well's cumulative production. This proxy worked well, is intuitive, and was ultimately chosen for subsequent analysis. The third proxy also used the first months of production, but it stipulated that oil production must be present in each month of production included. This proxy is called "First Months with Mask," a mask being a coding technique that allows months without oil production to be filtered out. Some wells have no oil production at all for the first few months of their life. This phenomenon seems to be a reporting error, and this proxy shows little difference between it and "First Months." This proxy only made the evaluation of gas reservoirs more complicated and, therefore, was not used. The final proxy was called "First Month Fraction." The notion was that most wells do not produce for the entire first month that they are online, so adding those lost days of production make a full month. There are no reports of the exact date of the first production, so instead, the first month's production, which includes BOE and water production, is divided by the second month's production to get some fraction of the following month. If the first month has more production than the second, it is just considered 1.0, or a full month. For example, if the first month's production is only half of the second month's production, the study adds an extra half month of production from the time specified for the proxy. This method proved unsuccessful, so the results will only be discussed briefly.

Additionally, in *Figure 9,* the cumulative production metric is displayed. This metric is simply the cumulative production for the child well and the parent's cumulative production when it has the same number of production months as the child. In the example in *Figure 9*, the child has 27 months of production. The study calculates the parent well's cumulative production at 27 months of production as well. These metrics also produce a percent change.

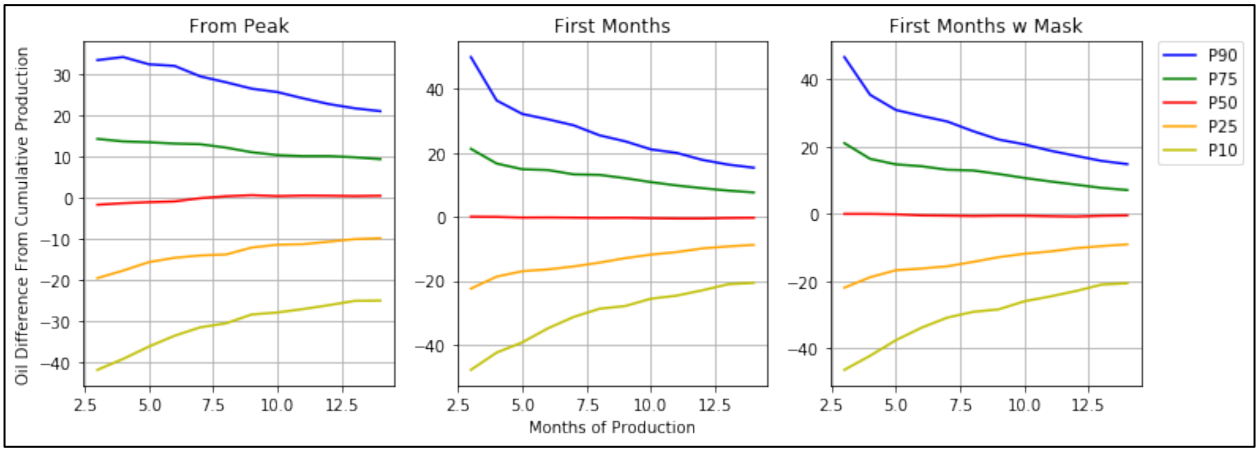
After calculating the percent change from parent to child for the proxies and the cumulative production, the study compares these metrics to each other according to the following formula.

$$Proxy\ Difference = Proxy\ Percent\ Change - Cumulative\ Percent\ Change \qquad \text{(Eq. 4)}$$

Or,

$$Proxy\ Difference = \left(\frac{Child\ Proxy\ Production}{Parent\ Proxy\ Produciton} - \frac{Child\ Cumulative\ Production}{Parent\ Cumulative\ Production}\right) * 100 \qquad \text{(Eq. 5)}$$

The results of this calculation for several basins that include the "From Peak," "First Months," and "First Months with Mask" show important percentiles of the proxy comparison's difference from the cumulative comparison. The partial results displayed in this section represent all the basins, but the full set of graphs are found in Appendix A.



From Peak

First Months

First Months w Mask

Figure 10. Midland Basin proxy difference from cumulative for oil production

As one might expect, the proxies increase in accuracy with the inclusion of additional months of production. Including only three months produces a large difference – greater than 40% in each direction in almost all cases. However, as the percentile lines converge, the closer the proxy estimate of production difference is to the real cumulative production difference. By the time fourteen included months are reached for the First Months routine, the P10 and P90 of the data are within 20% of their cumulative results. This graph demonstrates that for 80% of the well pairs, the proxy metric is within 20% of the cumulative difference in parent-child production in 14 months. For 50% of the wells, the proxy is within 10%. For the Midland Basin and other oil-dominant basins, the percent change in initial oil production from parent to child is a reliable indicator of cumulative oil production difference.

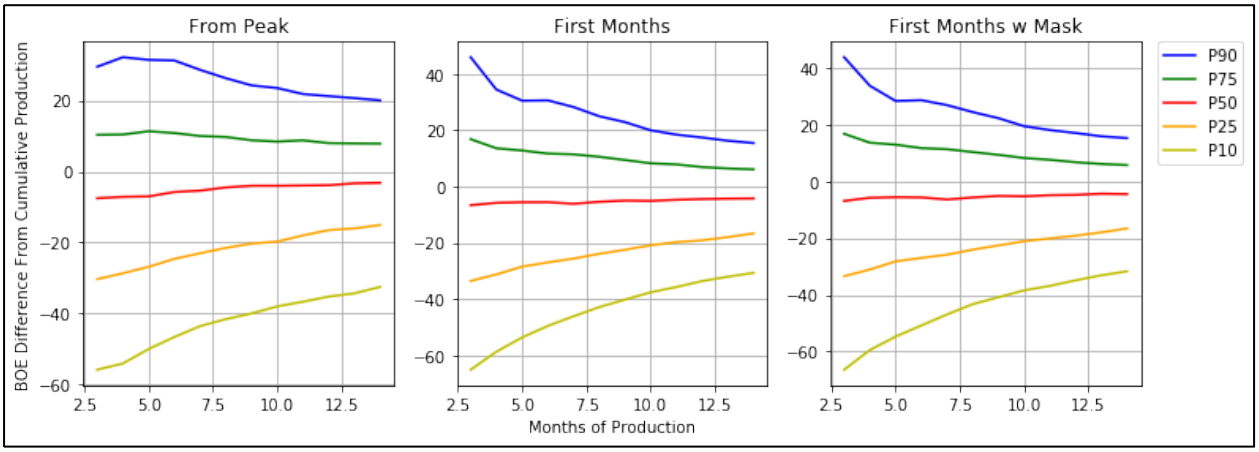


Figure 11. Midland Basin proxy difference from cumulative for BOE production

On the other hand, BOE proxies are less effective indicators of cumulative BOE production differences. For example, the P50 of most BOE graphs is less than 0, and the graphs tend to favor negative numbers. This trend appeared in most of the BOE proxy charts in the study. The oil charts do not typically exhibit this problem to the same degree as the BOE charts, implying that gas volumes are responsible for this disparity. The goal is the estimation of the cumulative production difference, leaving two possibilities. Either the child's early gas production is low relative to the cumulative gas production, or the early gas production of the parent well is high relative to the cumulative gas production. This finding does not invalidate the BOE metrics, but it is essential to know the impact.

When comparing the proxies, it clear that the From Peak routine begins with a tighter spread, and including more months marginally improves the metric. On the other hand, the First months and First Months with Mask proxies quickly improve and typically are much closer to the cumulative values by 14 months. However, the mask that forces the inclusion of oil production does not significantly impact its accuracy. The last proxy, First Months Edited, is shown below for the Midland Basin.

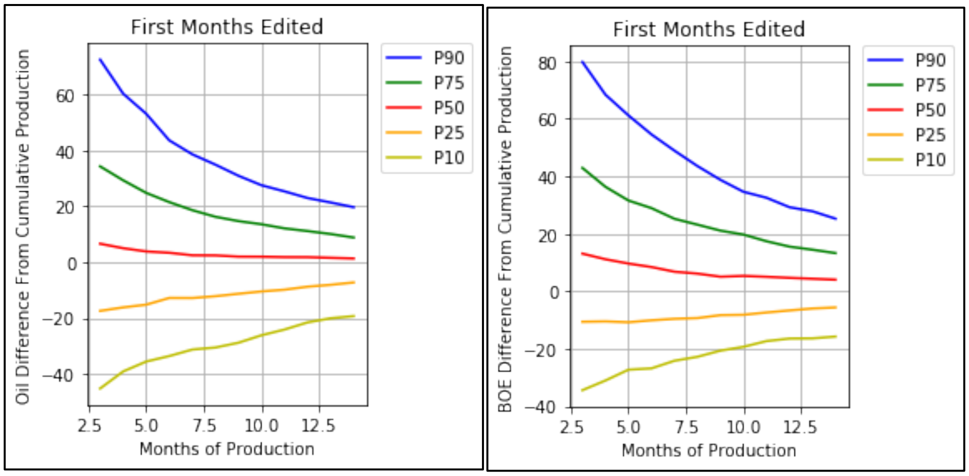


Figure 12. Midland Basin First Months Edited proxy difference from cumulative for production of a) oil and b) BOE

This proxy produces the opposite effect compared to the other proxies; the P50 differences from cumulative are greater than zero. For this to occur, the child wells must have a larger increase in proxy production than the parent wells. This effect could be due to more aggressive flowback of child wells compared to older parents. If the second month's production of the child wells were much larger than the first month's, then the child wells would see extra production added to compensate. If the parents flow back at lower rates, it would appear that the first month was flowing for a greater number of days, even though that is not true.

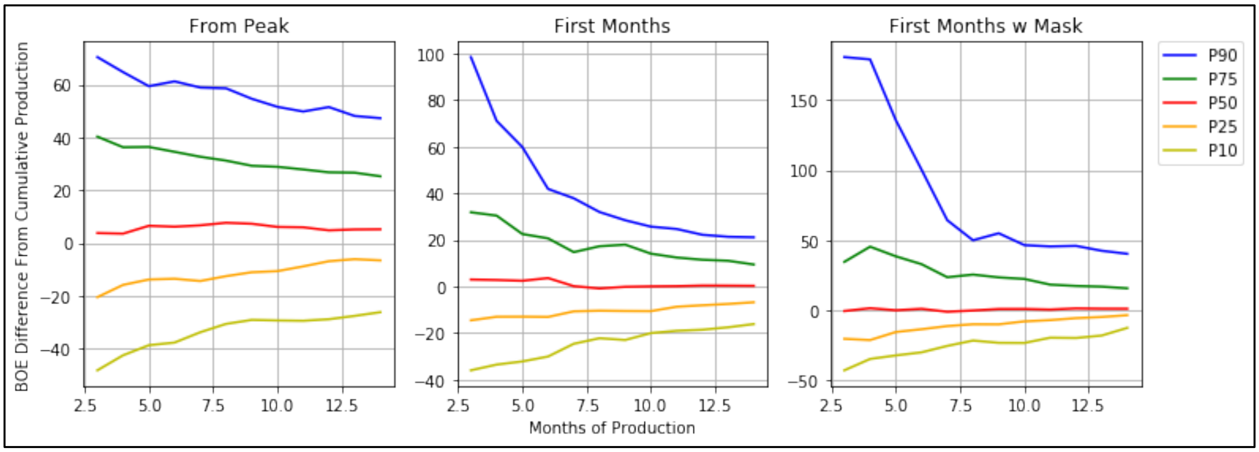


Figure 13. Marcellus/Utica Basins proxy difference from cumulative for BOE production

In natural gas basins, as seen in the Marcellus and Utica Basins in *Figure 13,* the First Months and First Months with Mask routines see significant child outperformance in the first few months but quickly return to within 20% of the cumulative BOE difference.

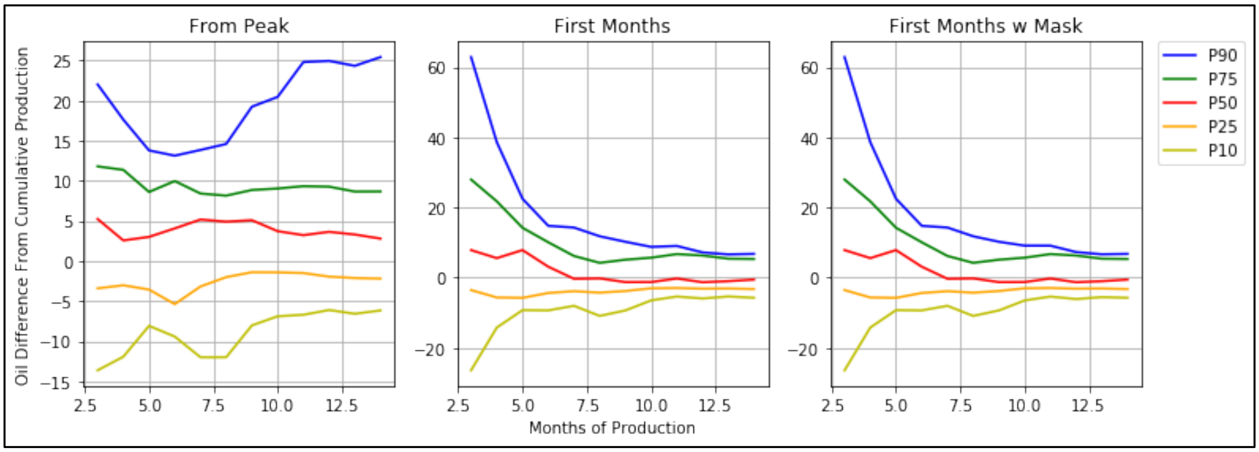


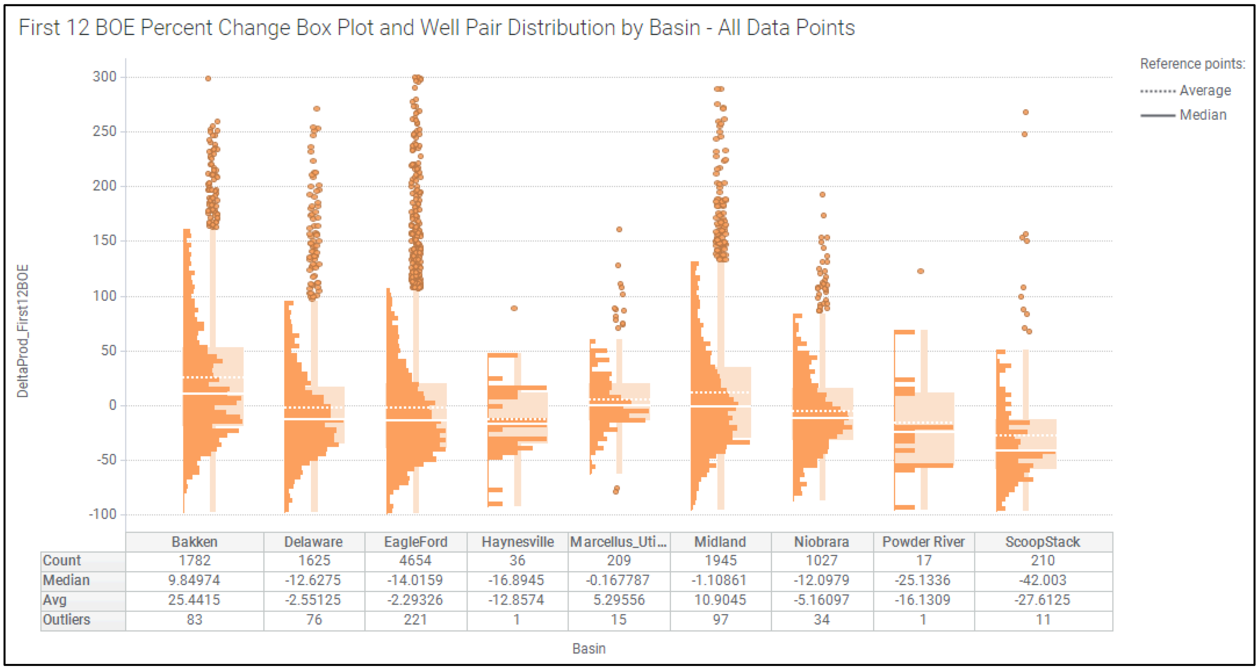
Figure 14. Powder River Basin proxy difference from cumulative for oil production

Finally, when beginning the analysis, the proxies were expected to result in a graph like the First Months proxy for the Powder River Basin in *Figure 14.* This proxy, while inaccurate with few months of data, quickly levels out. The P10 and P90 of all the proxies were within 10%

of the cumulative production difference within six months of included production, which would be ideal for analysis. In this case, only parent-child well pairs with less than six months require exclusion. However, the Powder River Basin data set is minimal, with only 21 parent-child well pairs and 14 with child wells with the 24 months of production to be included in this analysis. Many other basins have many more well pairs, which produces more inconsistent parent and child well results. As a result, it would not be appropriate to choose a metric with very few months of production for subsequent analysis as one may have wished to do. After evaluating the metrics, the study chose the First 12 Months of BOE production as the proxy for other production analysis in this study. By 12 months of production, almost all of the basins had the P10 and P90 within 20% of the cumulative production difference. Any more months used require the exclusion of more data points. While this metric is very similar to the Best 12-Months metrics used by Lindsay et al. (2018) and Xu et al. (2019), this analysis allows the reader to understand this metric's accuracy.

Basin Comparison

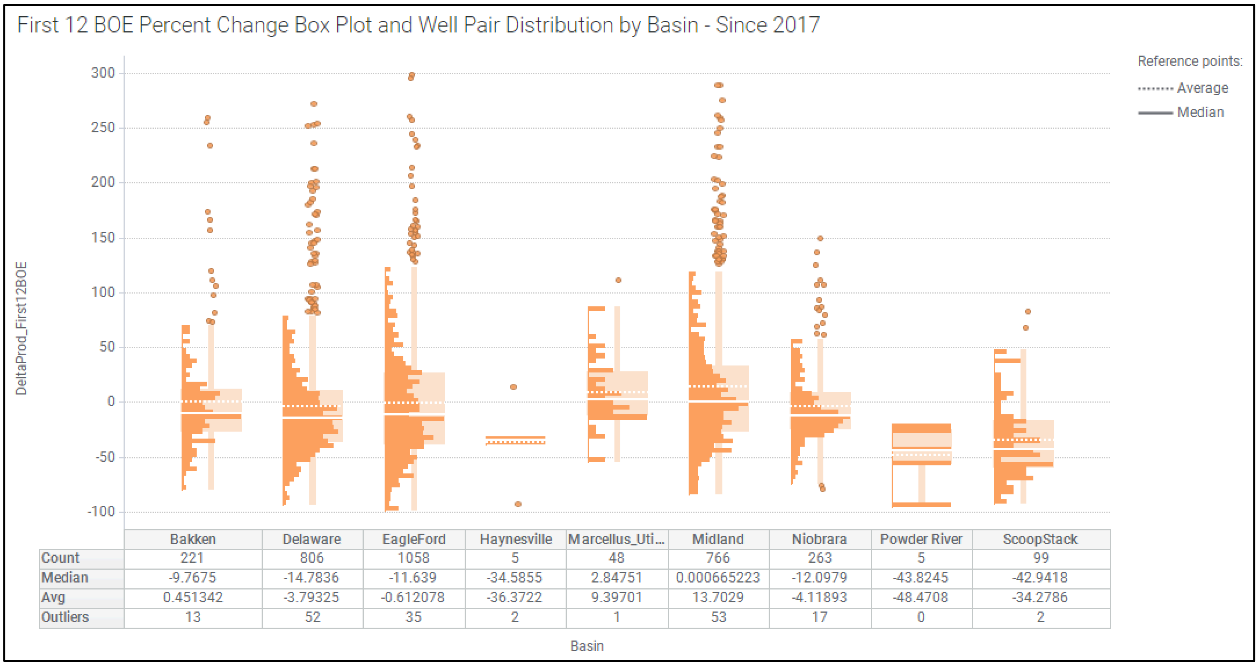
The study investigates the differences in child performance across the different basins using the First 12 Months proxy from the previous section. In performing this section of the analysis, the study entered the data into Spotfire, a data visualization software, to create boxplots of each basin's well pairs. Additionally, a feature of the boxplots allows the overlay of the distribution of data points on the boxplot, giving more clarity to child performance distribution. The result is displayed below.



