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16. ABSTRACT
The California Department of Transportation (Caltrans) Division of Equipment (DOE) initiated the testing of sand spreaders to compare the spreading performance of traditional spreaders and newer designs from vendors Henderson and Epoke. The newer designs can more accurately control spread rates. Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center and DOE personnel performed this testing in the fall of 2018 and in the summer of 2021. This report presents a brief summary of the previously documented 2018 testing and the results of the final 2021 testing.

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Comparison of New and Existing Caltrans Hopper Body and Tailgate Sanders

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Report Number: CA22-3300
AHMCT Research Report: UCD-ARR-22-03-31-01
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May 20, 2022

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Background

California Department of Transportation (Caltrans) has several different types of sand/salt spreaders in the fleet. Caltrans is motivated to reduce salt and sand usage, and needed quantifiable material distribution results via testing. Caltrans requested testing of the following spreader types:

1. One [Henderson Vbody FSH14 spreader with Direct Cast (2019 model) (http://www.hendersonproducts.com/spreaders.html)](http://www.hendersonproducts.com/spreaders.html)
2. One [Epoke S4900 with directional casting (http://www.epokena.com/products/bulk-spreaders/s49004902-sirius-ast-combi/)](http://www.epokena.com/products/bulk-spreaders/s49004902-sirius-ast-combi/)
3. Two [Henderson FRS with Direct Cast (2018 model and 2020 model) (http://www.hendersonproducts.com/assets/hp-050_firstresponse.pdf)](http://www.hendersonproducts.com/assets/hp-050_firstresponse.pdf)

Caltrans continuously seeks new methods and equipment for its winter maintenance operations in order to meet its mission and goals. Winter maintenance operations represent a significant challenge to Caltrans, and by implementing improved methods and equipment, Caltrans can realize operational and safety improvements, cost savings, and reduced environmental impacts. Increasing the efficiency of the sand/salt spreader fleet will:

a) Reduce the amount of excess sand/salt applied, addressing both environmental and cost concerns

b) Increase the efficiency of the operation, which will allow the operators to apply sand/salt longer between refills and increase road safety for the motoring public.

This research provided input and guidance for Caltrans' decision-making process regarding which spreaders to buy in the future in order to achieve its goals. The research also provided data which may allow Caltrans to revise spreader operations following procurement.

Overview of the Work and Methodology

The research methodology used controlled field testing to assess the sand spreading properties of the Henderson and Epoke spreader types. The focus of the current report is the summer 2021 testing and final research conclusions.

The key deliverables of this project include:

- Updated test procedure: The testing procedure was modified to collect a majority of samples in 2x1-meter increments.
- Sand collection system design: A re-designed vacuum system supported more rapid collection of samples.
- Sand spreader testing raw data and testing video: The data, photos, videos, and other information were provided in a shared folder.

The goal was to assess the efficiency and effectiveness of advanced spreader systems, and provide information to support quantitative comparison of these systems in support of future Caltrans procurement. As a result of the implementation of these research results, it is expected that the amount of sand/salt applied to the roadway will decrease, which will decrease winter maintenance costs, have positive environmental benefits, and reduce the wear and tear on the Caltrans sweeper fleet which must pick up the excess sand/salt after winter snow events.

The research included adapting existing standards and methods for testing and characterizing spreader systems, as well as development of novel methodologies and aggregate measures to analyze the test results. The effort also included developing an engineering understanding of the mechanisms of operation of the spreaders and evaluation of operational efficiency.

Major Results and Recommendations

This research project completed the goal of testing spreaders using Ice Slicer and dry sand. The test methodology was based on Section 6.4.2 Dynamic Test Method of the EU standard CEN/TS 15597-2:2012.

A detailed display of spread patterns was achieved by sampling 1x2-m sections for much of the grid.

The following key conclusions were made:

- Aggregated scoring based on all tests differentiates the systems:
    - The Epoke spreader operates more consistently than the Henderson spreader. The auger feed rate is better controlled. It also has a good F1-score across the range of spread rates. The lower delivery rate can be adjusted by altering the calibration value.
    - The Henderson FRS had the best 'In target' scores and FSH the worst.
- The FRS and FSH do not spread consistently below 300 lb/lnmi.
- The Henderson machines may require a longer operating distance before entering the grid to stabilize the auger and spinner speeds.
- Significant in-house engineering and field support is required to maintain the capabilities of these spreaders. Vendor technical support is required.

The lack of documented diagnostic information for in-house service personnel is a serious issue that all vendors need to address.