	Bakken	Delaware	EagleFord	Haynesville	Marcellus_Uti...	Midland	Niobrara	Powder River	ScoopStack
Count	1782	1625	4654	36	209	1945	1027	17	210
Median	9.84974	-12.6275	-14.0159	-16.8945	-0.167787	-1.10861	-12.0979	-25.1336	-42.003
Avg	25.4415	-2.55125	-2.29326	-12.8574	5.29556	10.9045	-5.16097	-16.1309	-27.6125
Outliers	83	76	221	1	15	97	34	1	11

Figure 15. First 12 BOE percent change boxplot and well pair distribution by basin – all data points

Figure 15 shows the histogram and box plot as well as the average of all of all the points for each basin. For this figure, the child well's percent change is filtered to below a 300% increase since the vast majority of data points fall into this range, and including those higher data points compresses the visualization too much, but otherwise, *Figure 15* includes all data points. The basins do not all behave in the same way. The average child performance in the Bakken is considerably better than the Eagle Ford or Niobrara. One crucial fact to keep in mind is that the Bakken BOE proxy distribution had a higher percent change than the cumulative percent change, while the distributions of the BOE proxy for the Delaware, Midland, Niobrara, and Scoop/Stack slightly underrepresent the cumulative production of the wells; however, that over-estimation or under-estimation is less than five percentage points. It is still clear that child wells in the Bakken perform better than other basins, and child wells in the Scoop/Stack, Powder River and Haynesville significantly underperform. Another important takeaway from this chart is that the distribution of child percent change is heavily skewed towards child overperformance. While the average performance of child wells in many of the basins is at or around zero, or equal performance to the parent well, the significant overperforming wells heavily influenced that value. In reality, the distributions across all shale basins indicate that child wells are underperforming their parent wells significantly.



	Bakken	Delaware	EagleFord	Haynesville	Marcellus_Uti...	Midland	Niobrara	Powder River	ScoopStack
Count	221	806	1058	5	48	766	263	5	99
Median	-9.7675	-14.7836	-11.639	-34.5855	2.84751	0.000665223	-12.0979	-43.8245	-42.9418
Avg	0.451342	-3.79325	-0.612078	-36.3722	9.39701	13.7029	-4.11893	-48.4708	-34.2786
Outliers	13	52	35	2	1	53	17	0	2

Figure 16. First 12 BOE Percent change boxplot and well pair distribution by basin – since 2017

Figure 15 includes all data points, but in *Figure 16,* the wells are only the pairs in which both parent and child were drilled from 2017 forward. This graph aims to illustrate how well pairs with current completion designs have performed. The year 2017 was chosen because that is when analysis by Xu et al. (2019) showed a plateau of proppant loading in Delaware Basin and Midland Basin wells. In these cases, the parent wells were likely more strongly stimulated and had better coverage of the reservoir than older wells that might have left rock volume unstimulated. In this case, the Bakken appears to have a dramatic shift in the productivity of child wells. The majority of this subset of wells underperform and the average percent change, even with outliers, is only just above zero. It appears that Bakken parent wells completed before 2017 might have been under-stimulated and left much of the reservoir undepleted; therefore, the child wells were still able to perform at a similar level to the parent wells.

Nevertheless, with younger parent wells likely employing larger completion designs, the child wells struggle to match the parent well production. Many of the other basins display similar results to the full data set; however, there is one important consideration. With the parent wells from 2017 and on and the requirement that the child wells must have 12 months of production for our proxy calculation, these well pairs were drilled within three years of each other, often completed with shorter time differences. When wells drilled in 2017 and 2018 finally have child wells drilled near them, they will have faced prolonged depletion from many wells in this filtered data set. It is plausible that although completing child wells within two or three years can mitigate the effects of a large parent completion design, waiting longer could lead to child wells that underperform the distribution seen in *Figure 15.* Overall, using a boxplot with an overlayed distribution is an effective way to compare parent-child performance in many different basins.

Spacing vs. Timing Example

Another way to demonstrate the effects of spacing and timing on parent-child well performance is to create a scatterplot of the data and test different completion time differences to observe how those subsets perform. In the following example, the study plots Bakken and Eagle Ford wells' performance on a scatter plots of spacing vs. First 12 Months percent change and filtered to 0-1 year completion time difference, 1-2 year completion time difference, and 2+ year completion time difference.

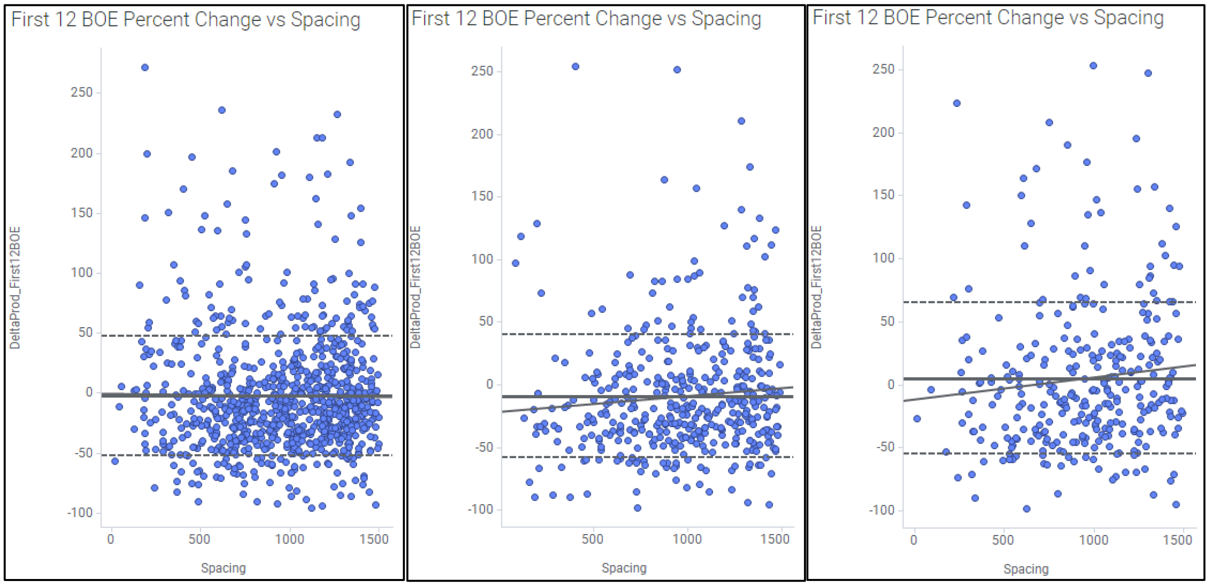


Figure 17. First 12 BOE percent change vs. spacing for completion date differences in the Bakken Basin between a) 0-1 year b) 1-2 years c) more than 2 years

First, as the completion time difference increases, the average percent change goes from about 0% to about negative 10% and then, interestingly, back up to about 5%. While the increase in average percent change is surprising given that simulations tend to show child well performance suffering from larger time gaps between parent and child completion, that expected decrease shows in the transition from less than 0-1 year of completion difference to 1-2 years difference. Additionally, the study fitted each graph with a trend line for percent change vs. spacing. The wells completed within one year of each other appear to be less affected by spacing differences than the wells drilled with larger time differences. In the last two graphs, the severity of the trend line's slope increases with time. That could mean that wells with larger completion time differences are more sensitive to spacing changes in the Bakken.

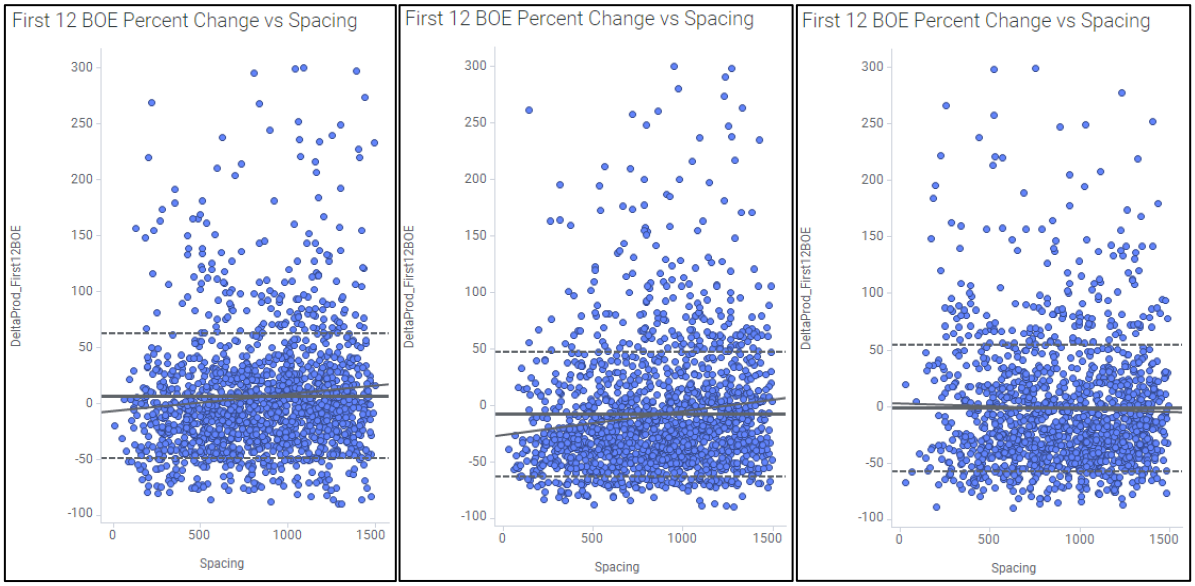


Figure 18. First 12 BOE percent change vs. spacing for completion date differences in the Eagle Ford Basin between a) 0-1 year b) 1-2 years c) more than 2 years

The same graphs for the Eagle Ford Basin show similar results. The child wells drilled within one year of the parent well perform better on average than the parent. Furthermore, while the 2+ year gap for the last group of wells does not increase in productivity with an increase in spacing, the other two subsets do manifest that trend. Additionally, following the well pair distributions, these graphs also demonstrate the heavy skew of the data set. While large outperformers exist, many of the data points indicate that the child wells are underperforming the parent wells in each category.

Basin Boxplot Analysis

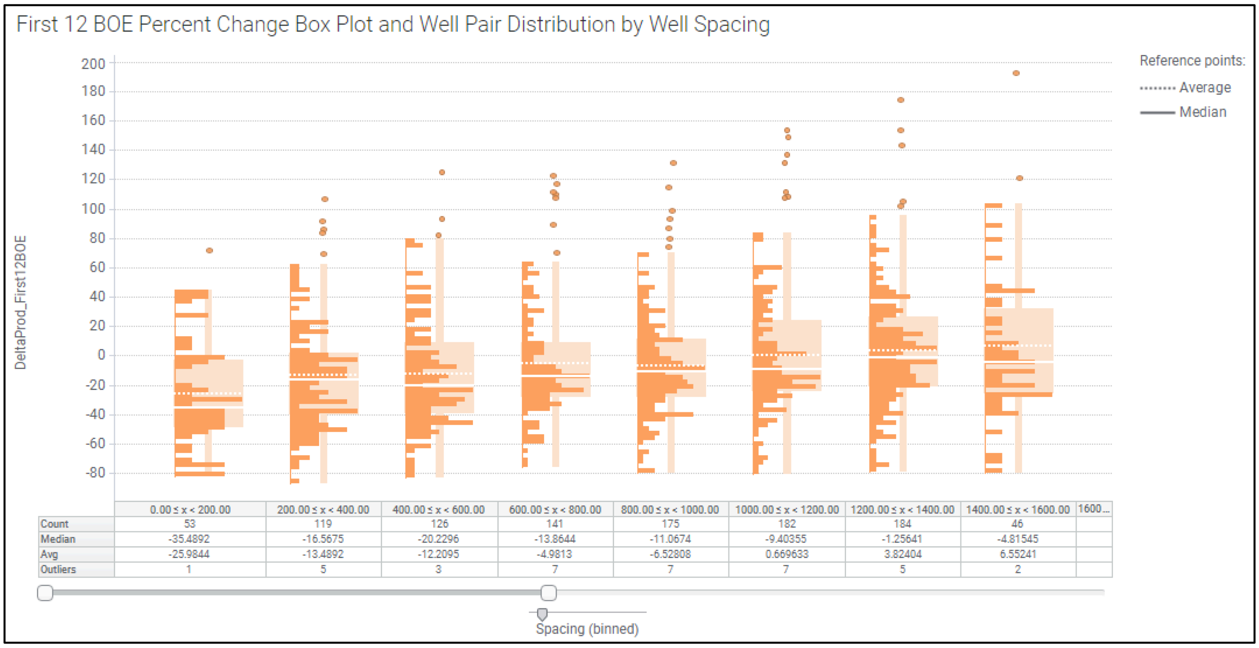
Not only do boxplots allow for the useful comparison of basins, but also, they can show the effect of a single variable within each basin. For this section of the analysis, the study binned each basin’s data points by spacing, completion timing difference, and parent produced volume at child completion. These metrics, as expected, were found to be the most influential on child performance. The figures for basins not discussed in the following sections appear in Appendix A.

Spacing. In each of the basins, the general trend of increasing child productivity with increasing spacing is clearly demonstrated. Some basins express this trend more severely than others. In the following figures, spacing is binned into 200-foot spacing intervals to highlight these changes.

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	54	131	207	274	326	326	324	119	
Median	-28.6023	-2.12495	1.41707	7.72965	15.6482	14.744	17.4791	24.1547	
Avg	-5.9961	1.3596	13.7277	22.131	31.725	31.5849	33.8907	35.7384	
Outliers	1	3	9	9	21	14	8	2	

Figure 19. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Bakken Basin

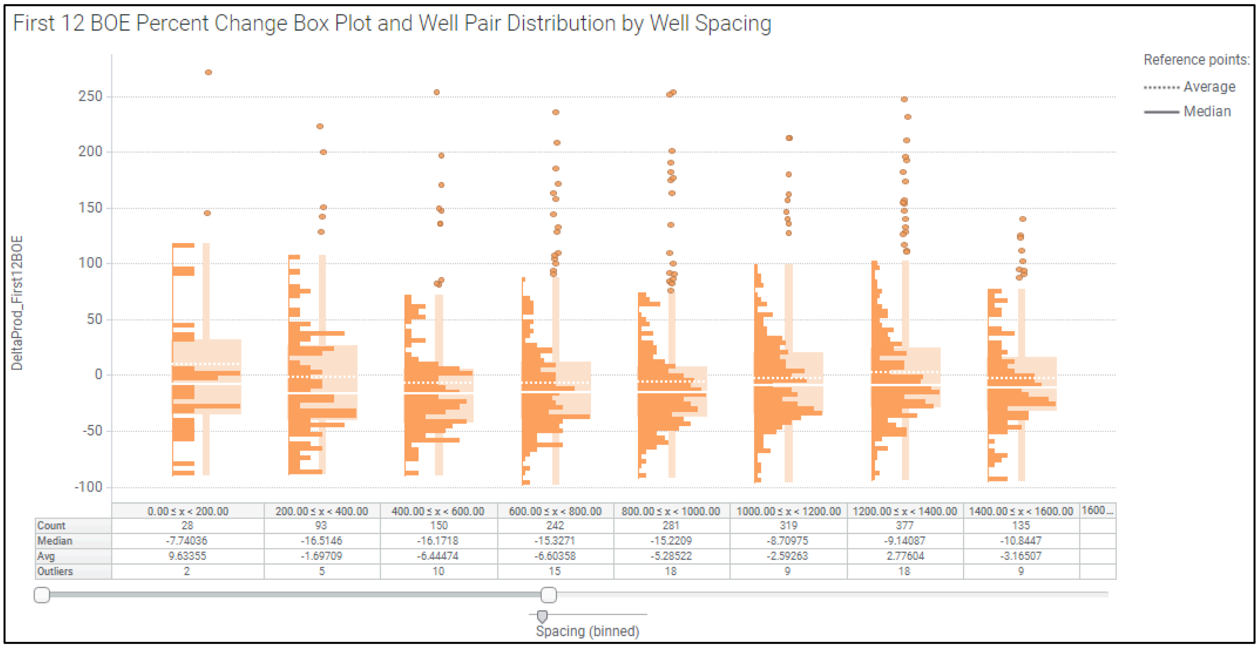
In *Figure 19,* the Bakken Basin displays a significant and consistent increase in child productivity with increasing spacing. Although noted earlier that Bakken child wells tend to perform well overall, they underperform at small spacing intervals. Also, as spacing intervals increase, the minimum production percent change increases as well. It appears that as spacing increases in the Bakken, so does the worst-case scenario well.



	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	53	119	126	141	175	182	184	46	
Median	-35.4892	-16.5675	-20.2296	-13.8644	-11.0674	-9.40355	-1.25641	-4.81545	
Avg	-25.9844	-13.4892	-12.2095	-4.9813	-6.52808	0.669633	3.82404	6.55241	
Outliers	1	5	3	7	7	7	5	2	

Figure 20. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Niobrara Basin

In *Figure 20,* the Niobrara exhibits a similar trend. Wells within 600-foot spacing, which would be considered especially tight spacing in other basins, perform at least twice as poorly as any other spacing category on average. In both the Niobrara and the Bakken Basins, it appears that spacing will have a massive effect on the outcome of a child well, so choosing the right spacing should be a serious concern in those basins.

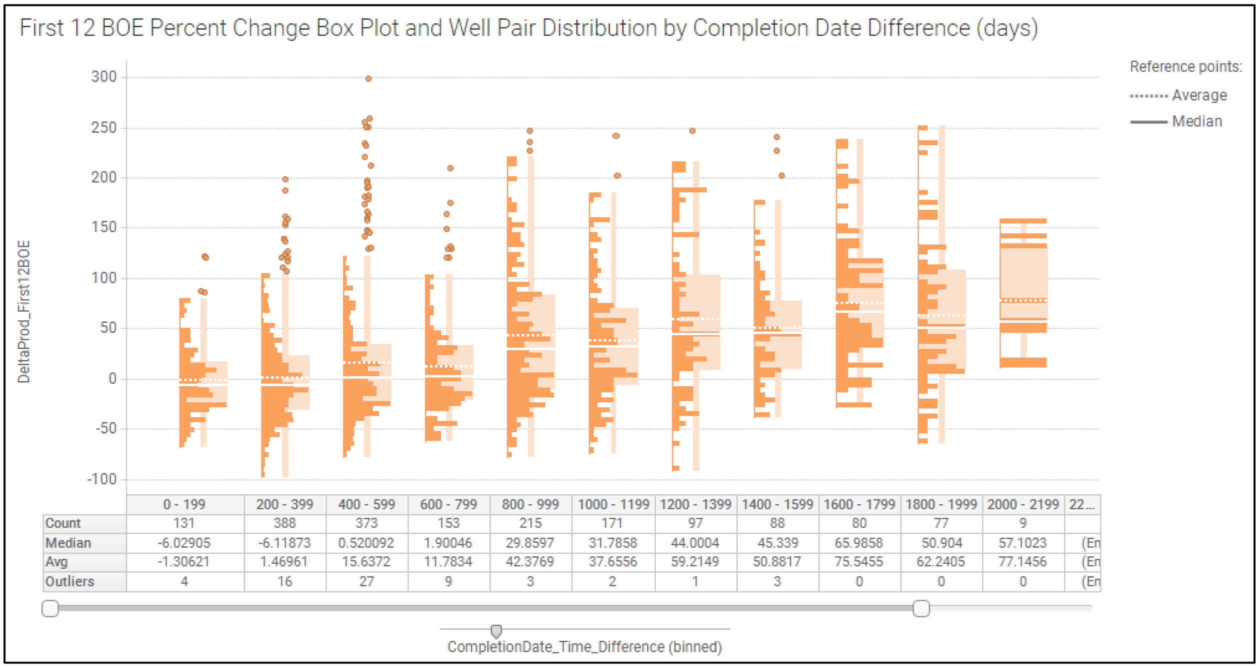


	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	28	93	150	242	281	319	377	135	
Median	-7.74036	-16.5146	-16.1718	-15.3271	-15.2209	-8.70975	-9.14087	-10.8447	
Avg	9.63355	-1.69709	-6.44474	-6.60358	-5.28522	-2.59263	2.77604	-3.16507	
Outliers	2	5	10	15	18	9	18	9	

Figure 21. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Delaware Basin

On the other hand, *Figure 21* displays that Delaware Basin child well's experience fewer adverse effect from spacing than the other two basins. While the spacing performance trend is still present, the magnitude of the decrease with tighter spacing is less severe.

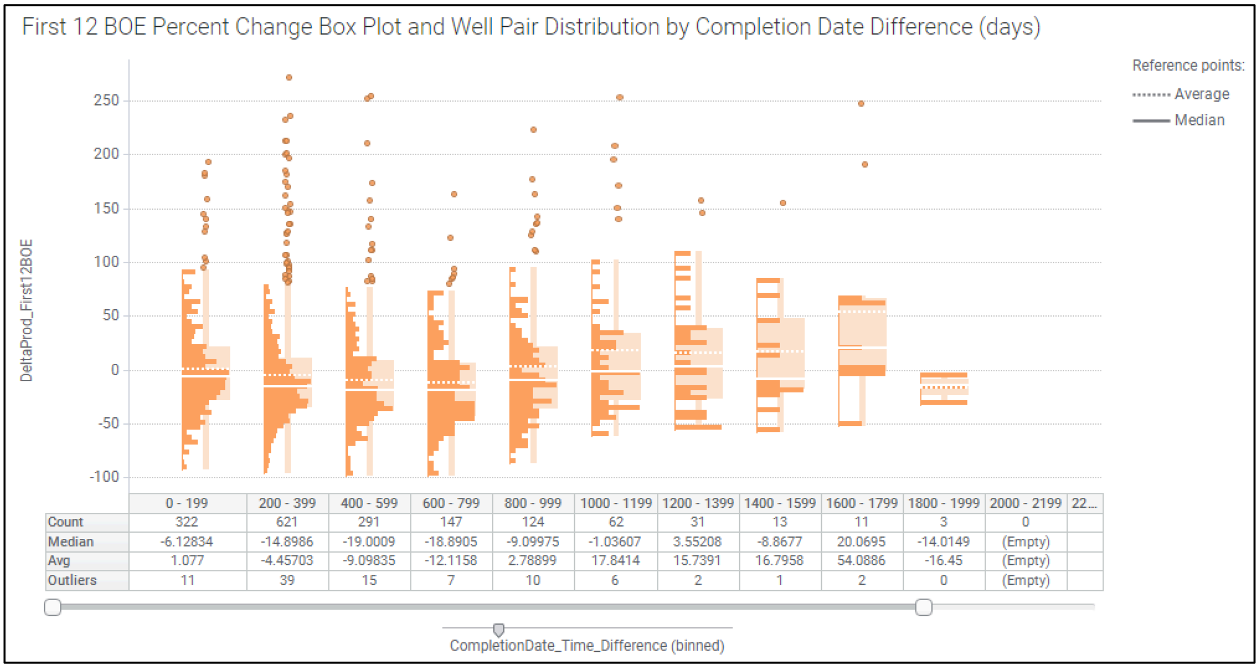
Completion Timing Difference. Infill timing is known to cause detrimental effects on child productivity. Furthermore, like spacing, the boxplots do show this trend in most basins; however, as completion timing increases, so does the parent's age. As discussed in Xu et al. (2019), completions in the Midland and Delaware Basins have significantly increased in proppant loading, and this trend is likely occurring in all US unconventional basins. For this reason, some of the bins with larger completion timing differences experience an increase in child production percent change.



	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	131	388	373	153	215	171	97	88	80	77	9	
Median	-6.02905	-6.11873	0.520092	1.90046	29.8597	31.7858	44.0004	45.339	65.9858	50.904	57.1023	(En
Avg	-1.30621	1.46961	15.6372	11.7834	42.3769	37.6556	59.2149	50.8817	75.5455	62.2405	77.1456	(En
Outliers	4	16	27	9	3	2	1	3	0	0	0	(En

Figure 22. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Bakken Basin

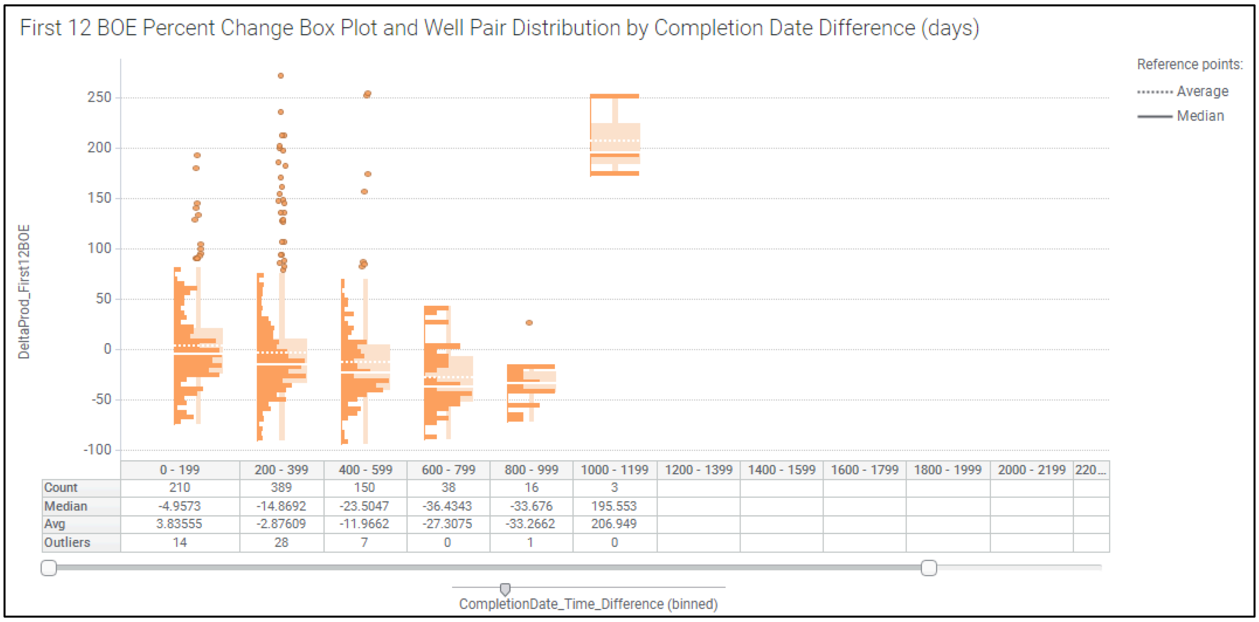
In *Figure 22,* child productivity increases with an increase in completion date difference, an unexpected positive effect if the wells are assumed identical with increasing timing differences; Kumar et al. (2020) simulates the opposite effect. However, from previous analysis, Bakken child wells have already seen decreases in performance significantly with the data filtered from 2017 onward. Those underperforming well pairs likely have shorter completion date differences. Additionally, in *Figure 17,* scatterplot analysis showed that wells with an infill timing greater than two years experienced a greater average percent change. This unexpected increase is likely a product of evolving completion techniques rather than the basin’s unique ability to counteract depletion effects.



	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	322	621	291	147	124	62	31	13	11	3	0	
Median	-6.12834	-14.8986	-19.0009	-18.8905	-9.09975	-1.03607	3.55208	-8.8677	20.0695	-14.0149	(Empty)	
Avg	1.077	-4.45703	-9.09835	-12.1158	2.78899	17.8414	15.7391	16.7958	54.0886	-16.45	(Empty)	
Outliers	11	39	15	7	10	6	2	1	2	0	(Empty)	

Figure 23. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Delaware Basin – all data points

All of the other basins except the Powder River Basin, which contained insufficient data to produce a trend, experience a similar trend to the one seen in *Figure 23*. In this plot, the Delaware Basin experiences a decrease in child well performance before reversing the trend and seeing the performance increase with completion date difference. Again, the increase in wells pairs with large age gaps is curious, but it likely can be explained by the same evolving completion design effect. Wells with much larger age gaps are likely to encounter previously unstimulated rock volume due to poor completion designs, which boosts performance. The increase seen in *Figure 23* occurs around the 800 to 999 days bin, or around three years. Add one more year for the production proxy to have sufficient months of production, and we are back at wells completed around 2017, the time when the industry trend of proppant loading plateaus in the Delaware Basin. Excluding all wells completed before 2017 leaves the wells having more advanced completion designs on average. The boxplot of completion date difference results in the following:

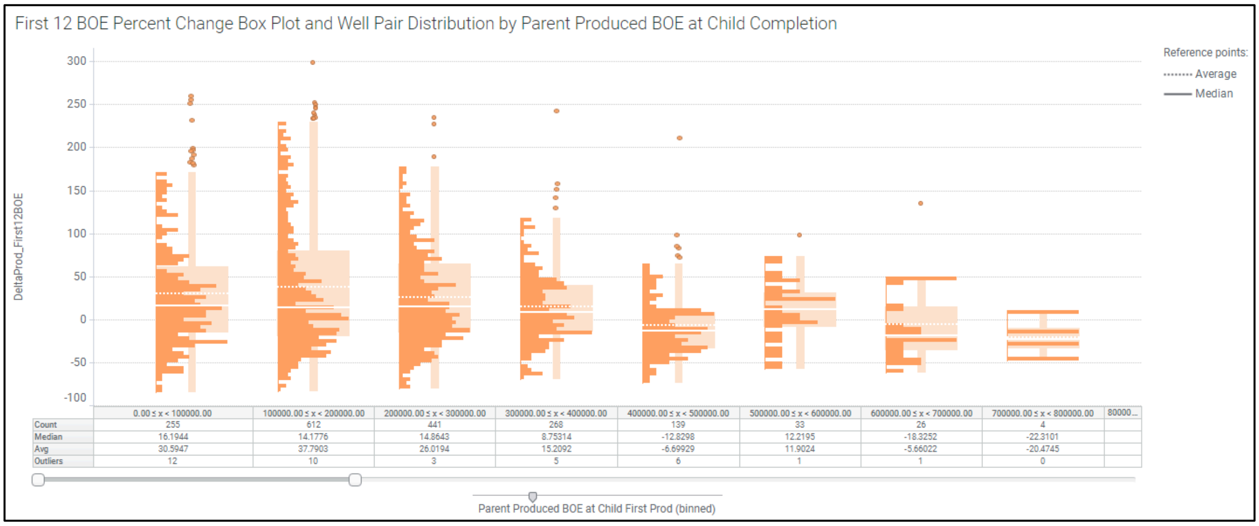


	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	220...
Count	210	389	150	38	16	3						
Median	-4.9573	-14.8692	-23.5047	-36.4343	-33.676	195.553						
Avg	3.83555	-2.87609	-11.9662	-27.3075	-33.2662	206.949						
Outliers	14	28	7	0	1	0						

Figure 24. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Delaware Basin – since 2017

In this case, the decrease in production with an increased age gap is even more precipitous than the decrease seen in *Figure 23.* This trend is a compelling indication that current parent completion designs can have a significant effect on future child wells' productivity in the Delaware Basin.

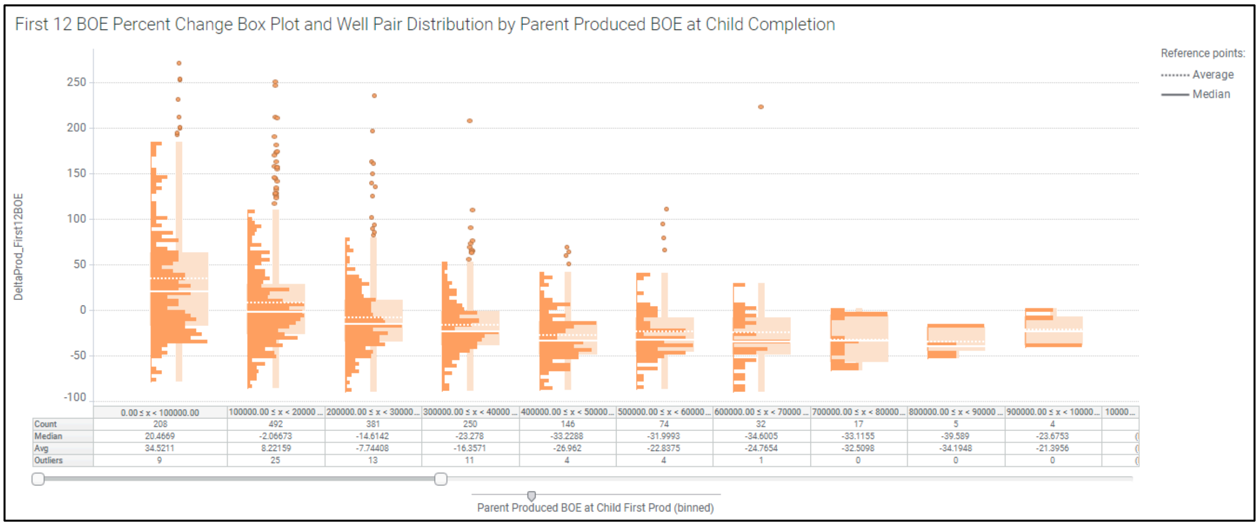
Parent Produced BOE at Child Completion. While completion date difference provides a compelling case to drill wells with shorter age gaps, there is another metric that may be a better indicator for child performance. Parent produced BOE at child completion is intuitively similar to completion date difference, but the metric considers the performance of the parent well as well. This metric may be a better indicator of a parent's depletion effect than purely age difference.



	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	400000.00 ≤ x < 500000.00	500000.00 ≤ x < 600000.00	600000.00 ≤ x < 700000.00	700000.00 ≤ x < 800000.00	80000...
Count	255	612	441	268	139	33	26	4	
Median	16.1944	14.1776	14.8643	8.75314	-12.8298	12.2195	-18.3252	-22.3101	
Avg	30.5947	37.7903	26.0194	15.2092	-6.69929	11.9024	-5.66022	-20.4745	
Outliers	12	10	3	5	6	1	1	0	

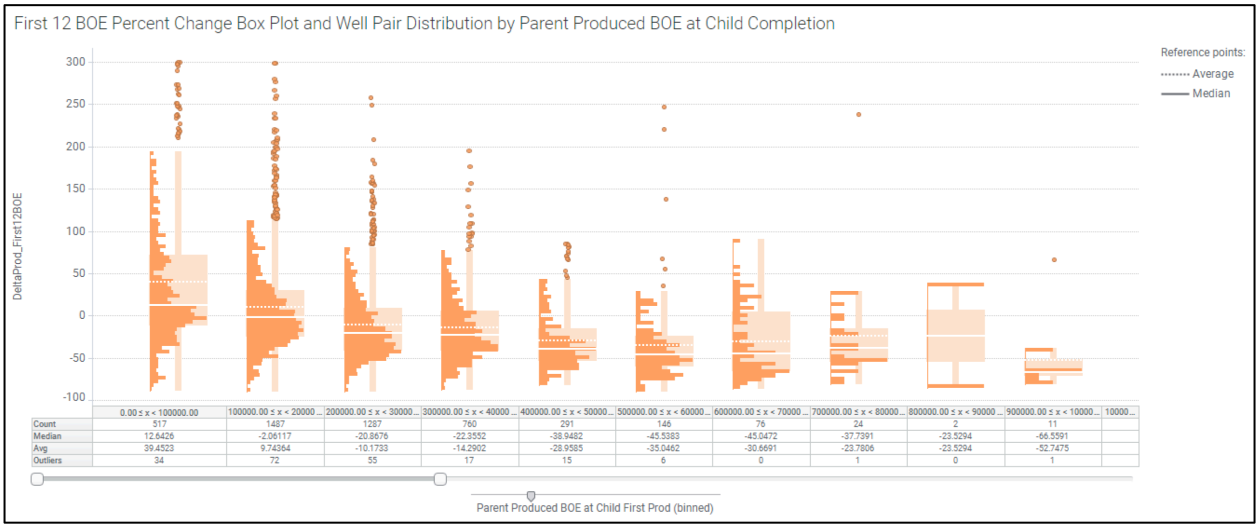
Figure 25. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Bakken Basin

For example, in the Bakken Basin, the surprising increase in child productivity with an increase in infill timing is nearly reversed by using parent produced BOE at child completion. The trend is still not as significant as other basins, but this metric would undoubtedly be a more useful indicator of child performance than completion date difference in the Bakken



	0.00 ≤ x < 100000.00	100000.00 ≤ x < 20000 ...	200000.00 ≤ x < 30000...	300000.00 ≤ x < 40000 ...	400000.00 ≤ x < 50000...	500000.00 ≤ x < 60000...	600000.00 ≤ x < 70000 ...	700000.00 ≤ x < 80000...	800000.00 ≤ x < 90000 ...	900000.00 ≤ x < 10000...	10000...
Count	208	492	381	250	146	74	32	17	5	4	
Median	20.4669	-2.06673	-14.6142	-23.278	-33.2288	-31.9993	-34.6005	-33.1155	-39.589	-23.6753	(
Avg	34.5211	8.22159	-7.74408	-16.3571	-26.962	-22.8375	-24.7654	-32.5098	-34.1948	-21.3956	(
Outliers	9	25	13	11	4	4	1	0	0	0	(

Figure 26. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Delaware Basin



	0.00 ≤ x < 100000.00	100000.00 ≤ x < 20000 ...	200000.00 ≤ x < 30000 ...	300000.00 ≤ x < 40000 ...	400000.00 ≤ x < 50000 ...	500000.00 ≤ x < 60000 ...	600000.00 ≤ x < 70000 ...	700000.00 ≤ x < 80000 ...	800000.00 ≤ x < 90000 ...	900000.00 ≤ x < 10000 ...	10000 ...
Count	517	1487	1287	760	291	146	76	24	2	11	
Median	12.6426	-2.06117	-20.8676	-22.3552	-38.9482	-45.5383	-45.0472	-37.7391	-23.5294	-66.5591	
Avg	39.4523	9.74364	-10.1733	-14.2902	-28.9585	-35.0462	-30.6691	-23.7806	-23.5294	-52.7475	
Outliers	34	72	55	17	15	6	0	1	0	1	

Figure 27. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Eagle Ford Basin

In *Figures 26* and *27,* the Delaware and Eagle Ford Basins illustrate basins where this trend can be very strong. While detrimental depletion effects certainly increase with time as the low pressure and low stress region permeates through the reservoir, a stronger indicator of child underperformance may be the parent production. It increases with time, but the magnitude of the depletion effect can vary widely based on the parent's productivity.