The following long-term actions are recommended for future spreader qualification testing:

- There is no significant apparent difference between the application of Ice Slicer and sand. Dry testing with sand is recommended.
- Develop the basis for a testing specification. Specification 15597 has been updated and it is a contender for standardizing this process.
- Sample sizes of 20 m or more should be considered to average out effects of turbulence and spreader function variables.
- Develop simpler procedures for validating spread patterns. The use of static spread patterns and other alternatives should be evaluated. These procedures will also be useful for calibrating spreaders.
- The calibration process for spreaders must be simple and convenient. The Muncie hydraulic system on both the Epoke and Henderson bodies can operate with an artificial speed setting while the vehicle is stationary. Stationary operation allows for convenient evaluation and calibration of spread patterns. The Epoke spread rate is calibrated by collecting and weighing deposited material while the vehicle is stationary. The Henderson spread rate calibration requires use of scales that weigh the whole truck in order to measure the amount of deposited material. The Henderson body calibration method should be modified to be similar to the Epoke. Only a large trash can is needed to collect deposited material on the Epoke, but the Henderson may require some form of customized catch basin.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology
Caltrans	California Department of Transportation
DOE	Caltrans Division of Equipment
DOM	Caltrans Division of Maintenance
DRISI	Division of Research, Innovation and System Information
I-80	Interstate 80
lnmi	lane-mile
META	Maintenance Equipment Training Academy
PPV	Positive Predicted Value

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Chapter 1: Introduction

Problem

Clearing snow and ice from California's roadways is a significant task, costing the state approximately $25 million annually of which about $20 million is spent on the Interstate 80 (I-80) corridor. Clearing and preventing ice and snow involves several steps, including de-icing and anti-icing. De-icing is a reactive snow and ice control strategy that seeks to break the bond between snow or ice and the pavement by chemical and mechanical means. Typically, chemicals are applied during or after a winter storm when snow or ice has already bonded to the pavement. Anti-icing involves the timely application of a winter maintenance chemical before the onset of a storm to weaken or prevent the bond from forming between compacted snow and the pavement surface in order to improve removal efforts. Sodium chloride (standard salt, NaCl) and magnesium chloride ($MgCl_2$) are the most commonly used products by the California Department of Transportation (Caltrans) for anti-icing. Caltrans also uses sand, cinders, and Ice Slicer[1] as part of its winter maintenance strategy. In general, such products can affect air quality, soil, roadside vegetation, and surface and groundwater. They also affect corrosion of both highway structures and vehicles. As such, Caltrans is motivated to reduce salt and sand usage.

Caltrans has several types of sand/salt spreaders in the fleet. To determine the most efficient and cost-effective long-term method, Caltrans needs quantifiable results via testing. For the 2018 testing, Caltrans requested comparison of the following spreader types:

1. One Swenson tailgate spreader
2. One Henderson Vbody FSH
3. One Henderson FRS
4. One Epoke SH 4900

as documented in the 2018 test report [1]. For the 2021 testing, Caltrans requested comparison of the following spreader types:

1. One Henderson Vbody FSH14 spreader with Direct Cast (2019 model) (http://www.hendersonproducts.com/spreaders.html)

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1 Ice Slicer (https://iceslicer.com/)

2. One [Epoke S4900 with directional casting (http://www.epokena.com/products/bulk-spreaders/s49004902-sirius-ast-combi/)](http://www.epokena.com/products/bulk-spreaders/s49004902-sirius-ast-combi/)
3. Two [Henderson FRS with Direct Cast (2018 model and 2020 model) (http://www.hendersonproducts.com/assets/hp-050_firstresponse.pdf)](http://www.hendersonproducts.com/assets/hp-050_firstresponse.pdf)

This report documents the 2021 testing and results, while the 2018 testing and results are provided in the earlier report [1].

Objectives

Caltrans continuously seeks new methods and equipment for its winter maintenance operations in order to meet its mission and goals. Winter maintenance operations represent a significant challenge to Caltrans, and by implementing improved methods and equipment, Caltrans can realize operational and safety improvements, cost savings, and reduced environmental impacts.

Increasing the efficiency of the sand/salt spreader fleet will:

a) Reduce the amount of excess sand/salt applied, addressing both environmental and cost concerns

b) Increase the efficiency of the operation, which will allow the operators to apply sand/salt longer between refills and increase road safety for the motoring public.

This research provided input and guidance for Caltrans' decision-making process regarding which spreaders to buy in the future in order to achieve its goals. The research also provided data which may allow Caltrans to revise spreader operations following procurement.