Production Heatmaps

One efficient way to determine how a child well's performance compared to the parent's changes for two completion metrics is to construct a heatmap, also known as a Python hexplot. This visualization groups wells by metrics on the two axes, coloring each area of the graph by the average of the third metric. In this analysis, the desired quality to understand is the production proxy chosen previously, First 12 Month BOE Percent Change. The metrics on the x and y axes change at will. Before making these graphs, some extreme outliers required exclusion to prevent the graph from skewing too severely to the larger values. While previous examples investigated the effect of parent well metrics on child well performance, in this example, child proppant loading (lb/ft) and child fluid loading (bbl/ft) will be analyzed to see the effects of child stimulation techniques on well results.

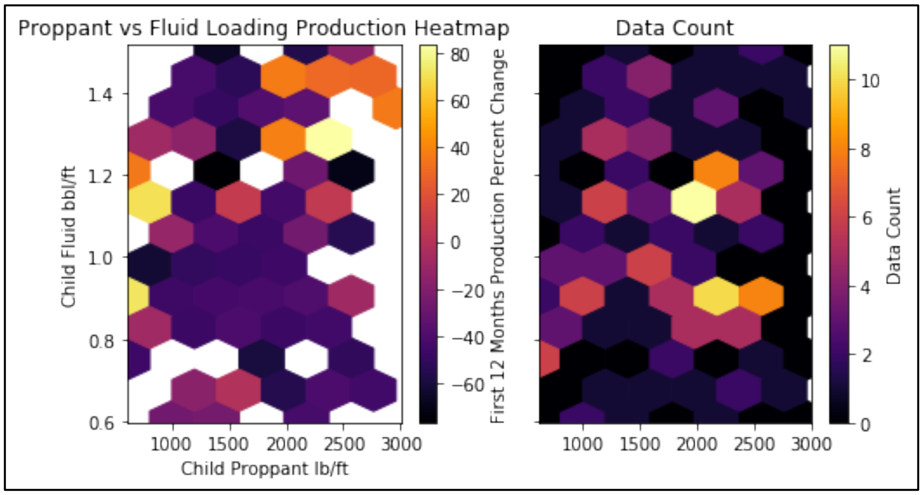


Figure 28. Scoop/Stack Basins child proppant and fluid loading heatmap colored by First 12 Months percent change

In this Scoop/Stack Basins example, high proppant and fluid loadings appear to drive child well production. The data is clustered more heavily towards the proppant loadings greater than 2,000 pounds per foot with fewer wells implementing larger fluid loading. However, in this case, the highest production areas can be seen situated at the top of the graph, indicating high fluid loading. In general, *Figure 28* indicates distinctly that using low proppant and low fluid loading will return child wells that underperform the parent wells.

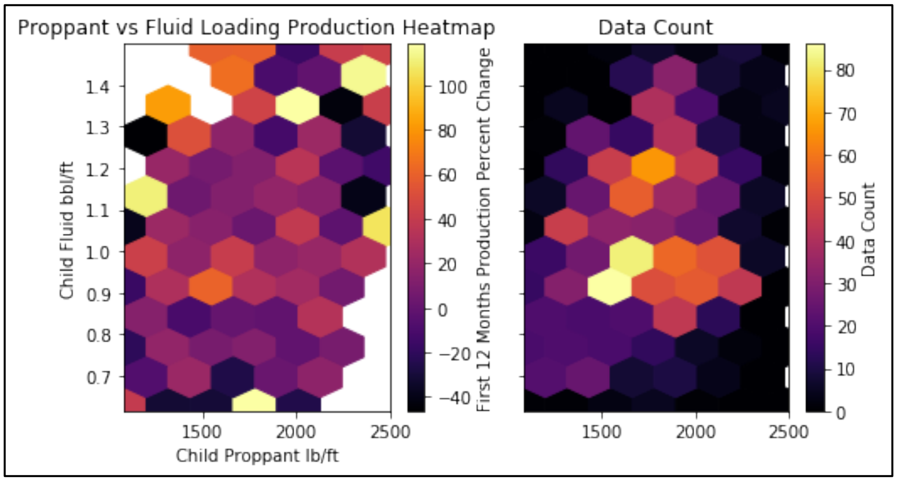


Figure 29. Midland Basin child proppant and fluid loading heatmap colored by First 12 Months percent change

The Midland Basin shows a less pronounced but similar trend. Although the data is sparse around the graph's edges, there appear to be more data points that indicate better child production. It is clear, though, that the bottom left of this graph populates with darker colors. In the Midland Basin, it appears that pumping too small of a child package is a mistake that operators should not make. In general, this analysis method allows for two completion metrics to be compared at once but does not give the distribution insights that boxplots can provide.

Conclusion

In this project, the Python code written enabled the identification and analysis of many parent-child well pairs across nine different basins in a consistent way. The analysis conducted confirmed the underperformance of child wells described by simulation studies such as Kumar et al. (2020) and by similar data analyses such as Lindsay et al (2018) and Xu et al. (2019). This study leveraged off the methodology of other public data analysis work to create original insights and analysis. The study also offers a new methodology for analyzing production proxies when decline curve analysis is not possible. This analysis helps engineers better understand a production proxy's usefulness and accuracy in their analysis. Other key observations made during the analysis include:

- The First 12 Months BOE production proxy consistently has 80% of its parent-child well data points within 20% of their cumulative production difference.
- The Scoop/Stack Basins experience the largest decrease in child well productivity while Marcellus/Utica child wells and Bakken child wells drilled alongside older parent wells with older completion designs experience some of the best child results.
- Increasing spacing has a clear positive effect on child well production in almost all basins; however, the magnitude of the effect differs with each basin.
- Increasing completion date difference, or infill timing, typically has a clear negative effect on child well production until large production gaps reverse the trend, likely due to older parent wells with smaller completion designs.
- Using parent produced BOE at child completion corrects for the increase in child productivity observed with larger infill timings. This metric is likely a better indicator of child performance and parent well depletion.
- Production heatmaps generally indicate that larger child completion jobs lead to increased child productivity.

Overall, while creating the code to generate the parent-child well pairs was a worthwhile endeavor and was necessary given the study's access to Enverus data, several significant limitations should be addressed in other analyses of a similar nature. First, the lack of access to geology data makes any analysis of any well difficult. A sizable portion of the significant scatter in the data may be attributable to geological heterogeneity and other geologic properties like reservoir flow barriers. This high-level method of analyzing basin-wide data must assume stationarity, or at least relative stationarity, which is likely not always a valid assumption. Energy data companies like Enverus and many oil and gas companies have access to this proprietary data and can conduct analysis that was not possible in this situation. Regardless, there is still much to learn about the subsurface and the factors determining child well performance. As the number of wells drilled grows and more completion techniques are employed, further public data analysis will undoubtedly be necessary.

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Yuan, G., Dwivedi, P., Kwok, C. K., & Malpani, R. (2017, June 12). *The Impact of Increase in Lateral Length on Production Performance of Horizontal Shale Wells*. Society of Petroleum Engineers. doi:10.2118/185768-MS