Scope

This research involved testing and evaluation of the performance of four spreader types: the Henderson FRS 2020, the Henderson FRS 2018, the Henderson FSH, and the Epoke S 4900. The goal was to assess the efficiency and effectiveness of advanced spreader systems, and provide information to support quantitative comparison of these systems in support of future Caltrans procurement. As a result of the implementation of these research results, it is expected that the amount of sand/salt applied to the roadway will decrease, which will decrease winter maintenance costs, have positive environmental benefits, and reduce the wear and tear on the Caltrans sweeper fleet which must pick up the excess sand/salt after winter snow events.

Research Methodology

The research methodology used controlled field testing to assess the sand spreading properties for the four spreaders. Subsequent analysis evaluated the effectiveness of the spreaders based on their individual test data. Testing was split into two periods, fall 2018 and summer 2021. The 2018 results were documented in a previous report [1]; these results are briefly summarized here. The focus of the current report is the summer 2021 testing and final research conclusions.

The research included adapting existing standards and methods for testing and characterizing spreader systems, as well as development of novel methodologies and aggregate measures to analyze the test results. The effort also included developing an engineering understanding of the mechanisms of operation of the spreaders and evaluation of operational efficiency. Detailed research tasks included:

- Review of existing standards and test methodologies
- Development of test methods and data acquisition approach
- Observation of new and existing spreader use and test participation
- Remediation of the final test site
- New spreaders engineering and performance evaluation
- Recommendations for future spreader procurement, use, and testing

Overview of Research Results and Benefits

The key deliverables of this project include:

- Updated test procedure: The testing procedure was modified to collect a majority of samples in 2x1-meter increments.
- Sand collection system design: A re-designed vacuum system allowed for more rapid collection of samples.
- Sand spreader testing raw data and testing video: The data, photos, videos, and other information were provided in a shared folder.

Chapter 2:
Summary of 2018 Sander Testing

The initial sander testing was completed in Fall 2018. This chapter provides a brief summary of that testing. Details of the 2018 testing are available in an interim report [1].

The spreader test group differed between 2018 and 2021 testing. In 2018, testing was performed on four systems: a tailgate spreader, a Vbody spreader, and recently designed Epoke and Henderson FRS spreaders. The 2018 testing demonstrated the potential improvement in spreader technology as demonstrated by the FRS and the Epoke designs. The following conclusions were made [1]:

- The tailgate spreader is not competitive with any of the other machines. Spread rate is neither accurate nor consistent. The spread direction is fixed for use on a two-lane road. The center of the spread pattern is not aligned with the center stripe of a two-lane road, which is the typical alignment.
- The Vbody is not competitive with the FRS and Epoke. The Vbody feed rate is neither accurate nor consistent. When spreading to the right or left, the deflector flaps cause sand to be concentrated near the vehicle center.
- The FRS and Epoke spreaders are generally more accurate and effective at spreading than the V-body in most cases. Both the FRS and Epoke performed relatively poorly in the All Lanes test.
- The FRS did not spread consistently below 200 lb/lnmi (lane-mile).
- During this testing, the operation of the FRS and Epoke spreaders was not completely understood. The calibration process was especially problematic due to limited information.
- Poor performance of any of the machines could be the result of errors in operation or calibration. Further evaluation and testing to determine the cause would require manufacturer support.
- The experience and results highlighted the need for a testing and qualification process for new commercial spreader technologies.

The following long-term actions were recommended:

- Develop a standardized material. The ratio of grain sizes affects spread patterns. Larger grains are thrown many times farther. Analysis of the samples from this series of tests could be used as a basis for developing a standardized material.
- Develop the basis for a testing specification that can be used in the purchase process and by customers to verify the capabilities of modern spreaders. European Technical Specification CEN/TS 15597-2:2012 (herein,

specification 15597) [2] is a contender for testing standards, but it requires further development. In order to meet the specification, a vendor would have to 'tune' in their machine ahead of any test. The specification does not require the detail necessary to ensure that the machine will operate in the field as specified by Caltrans.[2]

- Develop simpler procedures for validating spread patterns. The use of static spread patterns and other alternatives should be evaluated. These procedures will also be useful in equipment calibration.

[2] A 2019 version of this specification was released but has not been reviewed.

Chapter 3: Final Test Methodology

The Caltrans Division of Equipment (DOE) initiated the testing of sand spreaders to compare the spreading performance of traditional spreaders and newer designs from Henderson and Epoke. The newer designs can more accurately control spread rates. Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center and DOE personnel performed initial testing in the fall of 2018 (see Chapter 2), which was then followed by testing in the summer of 2021. The focus of this report is on the results of the 2021 testing.

Testing Procedure

The testing procedure was developed using specification 15597 as a guide [2]. The specification can be used to certify spreaders, but it is not known whether machines in Europe are actually delivered to this specification. Testing was limited to measurements of sand distribution on a grid, referred to as 'dynamic testing' in specification 15597. Figure 1 shows the test strip grid that is the basis for the Caltrans testing.

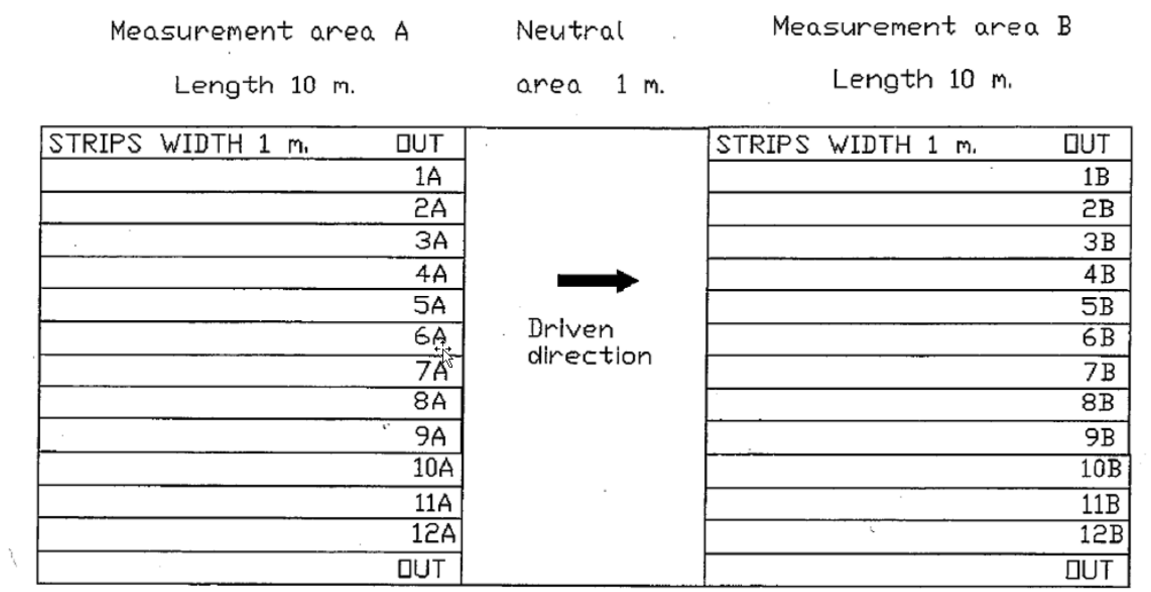


Figure 1: Layout of test strip grid (Figure 7c of CEN/TS 15597-2:2012)

In specification 15597, dynamic testing on the grid is used to verify that the distribution of the material is correct, and separate static testing verifies that the quantity and rate of material is correctly dispensed. In the Caltrans testing as performed in this research, the grid test results were used to determine that the quantity, rate, and the distribution were correct.

DOE defined the general testing requirements. All testing in 2018 and 2021 used the four lane configurations, Left Lanes, Center Lane, Right Lanes, and All Lanes, shown in Figure 2.