Appendix A

Production Proxies

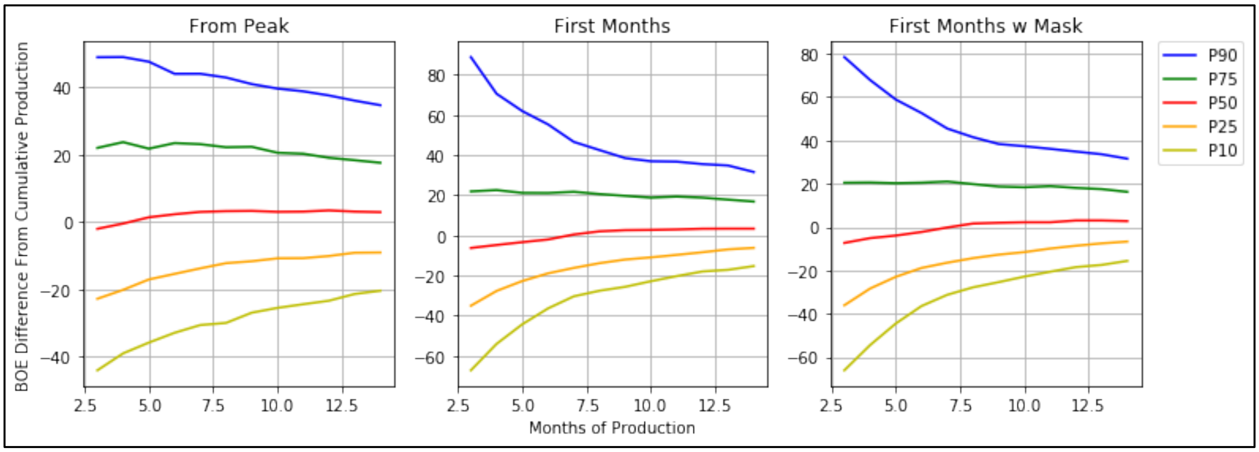


Figure A1. Bakken Basin proxy difference from cumulative for BOE production

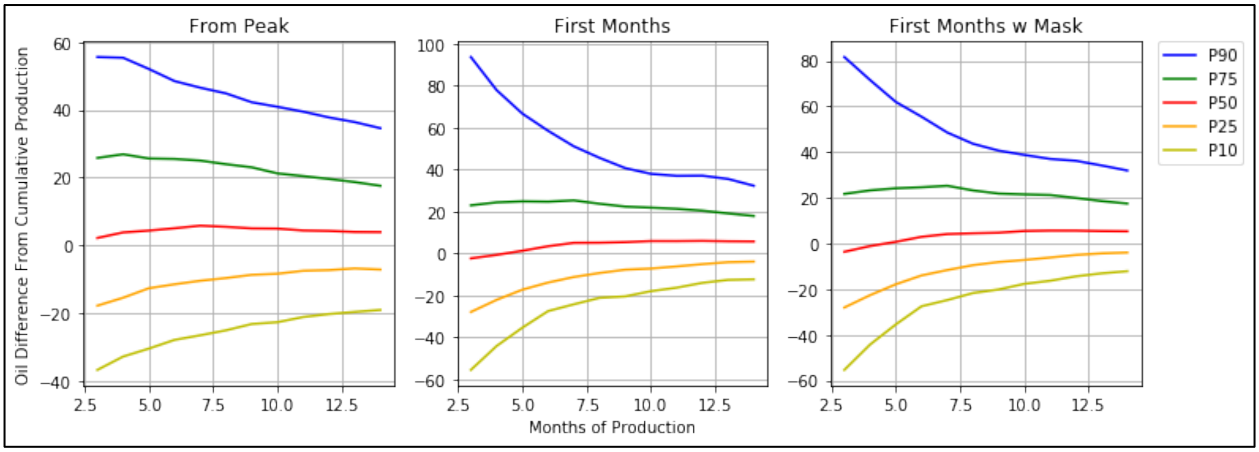


Figure A2. Bakken Basin proxy difference from cumulative for oil production

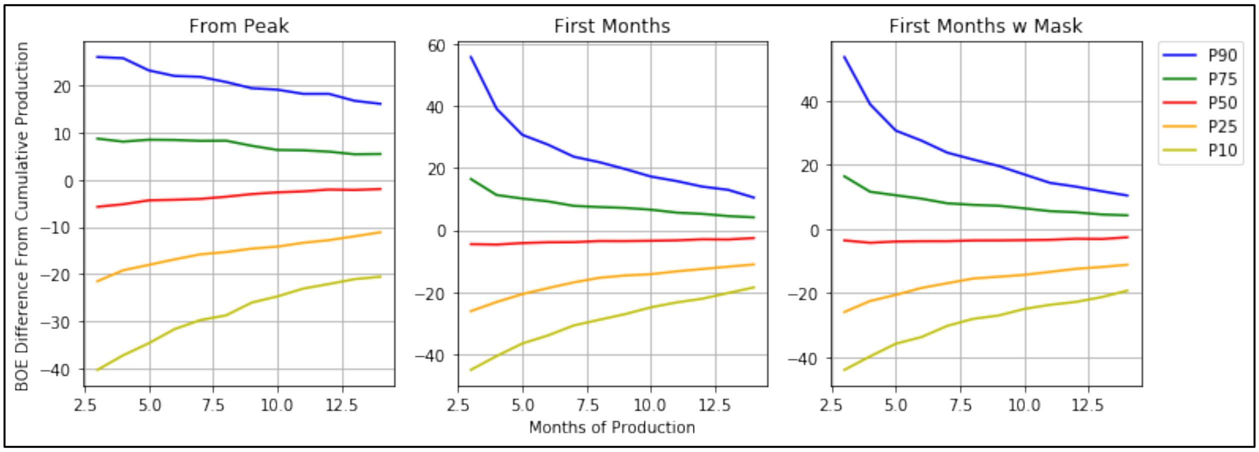


Figure A3. Delaware Basin proxy difference from cumulative for BOE production

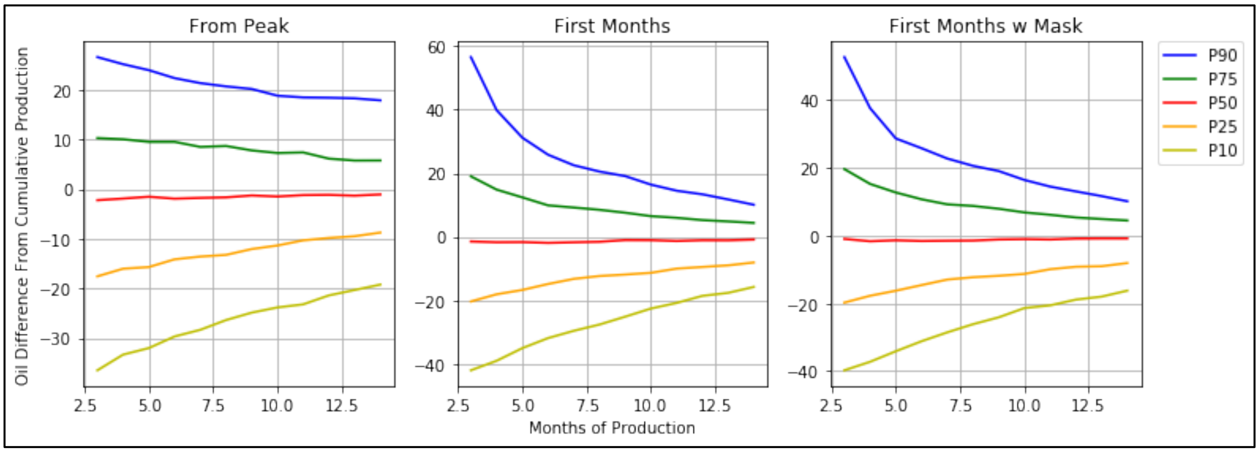


Figure A4. Delaware Basin proxy difference from cumulative for oil production

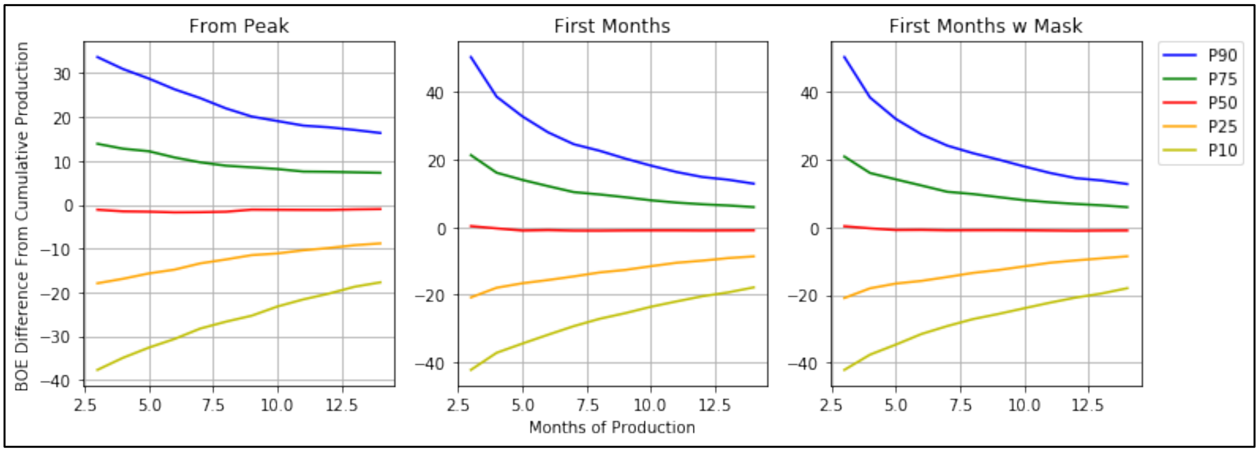


Figure A5. Eagle Ford Basin proxy difference from cumulative for BOE production

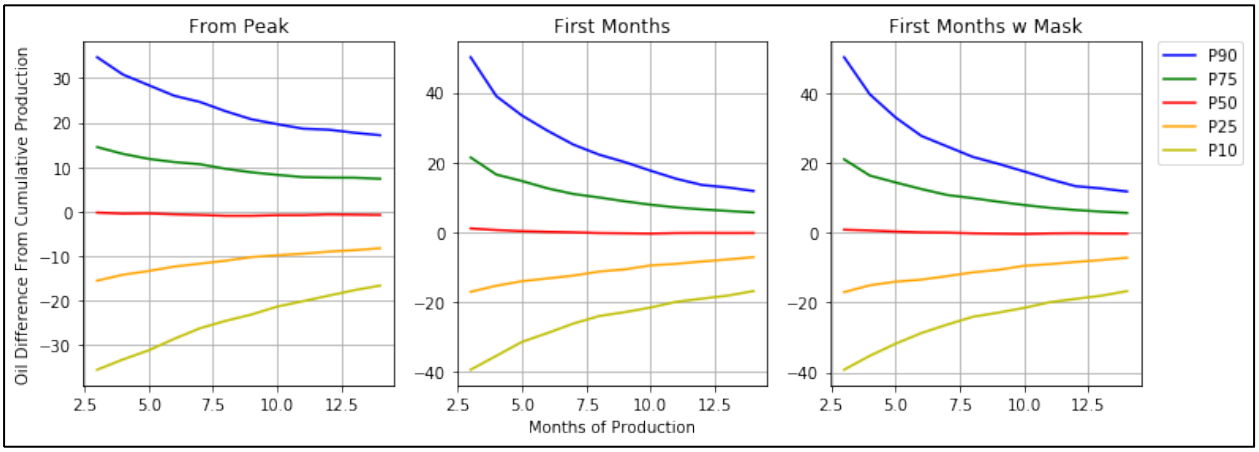


Figure A6. Eagle Ford Basin proxy difference from cumulative for oil production

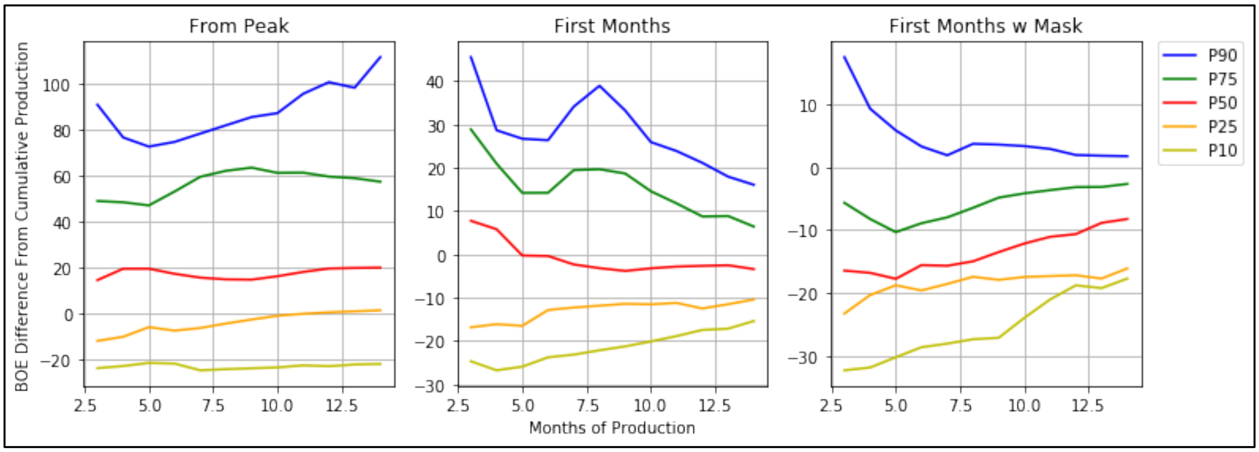


Figure A7. Haynesville Basin proxy difference from cumulative for BOE production

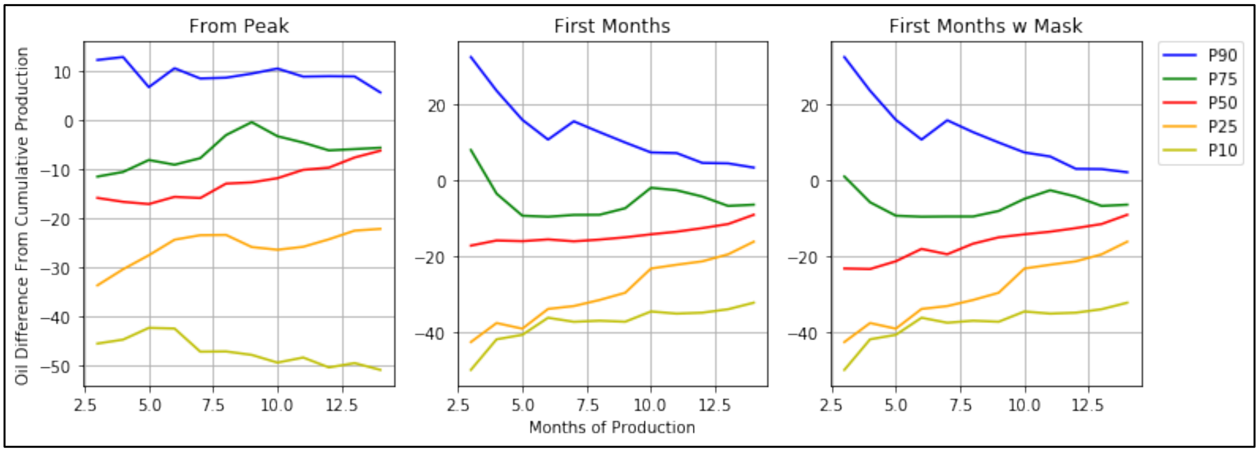


Figure A8. Haynesville Basin proxy difference from cumulative for oil production

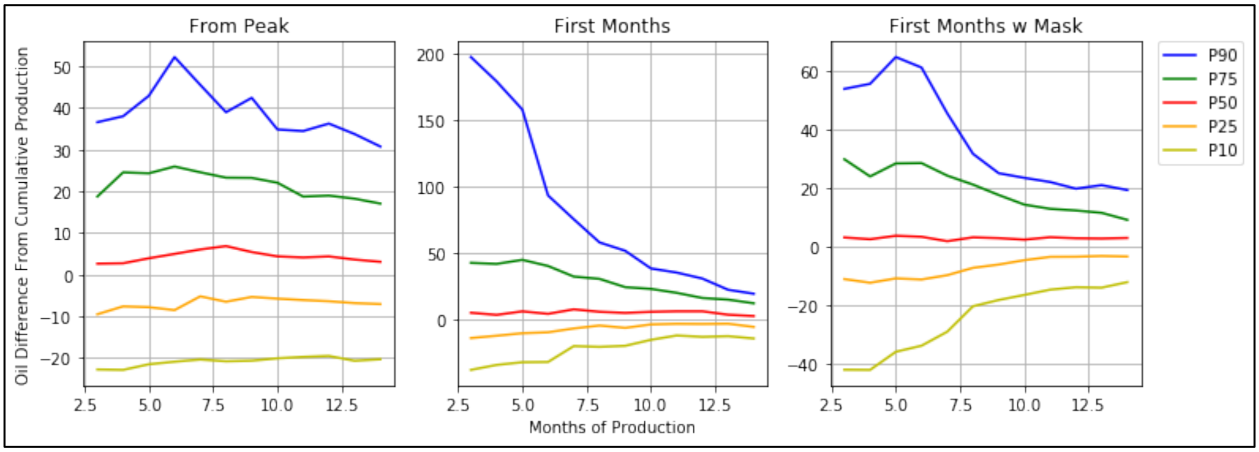


Figure A9. Marcellus/Utica Basins proxy difference from cumulative for oil production

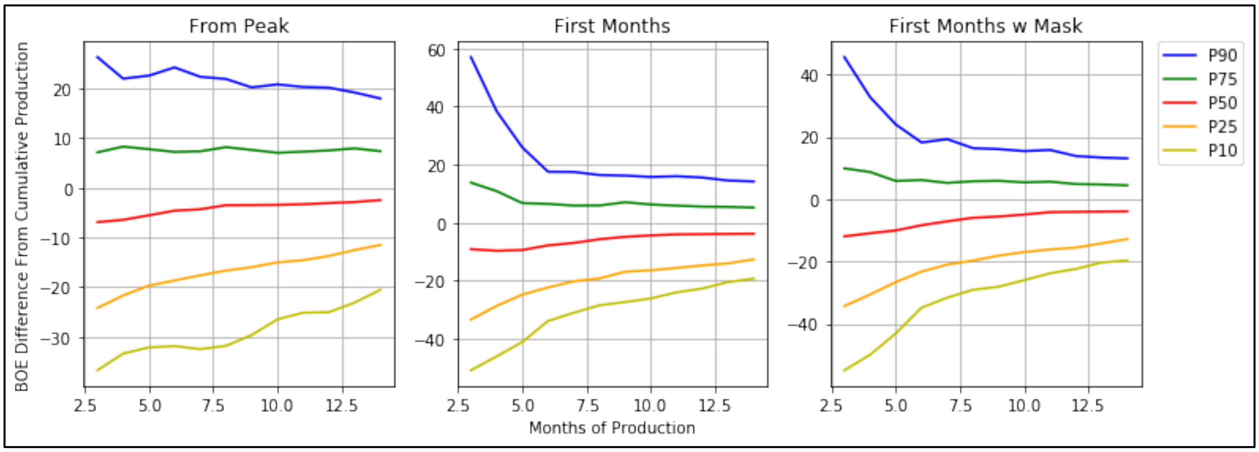


Figure A10. Niobrara Basin proxy difference from cumulative for BOE production

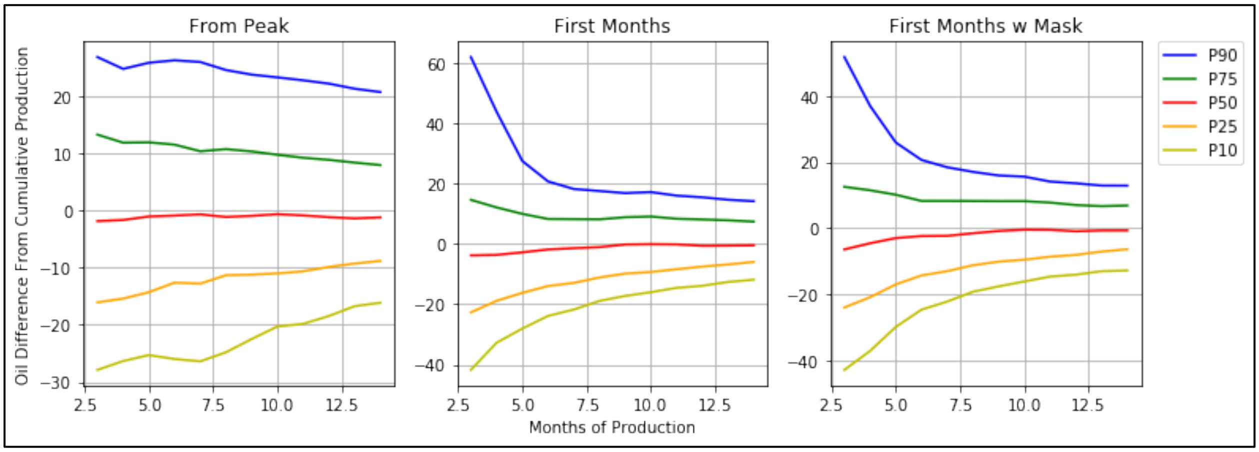


Figure A11. Niobrara Basin proxy difference from cumulative for oil production

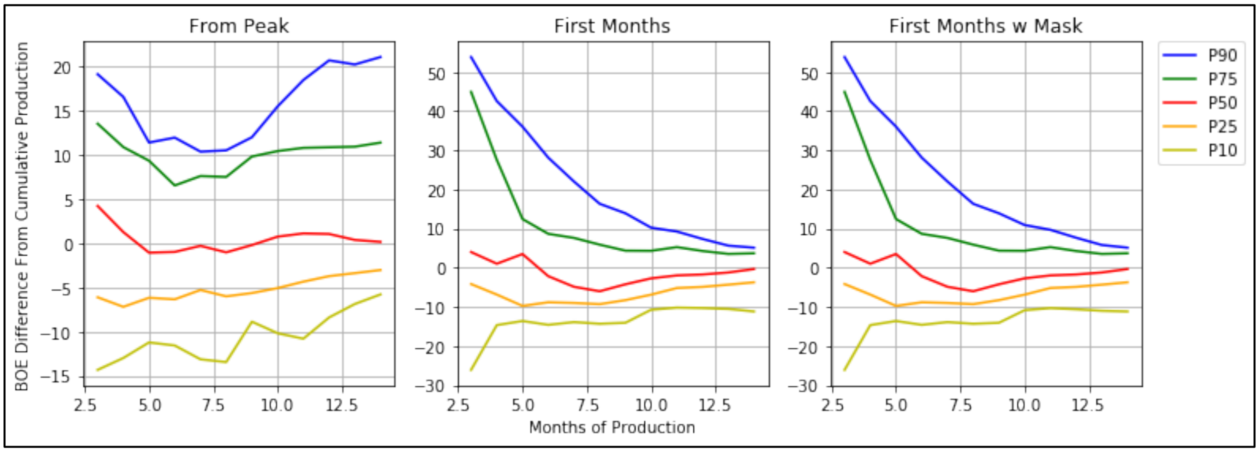


Figure A12. Powder River Basin proxy difference from cumulative for BOE production

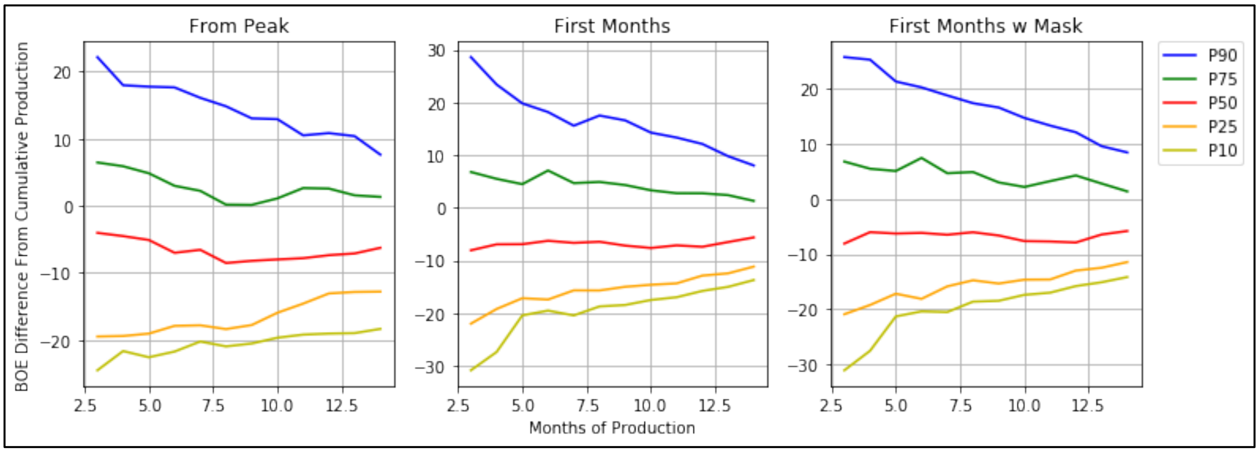


Figure A13. Scoop/Stack Basins proxy difference from cumulative for BOE production

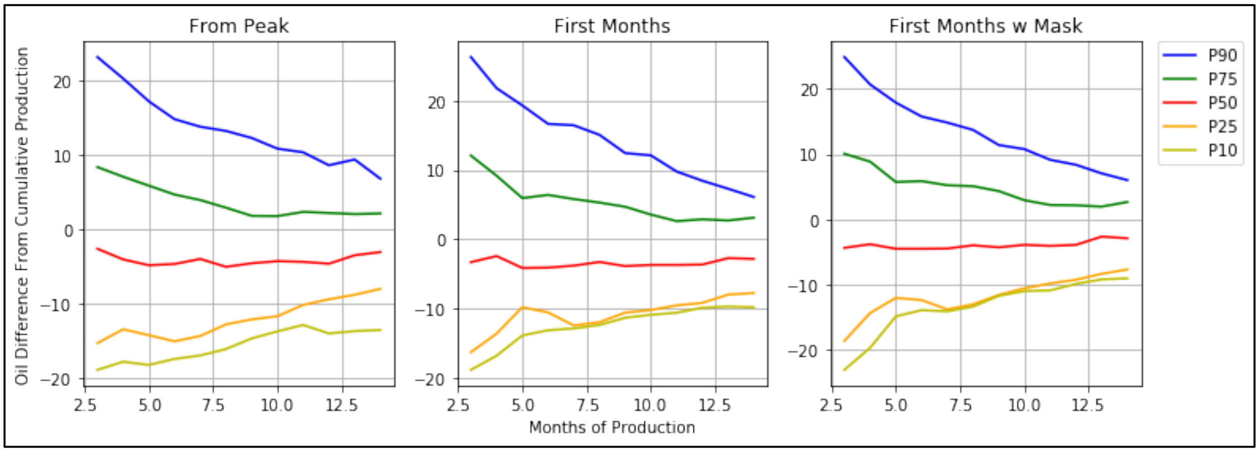
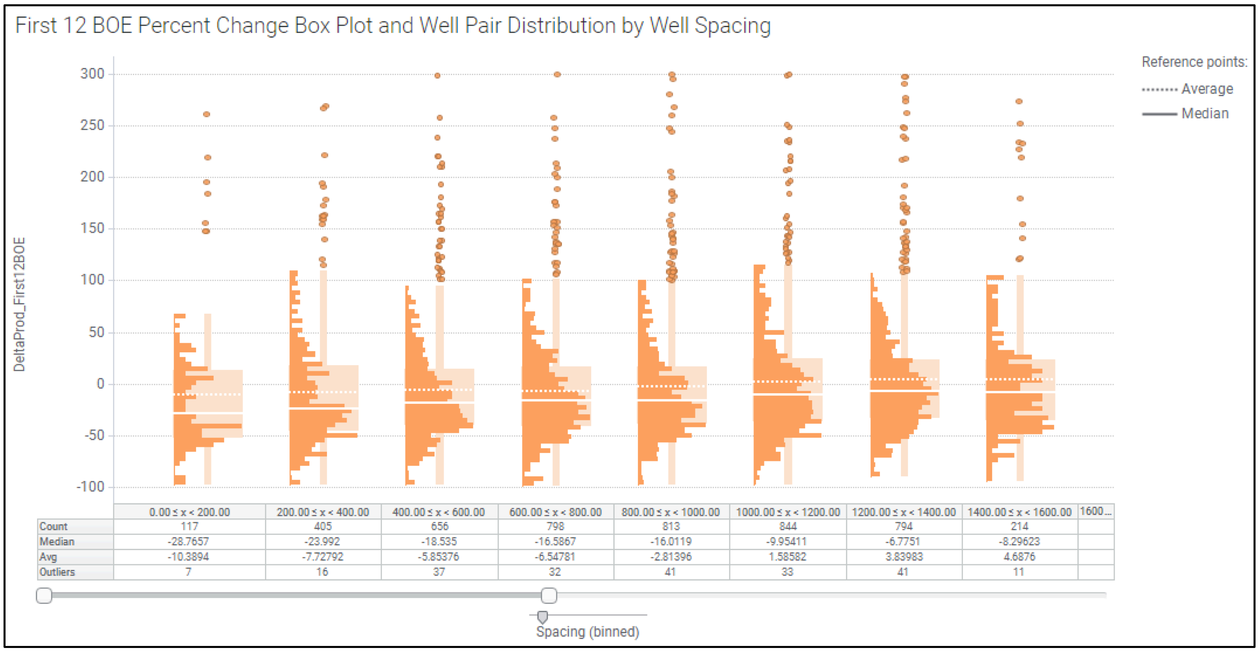