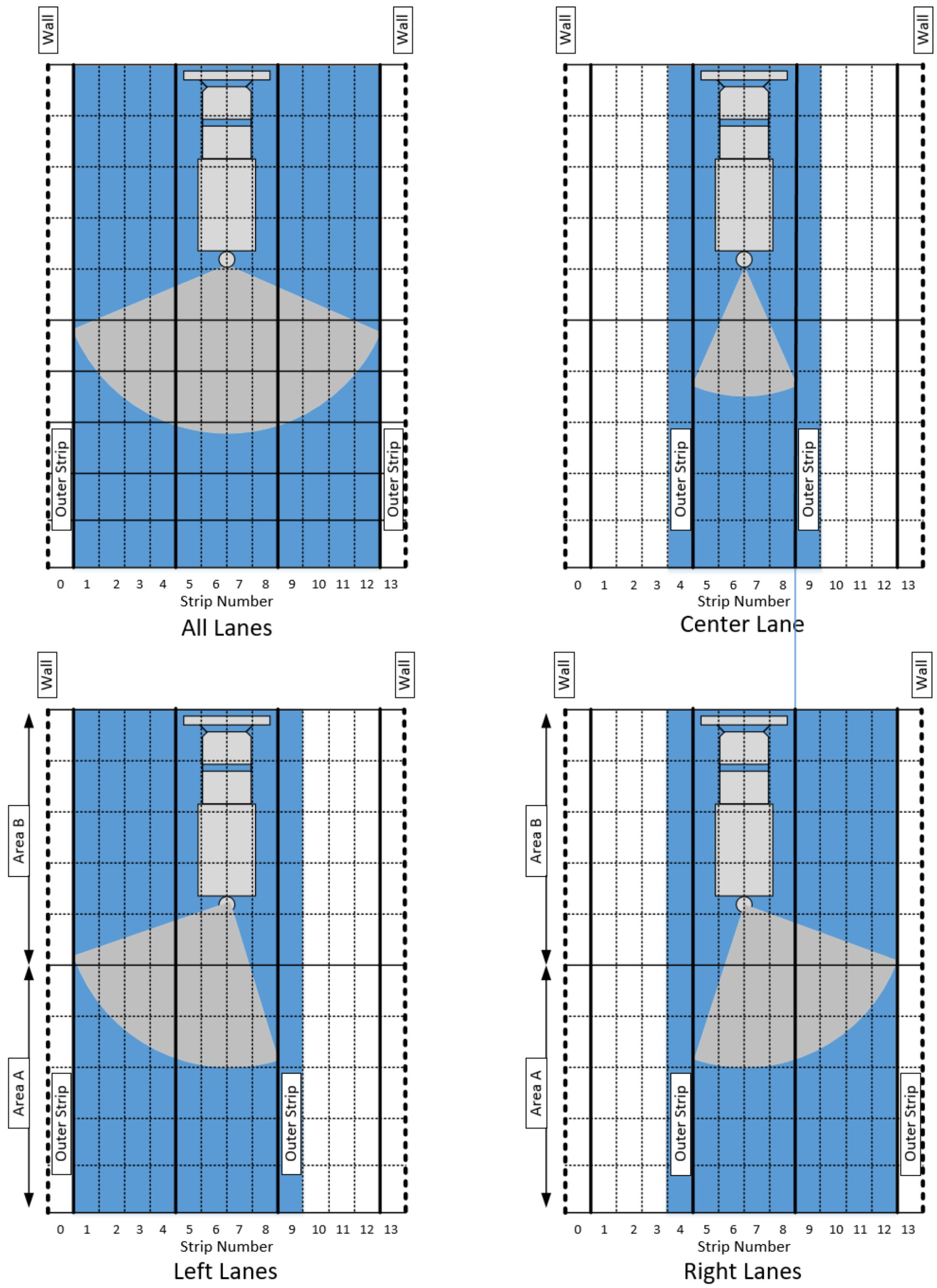


Figure 2: Spread configurations on grid used in testing

Testing in fall 2018 was performed as follows:

- Material: sand
- Spread rates:150 and 450 lb/lane mile (lb/lnmi)). Minimum application rate 200 lb/lnmi for the 2018 FRS body.
- Vehicle speeds: 18, 25, and 37 mph.
- Spreader vehicles: Tailgate, Vbody, Henderson FRS 2018, Epoke
- Four lane configurations were run for each vehicle (tailgate used only one)
- Total tests 78: 24 per spreader (6 for tailgate spreader)

Testing in summer 2021 was performed as follows:

- Material: sand and Ice-slicer
- Spread rates:
    - Sand – 300, 500, 700, 1000, 1200 lb/lnmi
    - Ice-slicer – 150, 200, 300 lb/lnmi
- Vehicle speed: 30 mph only
- Spreader vehicle: Henderson FSH, Henderson FRS 2018, Henderson FRS 2020, and Epoke. The Direct Cast option is included on all the Henderson machines.
- Total tests 128: 32 per spreader

The Epoke and Henderson FRS 2018 tested in both years were the same spreaders but mounted on a different chassis. All of these Caltrans spreaders are installed on a slip-on chassis to allow for easy removal in the off-season. Figure 3 shows the four spreaders that were tested.

Figure 3: Four spreaders tested

All the machines in the 2021 testing have closed-loop control of the hopper material feed rate and the spinner speed. They also support directional casting from the spinner.

Caltrans typically uses a spread rate of 450 lb/lnmi for sand during typical chain control conditions. The speeds selected in 2018 correspond approximately to the 30, 40, and 50 kph speeds (19 to 31 mph) used in specification 15597. During chain control conditions, traffic speeds are limited to 35 mph.