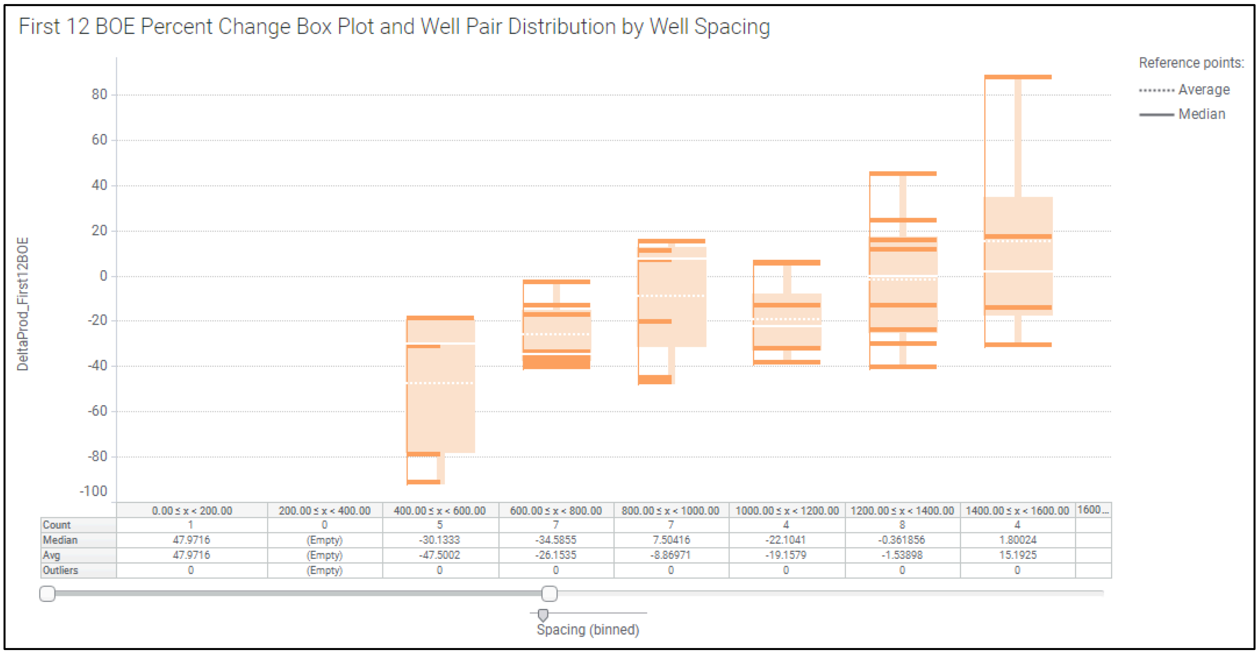
Figure A14. Scoop/Stack Basins proxy difference from cumulative for oil production

Spacing Boxplots by Basin


First 12 BOE Percent Change Box Plot and Well Pair Distribution by Well Spacing

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	117	405	656	798	813	844	794	214	
Median	-28.7657	-23.992	-18.535	-16.5867	-16.0119	-9.95411	-6.7751	-8.29623	
Avg	-10.3894	-7.72792	-5.85376	-6.54781	-2.81396	1.58582	3.83983	4.6876	
Outliers	7	16	37	32	41	33	41	11	

Figure A15. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Eagle Ford Basin


First 12 BOE Percent Change Box Plot and Well Pair Distribution by Well Spacing

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	1	0	5	7	7	4	8	4	
Median	47.9716	(Empty)	-30.1333	-34.5855	7.50416	-22.1041	-0.361856	1.80024	
Avg	47.9716	(Empty)	-47.5002	-26.1535	-8.86971	-19.1579	-1.53898	15.1925	
Outliers	0	(Empty)	0	0	0	0	0	0	

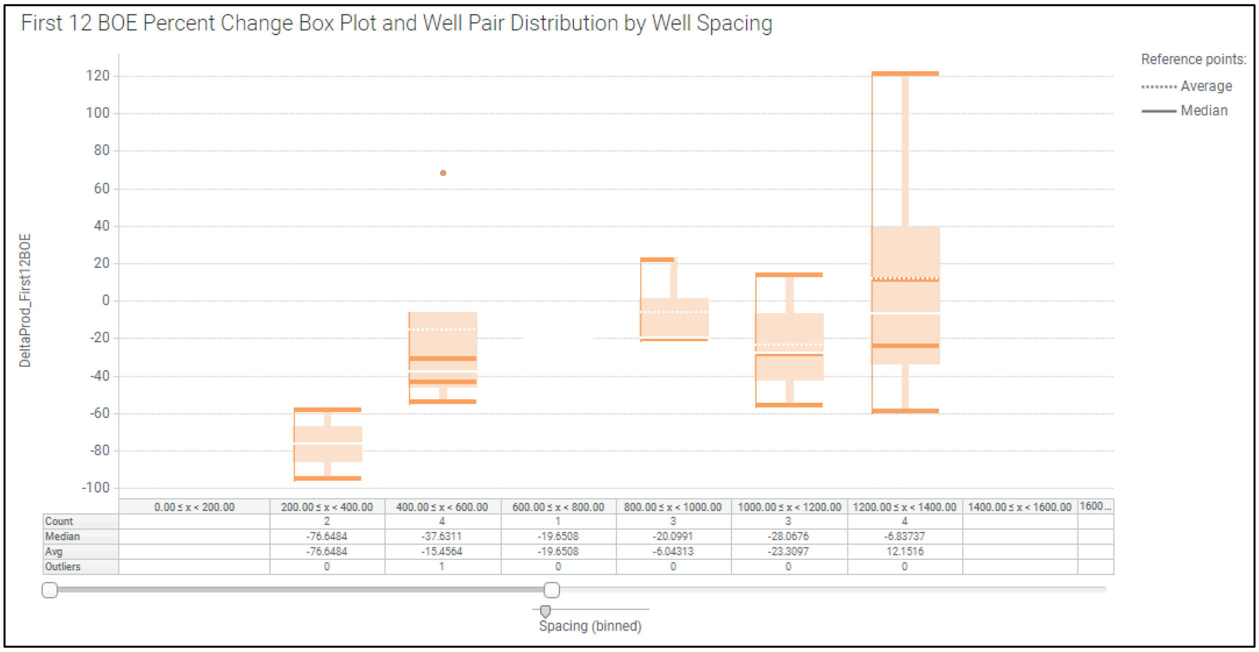
Figure A16. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Haynesville Basin

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	0	27	41	41	49	35	13	3	
Median	(Empty)	-0.0754143	-4.24563	-2.45302	-0.0300091	0.745437	26.5093	-20.861	
Avg	(Empty)	2.40536	-1.2531	2.38326	10.8797	4.37612	27.5399	-16.2653	
Outliers	(Empty)	2	3	3	3	2	1	0	

Figure A17. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Marcellus/Utica Basins

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	42	130	185	339	337	363	406	143	
Median	-17.2787	-12.1623	-8.68126	-5.76429	3.20842	-0.60376	5.5881	-4.31528	
Avg	6.09733	2.01827	1.36525	2.12485	15.0801	15.5693	17.4911	13.1664	
Outliers	2	10	6	14	18	20	20	5	

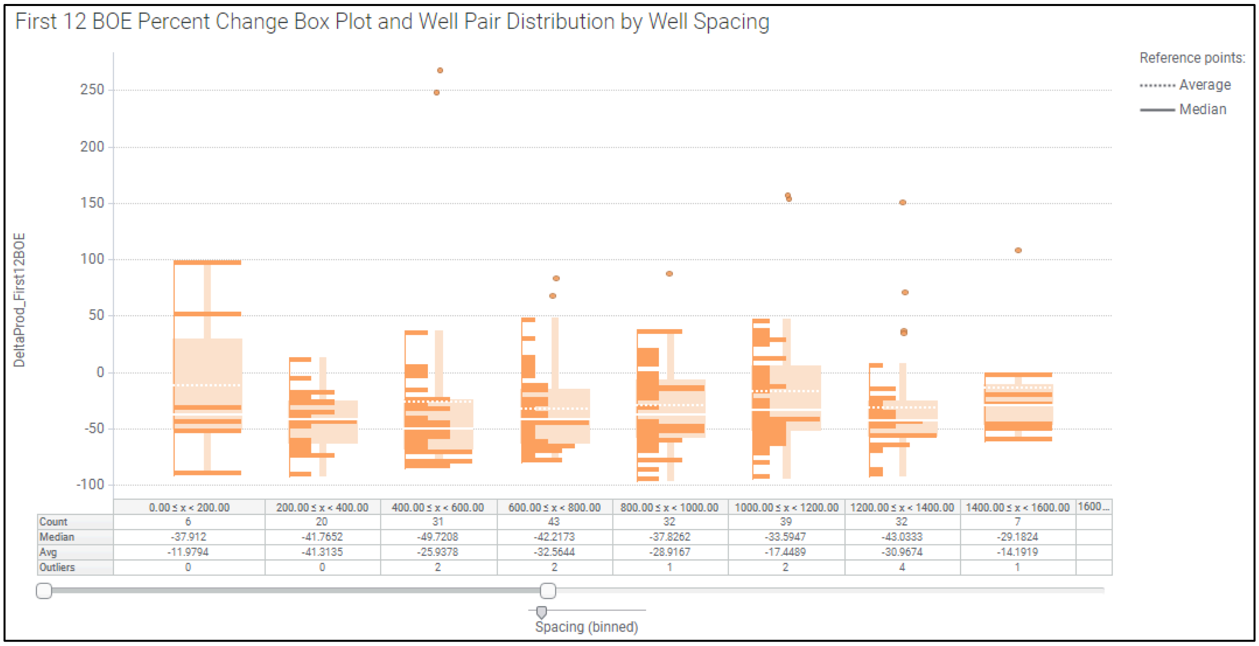
Figure A18. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Midland Basin



First 12 BOE Percent Change Box Plot and Well Pair Distribution by Well Spacing

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count		2	4	1	3	3	4		
Median		-76.6484	-37.6311	-19.6508	-20.0991	-28.0676	-6.83737		
Avg		-76.6484	-15.4564	-19.6508	-6.04313	-23.3097	12.1516		
Outliers		0	1	0	0	0	0		

Figure A19. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Powder River Basin

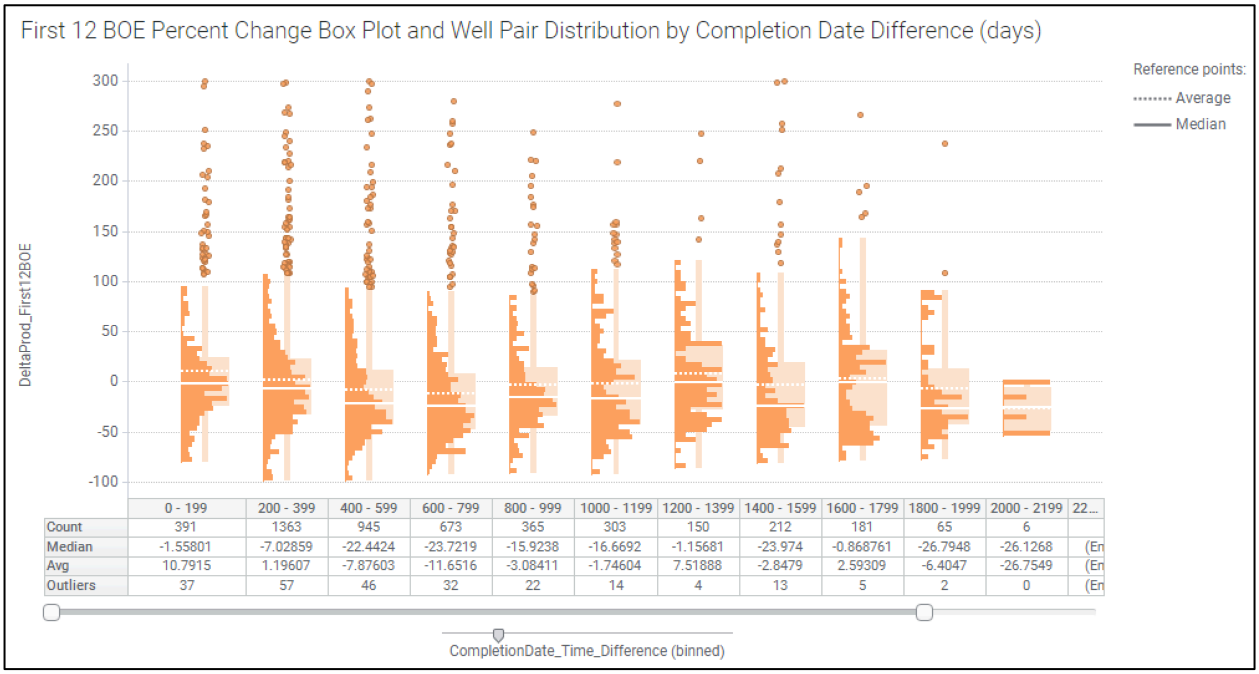


First 12 BOE Percent Change Box Plot and Well Pair Distribution by Well Spacing

	0.00 ≤ x < 200.00	200.00 ≤ x < 400.00	400.00 ≤ x < 600.00	600.00 ≤ x < 800.00	800.00 ≤ x < 1000.00	1000.00 ≤ x < 1200.00	1200.00 ≤ x < 1400.00	1400.00 ≤ x < 1600.00	1600...
Count	6	20	31	43	32	39	32	7	
Median	-37.912	-41.7652	-49.7208	-42.2173	-37.8262	-33.5947	-43.0333	-29.1824	
Avg	-11.9794	-41.3135	-25.9378	-32.5644	-28.9167	-17.4489	-30.9674	-14.1919	
Outliers	0	0	2	2	1	2	4	1	

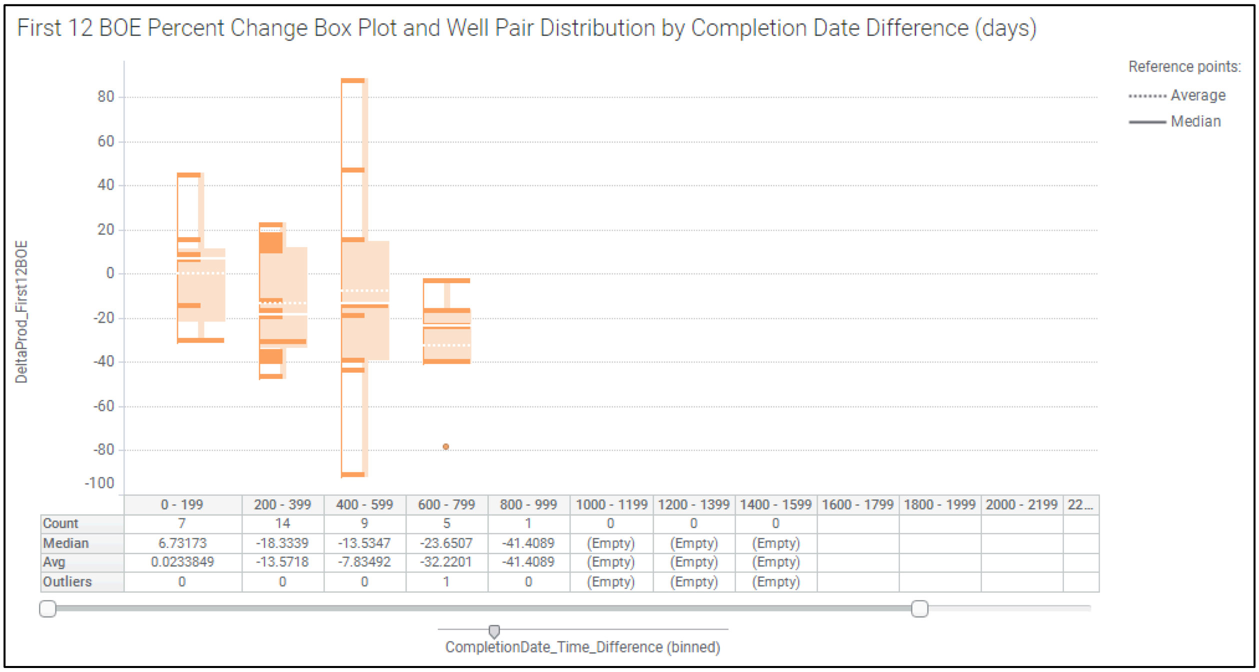
Figure A20. First 12 BOE percent change boxplot and well pair distribution by well spacing for the Scoop/Stack Basins

Completion Date Difference Boxplots by Basin



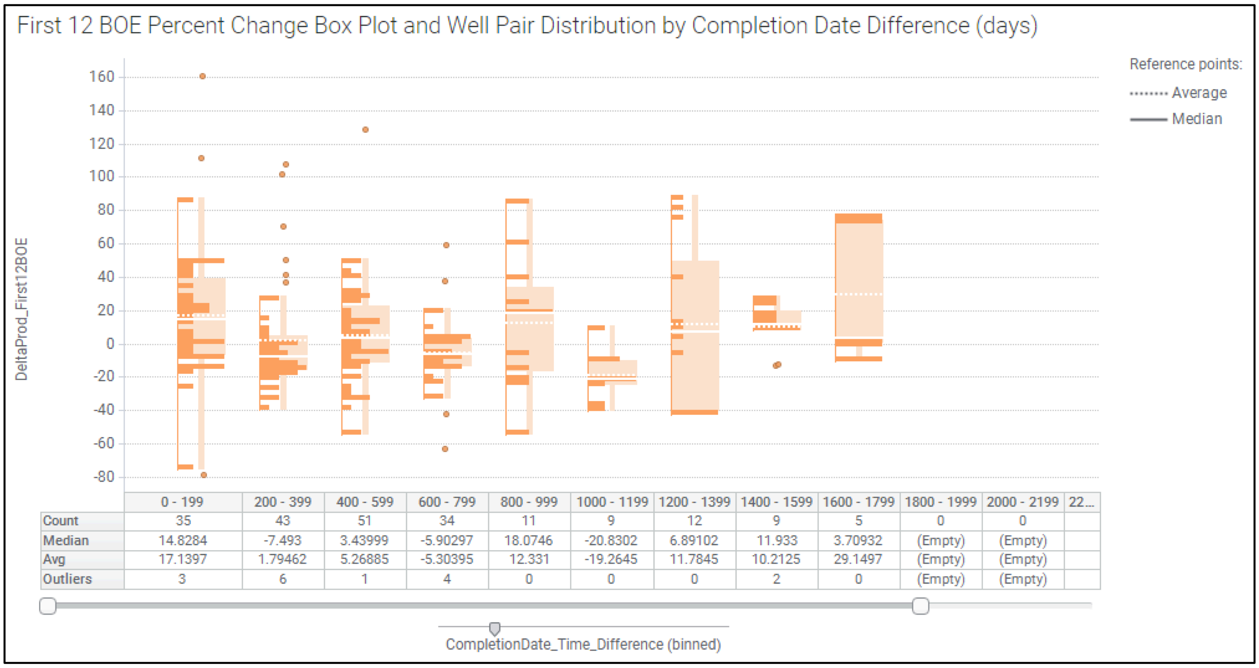
	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	391	1363	945	673	365	303	150	212	181	65	6	
Median	-1.55801	-7.02859	-22.4424	-23.7219	-15.9238	-16.6692	-1.15681	-23.974	-0.868761	-26.7948	-26.1268	(En
Avg	10.7915	1.19607	-7.87603	-11.6516	-3.08411	-1.74604	7.51888	-2.8479	2.59309	-6.4047	-26.7549	(En
Outliers	37	57	46	32	22	14	4	13	5	2	0	(En