Specification 15597 calls for moving the walls so that all the material is contained within the outer strip. The walls in the both the 2018 and 2021 testing were left in place, and material was collected on the whole area. In the 2018 testing, two 10-m samples were collected for each strip. In the 2021 testing, 2-m samples were taken from the strips shown in blue in Figure 2. Table 1 describes the test spread configurations and the sampling pattern.

Table 1: Target strips and sampling pattern for each spread configuration

	Spread Configuration and Test Samples				
Spread Configuration	Spread width (# lanes)	Target strips	2-m samples in strips	10-m samples in strips	Samples per test
All Lanes	3	1-12	1-12	0, 13	124
Center Lane	1	5-8	4-9	0-3, 10-13	76
Left Lanes	2	1-8	1-9	0, 10-13	100
Right Lanes	2	5-12	4-12	0-3,13	100

Figure 4 shows the grid used in the 2021 testing. The truck was always run down the middle between the cones. The grid was marked with narrow white lines, independent from the markings for a 2-lane road seen in the image.

Figure 4: View of track and grid looking south

Test Site Enhancements

The testing site was substantially improved for the 2021 tests. The 2018 test site was no longer available and no other temporary sites were found. Testing requires continuous access during most days and sharing the location with other activities is difficult. To support the 2021 testing, Caltrans invested in the installation of a 48-ft-wide section of pavement at the Maintenance Equipment Training Academy (META) in Sacramento. The section of pavement shown in Figure 5 connected two paved areas and created a length of pavement allowing the spreaders to reach steady speed before reaching the test pad and then slow down safely at the end of the test. Because the normal META training schedule was reduced due to the COVID-19 pandemic, the site pad was continuously available to the researchers from June 2021 through September 2021. Spreader test runs were staged in coordination with other users of the facility as needed.

Figure 5: Test grid location at META site

Personnel

The following personnel were directly involved in facilitating and performing the tests:

- Jeff Pike, META, Division of Maintenance (DOM), Caltrans
- Geno Cervantes, Statewide Equipment Manager, DOM, Caltrans
- James Henry, Equipment Engineer, DOE, Caltrans
- Larry Baumeister, Project Manager, Division of Research, Innovation and System Information (DRISI), Caltrans
- Victor Reveles, Research Technician, AHMCT, UC Davis
- Wil White, Senior Research and Development Engineer, AHMCT, UC Davis
- Sarah Portnell, student, field testing and analysis, UC Davis

- Alejandro Estrada Berlanga, student, field testing and analysis, UC Davis

Updated Vacuum System and Automation for Sand Collection

The vacuum systems were redesigned to reduce the time required for testing. Figure 6 and Table 2 describe the systems. Two major redesigns changes were implemented:

1. *Increase the nozzle width to allow material collection in a single pass.* The pick-up nozzle was increased from 0.5 m to 1.0 m (39.4 in). In previous testing with the small nozzle, two full passes were made to collect a sample in the 1x10-m area. This resulted in walking the vacuum machine 40 meters per sample, which required significantly more time. The 2021collection procedure was designed to collect material and resulting data in a single pass.
2. *Collect and weigh the material on board the vacuum system.* This design attempted to avoid the individual steps of collecting, bagging, and weighing for each sample. The design intent was to allow the collected sand to be contained and weighed continuously. Once two meters worth of sand was collected, the weight was recorded and subtracted from the reading at the beginning of that 2-m strip. Individual samples were not bagged separately once weighed. The final vacuum design was a hybrid in which one operator collected the material, removed it from the machine, and handed it off to the second operator who weighed the sample. An Ohaus SPX 2200 scale connected to a laptop was used to enter data in a spreadsheet. Figure 7 shows the 2018 and 2021 operations.