Figure A21. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Eagle Ford Basin



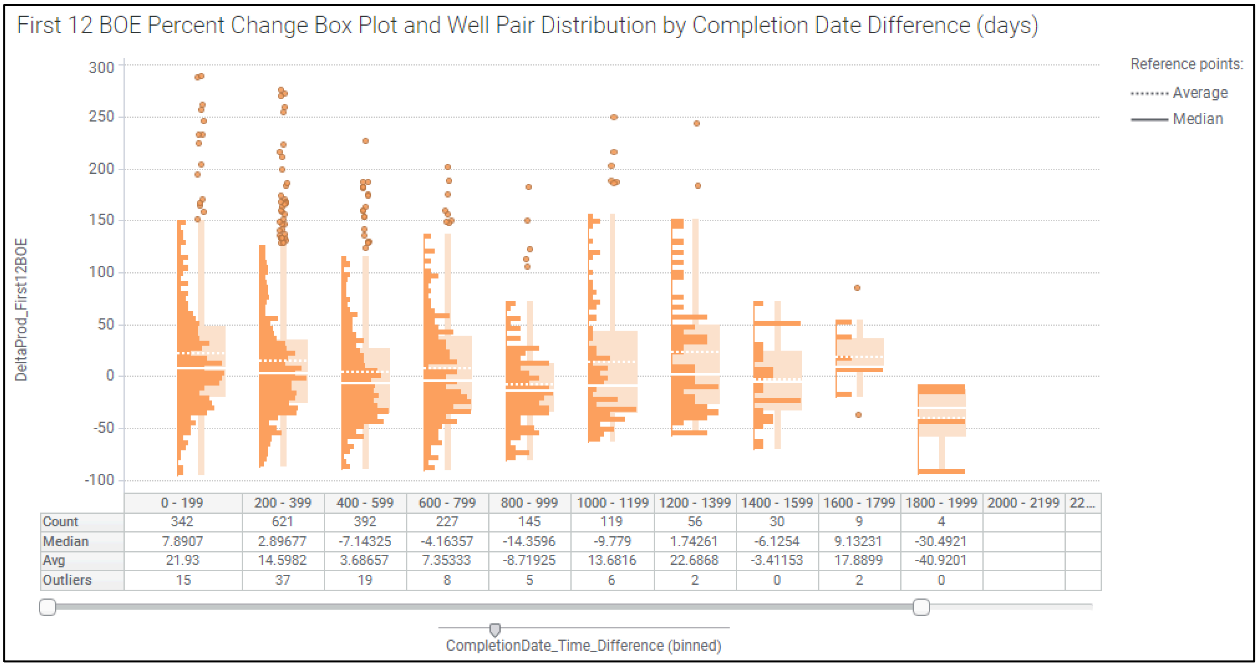
	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	7	14	9	5	1	0	0	0				
Median	6.73173	-18.3339	-13.5347	-23.6507	-41.4089	(Empty)	(Empty)	(Empty)				
Avg	0.0233849	-13.5718	-7.83492	-32.2201	-41.4089	(Empty)	(Empty)	(Empty)				
Outliers	0	0	0	1	0	(Empty)	(Empty)	(Empty)				

Figure A22. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Haynesville Basin



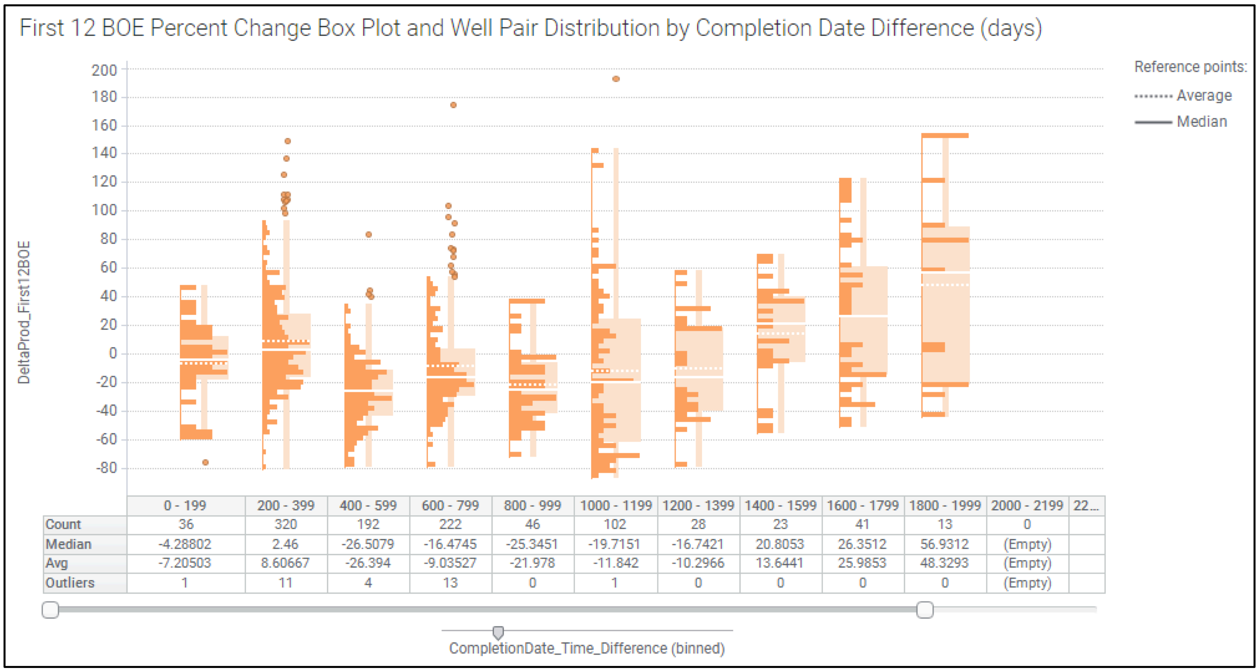
	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	35	43	51	34	11	9	12	9	5	0	0	
Median	14.8284	-7.493	3.43999	-5.90297	18.0746	-20.8302	6.89102	11.933	3.70932	(Empty)	(Empty)	
Avg	17.1397	1.79462	5.26885	-5.30395	12.331	-19.2645	11.7845	10.2125	29.1497	(Empty)	(Empty)	
Outliers	3	6	1	4	0	0	0	2	0	(Empty)	(Empty)	

Figure A23. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Marcellus/Utica Basins



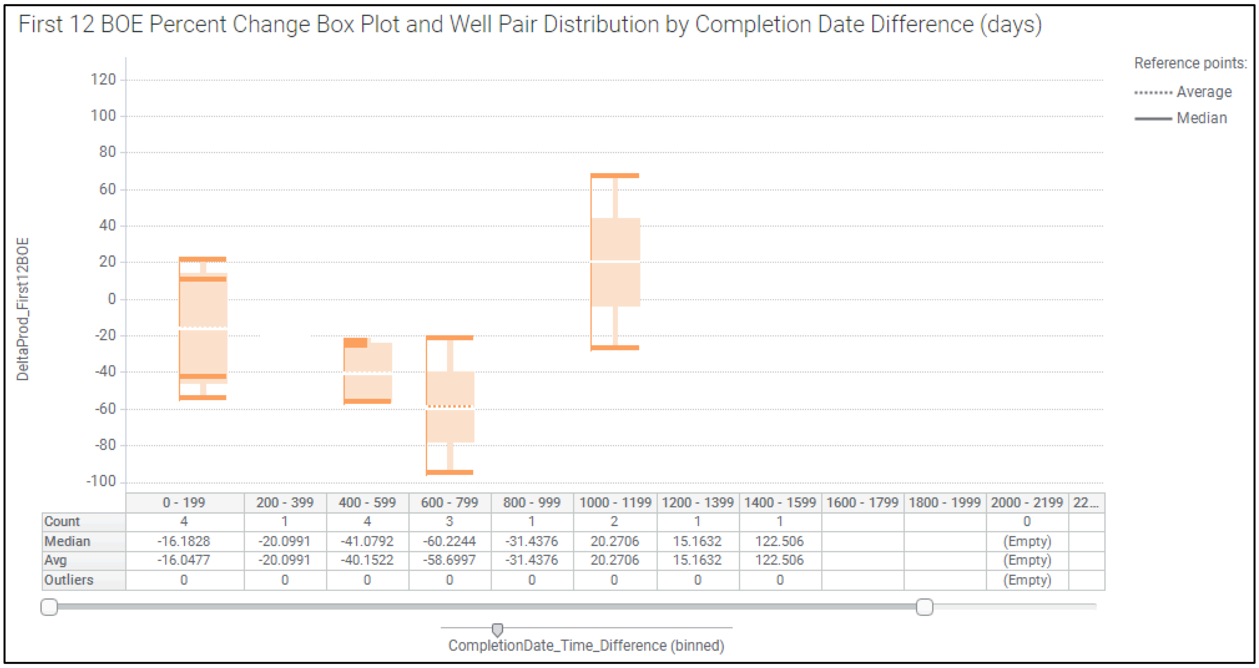
	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	342	621	392	227	145	119	56	30	9	4		
Median	7.8907	2.89677	-7.14325	-4.16357	-14.3596	-9.779	1.74261	-6.1254	9.13231	-30.4921		
Avg	21.93	14.5982	3.68657	7.35333	-8.71925	13.6816	22.6868	-3.41153	17.8899	-40.9201		
Outliers	15	37	19	8	5	6	2	0	2	0		

Figure A24. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Midland Basin



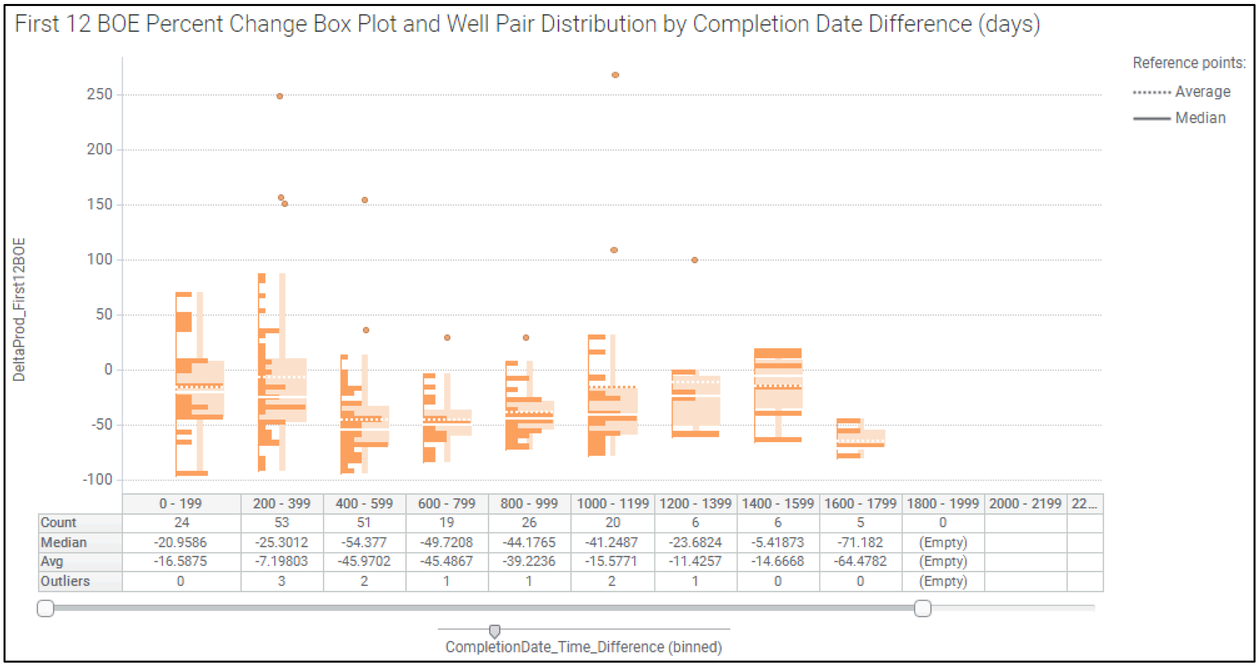
	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	36	320	192	222	46	102	28	23	41	13	0	
Median	-4.28802	2.46	-26.5079	-16.4745	-25.3451	-19.7151	-16.7421	20.8053	26.3512	56.9312	(Empty)	
Avg	-7.20503	8.60667	-26.394	-9.03527	-21.978	-11.842	-10.2966	13.6441	25.9853	48.3293	(Empty)	
Outliers	1	11	4	13	0	1	0	0	0	0	(Empty)	

Figure A25. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Niobrara Basin



	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	4	1	4	3	1	2	1	1			0	
Median	-16.1828	-20.0991	-41.0792	-60.2244	-31.4376	20.2706	15.1632	122.506			(Empty)	
Avg	-16.0477	-20.0991	-40.1522	-58.6997	-31.4376	20.2706	15.1632	122.506			(Empty)	
Outliers	0	0	0	0	0	0	0	0			(Empty)	

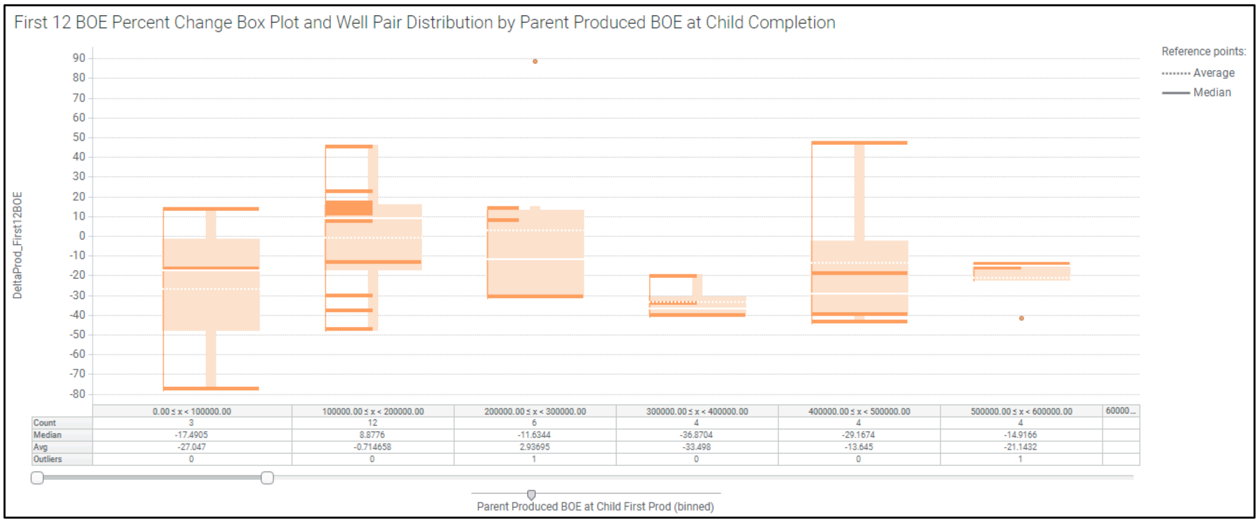
Figure A26. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Powder River Basin



	0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	2000 - 2199	22...
Count	24	53	51	19	26	20	6	6	5	0		
Median	-20.9586	-25.3012	-54.377	-49.7208	-44.1765	-41.2487	-23.6824	-5.41873	-71.182	(Empty)		
Avg	-16.5875	-7.19803	-45.9702	-45.4867	-39.2236	-15.5771	-11.4257	-14.6668	-64.4782	(Empty)		
Outliers	0	3	2	1	1	2	1	0	0	(Empty)		

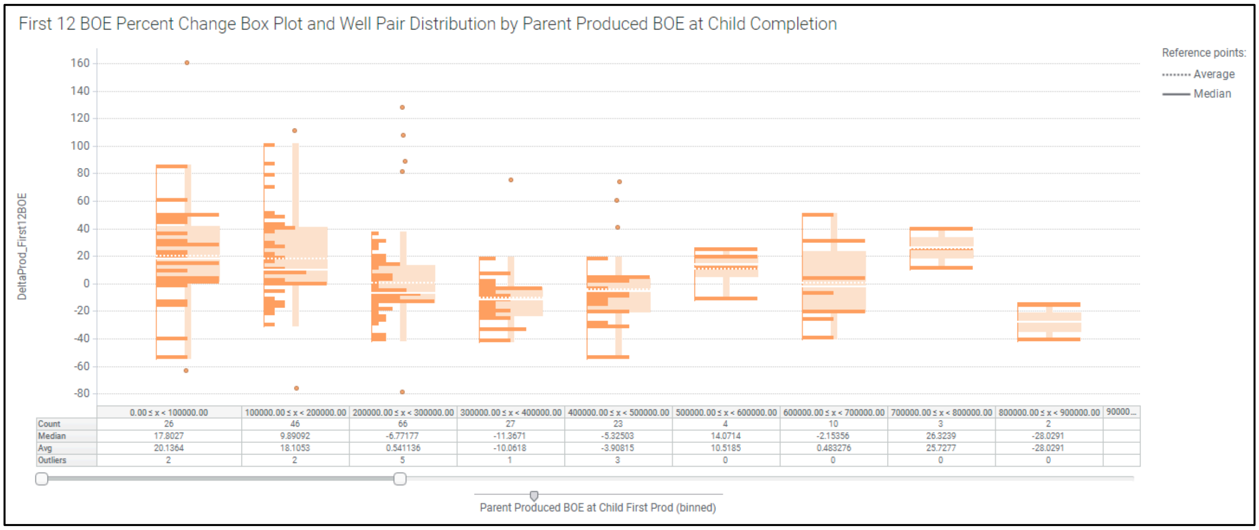
Figure A27. First 12 BOE percent change boxplot and well pair distribution by completion date difference for the Scoop/Stack Basins

Parent Produced Volume at Child Completion Boxplots by Basin



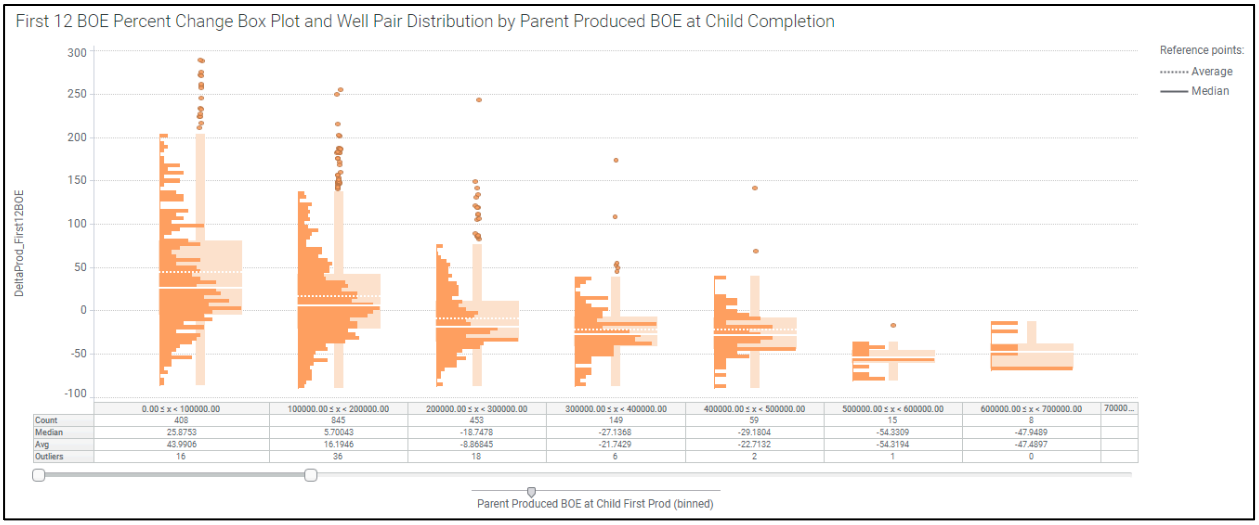
	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	400000.00 ≤ x < 500000.00	500000.00 ≤ x < 600000.00	60000...
Count	3	12	6	4	4	4	
Median	-17.4905	8.8776	-11.6344	-36.8704	-29.1674	-14.9166	
Avg	-27.047	-0.714658	2.93695	-33.498	-13.645	-21.1432	
Outliers	0	0	1	0	0	1	

Figure A28. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Haynesville Basin



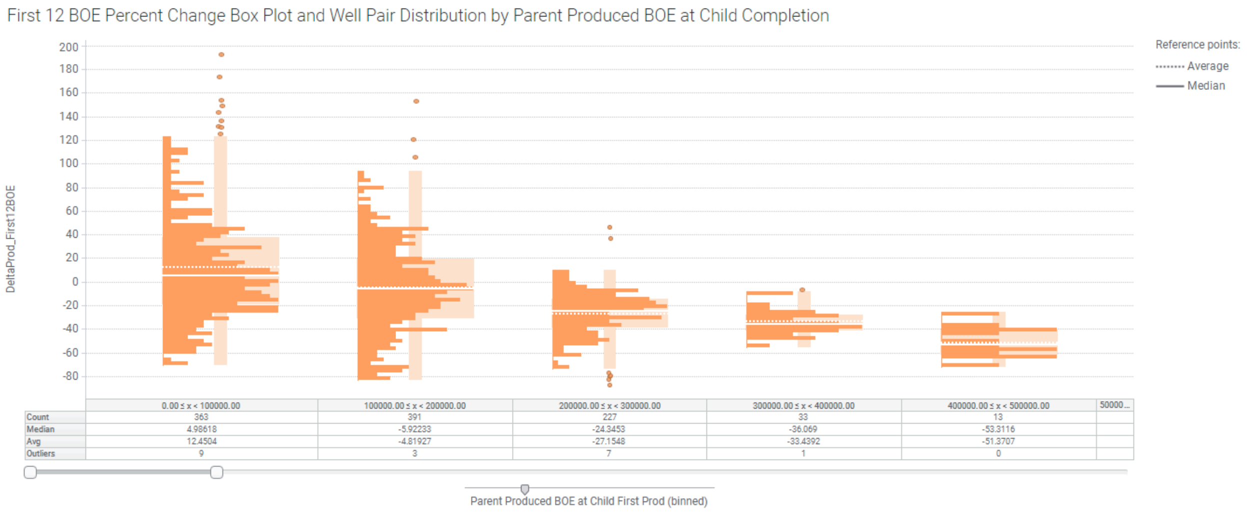
	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	400000.00 ≤ x < 500000.00	500000.00 ≤ x < 600000.00	600000.00 ≤ x < 700000.00	700000.00 ≤ x < 800000.00	800000.00 ≤ x < 900000.00	90000...
Count	26	46	66	27	23	4	10	3	2	
Median	17.8027	9.89092	-6.77177	-11.3671	-5.32503	14.0714	-2.15356	26.3239	-28.0291	
Avg	20.1364	18.1053	0.541136	-10.0618	-3.90815	10.5185	0.483276	25.7277	-28.0291	
Outliers	2	2	5	1	3	0	0	0	0	

Figure A29. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Marcellus/Utica Basins



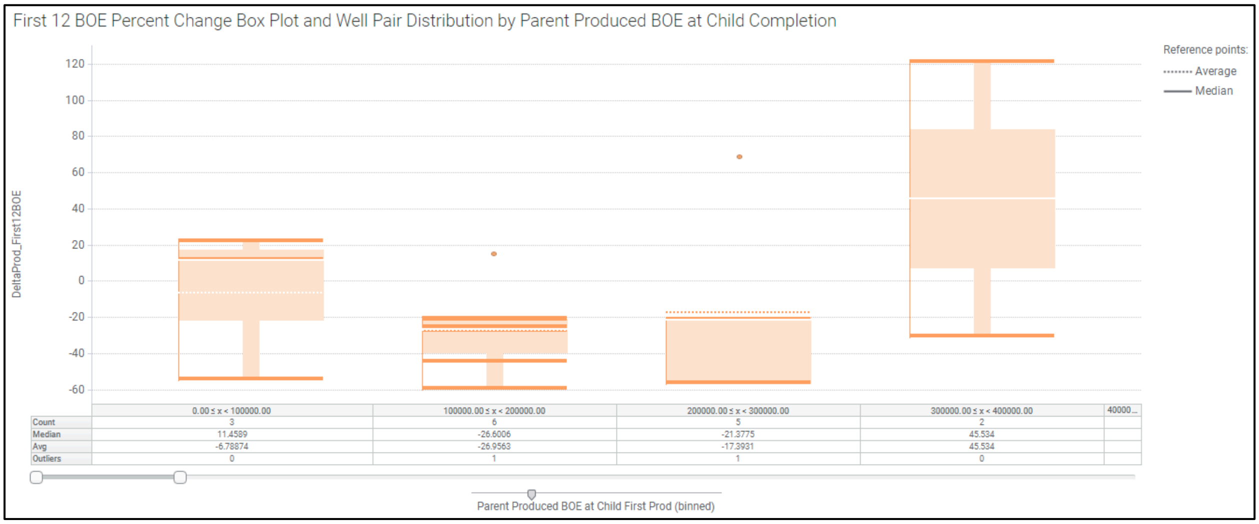
	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	400000.00 ≤ x < 500000.00	500000.00 ≤ x < 600000.00	600000.00 ≤ x < 700000.00	70000...
Count	408	845	453	149	59	15	8	
Median	25.8753	5.70043	-18.7478	-27.1368	-29.1804	-54.3309	-47.9489	
Avg	43.9906	16.1946	-8.86845	-21.7429	-22.7132	-54.3194	-47.4897	
Outliers	16	36	18	6	2	1	0	

Figure A30. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Midland Basin



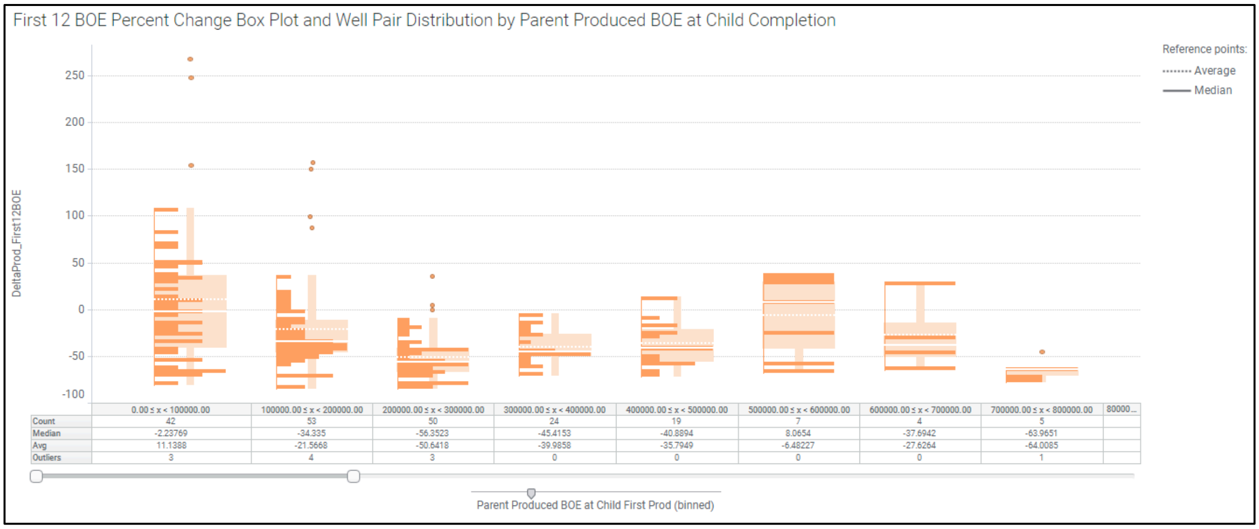
	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	400000.00 ≤ x < 500000.00	50000...
Count	363	391	227	33	13	
Median	4.98618	-5.92233	-24.3453	-36.069	-53.3116	
Avg	12.4504	-4.81927	-27.1548	-33.4392	-51.3707	
Outliers	9	3	7	1	0	

Figure A31. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Niobrara Basin



	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	40000...
Count	3	6	5	2	
Median	11.4589	-26.6006	-21.3775	45.534	
Avg	-6.78874	-26.9563	-17.3931	45.534	
Outliers	0	1	1	0	

Figure A32. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Powder River Basin



	0.00 ≤ x < 100000.00	100000.00 ≤ x < 200000.00	200000.00 ≤ x < 300000.00	300000.00 ≤ x < 400000.00	400000.00 ≤ x < 500000.00	500000.00 ≤ x < 600000.00	600000.00 ≤ x < 700000.00	700000.00 ≤ x < 800000.00	80000...
Count	42	53	50	24	19	7	4	5	
Median	-2.23769	-34.335	-56.3523	-45.4153	-40.8894	8.0654	-37.6942	-63.9651	
Avg	11.1388	-21.5668	-50.6418	-39.9858	-35.7949	-6.48227	-27.6264	-64.0085	
Outliers	3	4	3	0	0	0	0	1	

Figure A33. First 12 BOE percent change boxplot and well pair distribution by parent produced BOE at child completion for the Scoop/Stack Basins

Child Proppant vs. Fluid Loading Production Heatmaps by Basin

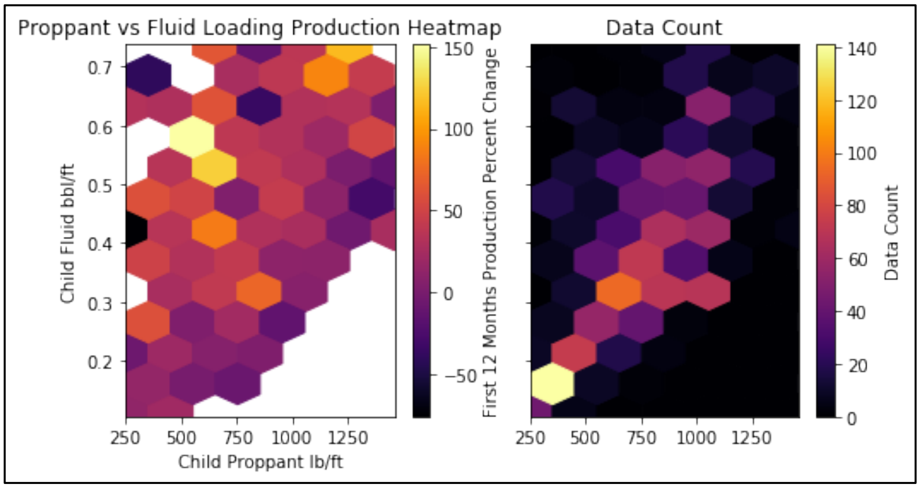


Figure A34. Bakken Basin child proppant and fluid loading heatmap colored by First 12 Months percent change

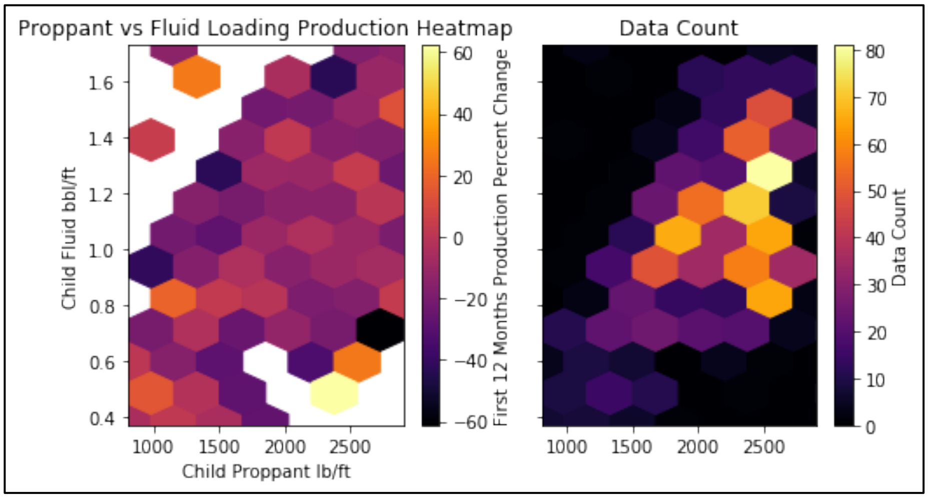


Figure A35. Delaware Basin child proppant and fluid loading heatmap colored by First 12 Months percent change

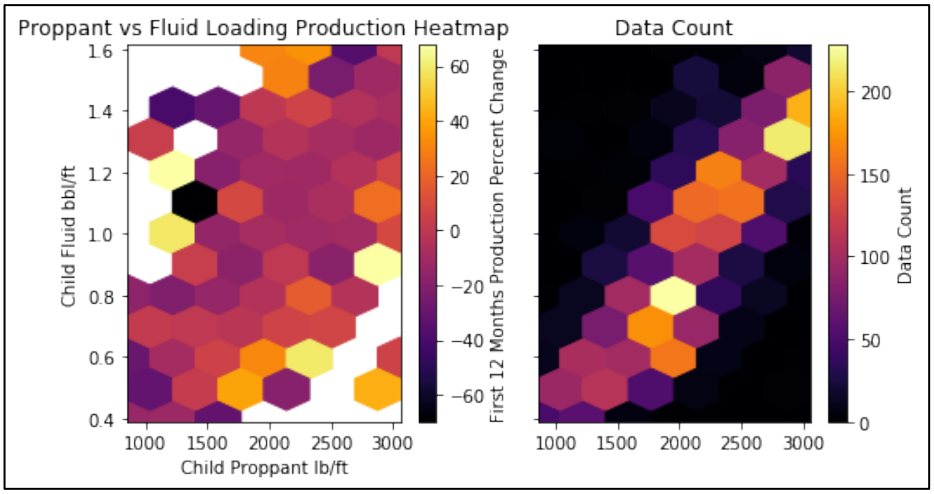


Figure A36. Eagle Ford Basin child proppant and fluid loading heatmap colored by First 12 Months percent change

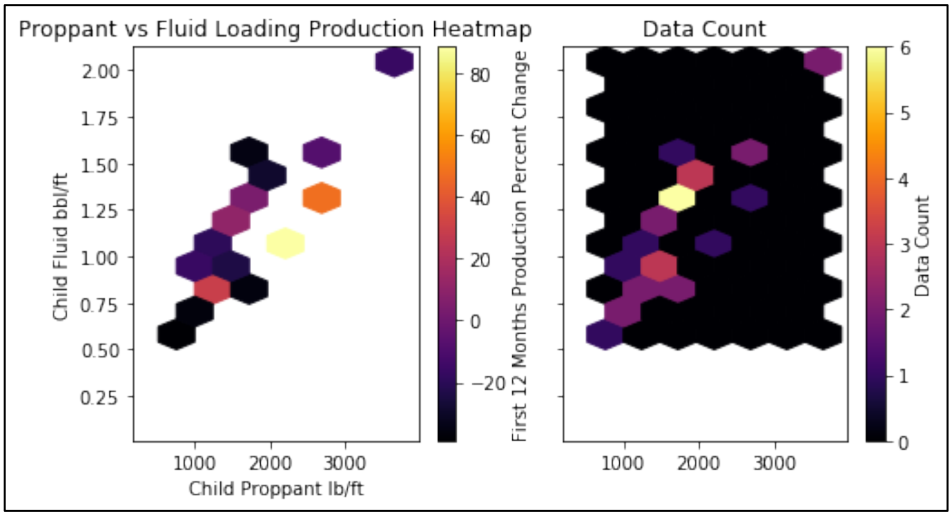


Figure A37. Haynesville Basin child proppant and fluid loading heatmap colored by First 12 Months percent change

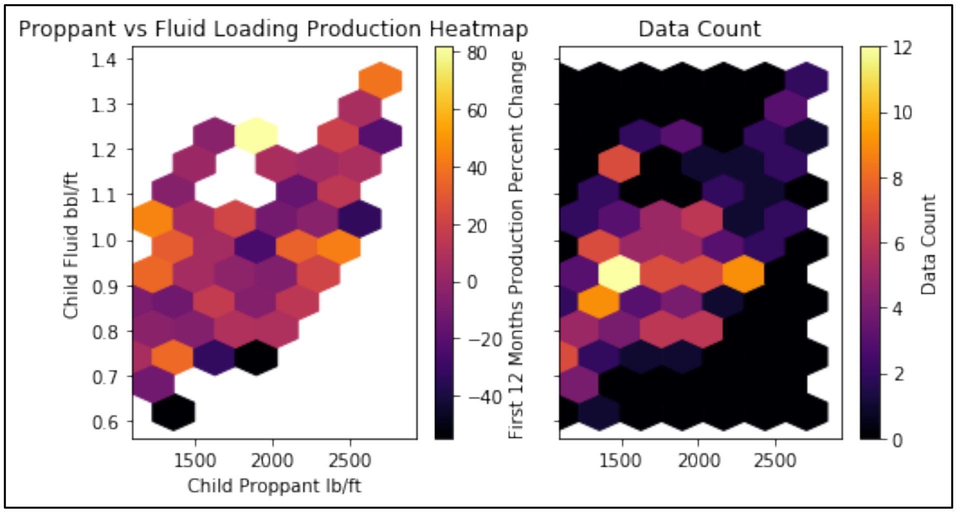


Figure A38. Marcellus/Utica Basins child proppant and fluid loading heatmap colored by First 12 Months percent change

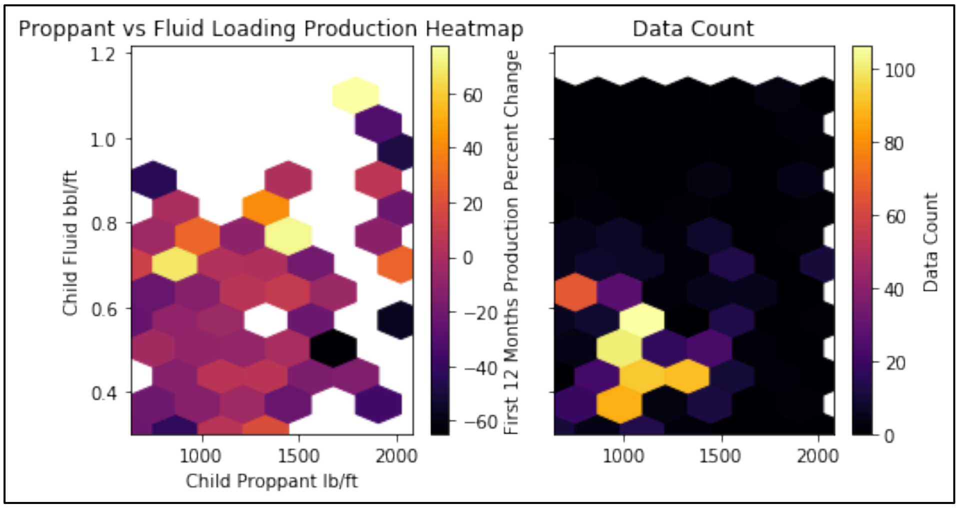


Figure A39. Niobrara Basin child proppant and fluid loading heatmap colored by First 12 Months percent change

Biography

From Houston, Texas, Joe W. Cozby is a graduating senior majoring in Petroleum Engineering Honors in the Cockrell School of Engineering and in the Plan II Honors Program in the College of Liberal Arts at the University of Texas at Austin. Mr. Cozby completed his undergraduate studies in December of 2020 and will begin his professional career working for EOG Resources in Midland, Texas. His involvement on campus includes being President of Pi Epsilon Tau – UT Petroleum Engineering's honor society, the Society of Petroleum Engineers (SPE) and the American Association of Drilling Engineers (AADE). Mr. Cozby is a UT Distinguished College Scholar, National Merit Scholar, Eagle Scout Award Recipient and member of Phi Beta Kappa and Phi Kappa Phi.