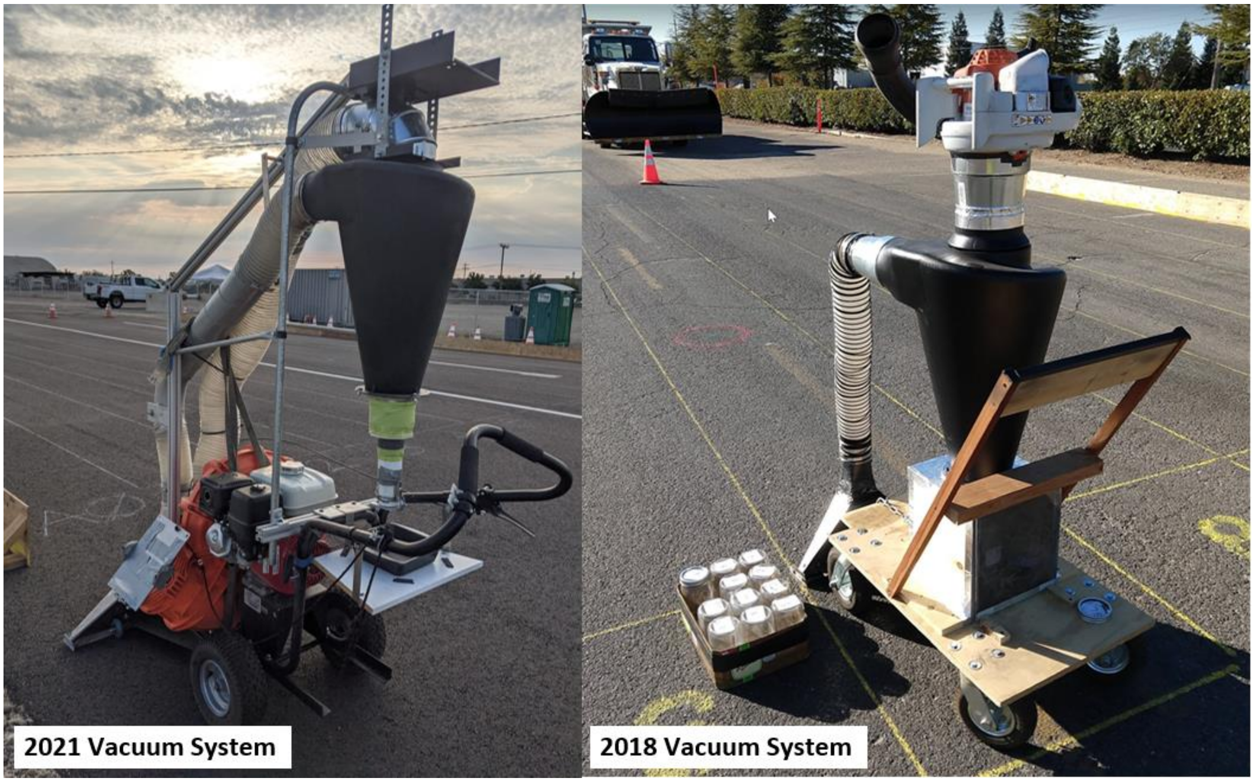


Figure 6: Vacuum systems used to collect sand sample

Table 2: Vacuum system specifications

Vacuum Components	**2021 Testing**	**2018 Testing**
Fan	Billy Goat F10 with 9 hp Honda engine	Stihl model SH 86 Mounted on top of the cyclone
Cyclone	Oneida Super Dust Deputy 5	Oneida Super Dust Deputy 5
Weight	233 lb	94 lb
Design flow rate	1500 cfm	400 cfm

Figure 7: Vacuum and weighing station

Description of Typical Test Run Steps

The general sequence and activities for testing are described below. Minimum times for the activities are also indicated.

<u>Site Setup</u>: Daily test setup (30 min) and take down (15 min) was required. All test supplies and equipment were stored in a rented construction storage container. Chairs, tables, and a tarp were set up for each test. Time was saved by locating the equipment storage container immediately next to the test grid. Water and ice were supplied from the nearest building, one-eighth mile from the test site. A portable bathroom and hand washing station was located at the test site. Walls on the grid were left in place between testing days and did not need to be removed between tests.

<u>Step 1 Testing preparation</u> (15 min): At the beginning of each run, the truck was started and the hydraulics were brought to operating temperature. The controls were powered up and the test configuration settings were entered. The spreader camera was set up. The grid was cleaned off with the blowers and equipment was fueled.

<u>Step 2 Spreader pass</u>: The truck was driven to the far end of the test strip. Spreader system functions and settings were verified. Truck warning lights were turned on to communicate that the truck was ready. Persons at the grid verified that the grid was ready and the area was clear. The person with the camera signaled to start the run. The truck operator accelerated to speed and started the spreader at about 200 ft (60 m) before the grid. The spreader was turned off 100 ft (30 m) after the grid. Video was reviewed and the track inspected to

verify that the spreader operated correctly. Photos were made from the top of the truck and other locations.

Step 3 Collection (45-75 min): Two people collected and weighed the material on the grid while one or two others removed material from outside of the grid and prepared for the next run.

Step 4 Post-Collection (15 min): The vacuum system and blowers were used to collect all material that was not collected in Step 3. Post-collection material weight was recorded.

Additional on- and off-site activities included:

- Maintenance of data and batteries. Repair and modification of vacuum and other systems.
- Sand and Ice Slicer were loaded and unloaded into the spreaders once for each spreader. Material was collected and recycled when possible.
- Modified testing was performed to support spreader calibration efforts.
- Repeated tests were required if the spreader had technical difficulties requiring repairs and/or recalibration. Runs in which no material was deposited required sweeping and clean up as material was shaken off the chassis and spreader system.

Testing times ranged from 1 to 1.5 hours depending on lane configuration. Six to seven tests were completed in a typical day.

Test System and Facility Design Issues

The following points are noted as recommendations for future testing.

Facility: The access to the pavement at the META facility was a great improvement over the 2018 testing location. Given the increased weight and size of the vacuum system, storage space for equipment at the test site is required. Portable toilets, a hand washing station, and shade structures are required. Electrical power at the site may potentially be needed.

Vacuum system: Future testing at this scale will require a redesign of the vacuum system. Minimizing the operator workload is important for consistent and accurate measurements. Forward travel speed should be controlled automatically to maintain a constant speed. A slow travel speed is needed to collect a higher percentage of material in a single pass. Semi-automation with mechanical indexing at every 2-m stop is important.

The vacuum will require further refinements. The 1-m-wide nozzle permitted a single pass, but a significant amount of sand remained on the test surface. Increasing the turbulence at the interface will be necessary to increase vacuum speed and efficiency. Incorporation of an air knife or other mechanism to dislodge the sand and salt particles will be required.

The use of scales on the machine did not work well in this research as the reading did not stabilize. Further development of methods to isolate the scale from vibration and wind forces is necessary. It may be optimal to have two persons working together to vacuum and weigh samples. A one-person operation will require significant redesign to the cyclone system and air flow control. Electrification of the vacuum system would also be advantageous.

Human factors challenges remain. Persons in this testing process are exposed to high levels of noise, vibration, heat, sun, dust, and physical exertion. Facility and vacuum system designs need to be improved to reduce exposure.

<u>Environment</u> – In California, the testing of the equipment is likely to be accomplished in the summer. Excessive heat is a challenge. Exposure to wind was problematic and could potentially be resolved with temporary walls or a fabricated fence.

Chapter 4: Test Results

The test results are provided in the following three formats:

A. Quad Plots: The researchers used MathWorks Matlab to generate a set of four plots for each test. This set is referred to herein as a Quad Plot. These provide four different graphical representations of the test data illustrating the material spread results. Appendix A contains the Quad Plots for all 2021 tests.

B. Tables and Graphs: The data was analyzed using patterns similar to the patterns used in the 2018 testing. Appendix B contains selected plots and tables.

C. F1 Scoring: A machine learning procedure was used to develop a scoring system to provide a single quantitative result (F1-score) that captures the results. Appendix C contains selected plots of mean F1-scores at the different spread rates.

Description and analysis are included in the following sections.

In specification 15597, the spread rates are defined in units of gm/m^2. The conversion formula 1 gm/m^2 = 12.98 lb/lnmi is used in this report. This conversion assumes that a lane is the typical 12 ft wide standard in the United States. Since nominal lane widths vary internationally, the spreader control systems require the setting of a lane width parameter to correctly dispense material. The parameter was set at 12 ft on each spreader.

In Table 1 and Figure 2, the referenced target lanes are four 1-m strips 13.12 ft (4 m) wide. The target lanes are therefore wider than standard lanes. All calculations assume a multiple of the 12-ft-wide lane width of material was spread. Reported results of the percentage of material within target lanes will therefore be higher than in actual real world application.

After the samples were collected using a single pass of the vacuum, a quick second pass (post-collection) was made to gather material that was missed. Based on the results, a mean value of 7.3% of sand and 7.7% of Ice Slicer was missed in the first pass collection of sand. The mean values of this post-collection material was used in reported results to account for the missed material. Table 3 shows the adjustments to the nominal required when evaluating the reported collected sample weights.

Table 3: Spread rates - nominal and adjusted

Spread Rate		Weight in 2-m² Sample Area (gm)		
lb/lnmi	gm/m²	Nominal	Adjusted Sand	Adjusted Ice Slicer
100	7.7	15	-	14
200	15.4	31	-	28
300	23.1	46	43	42
500	38.5	77	71	-
700	53.9	108	100	-
1000	77.0	154	143	-
1200	92.4	185	171	-

Compilation and Analysis

Quad Plots

Heat maps with different color schemes and scaling were produced in Microsoft Excel and then Matlab. The Matlab software was used to generate the four different Quad Plots, with a sample provided in Figure 8. The Quad Plots document the actual test sample weights and provide a visual, detailed representation of the spread pattern. The following points are noted:

- The measured weight in grams is shown for each of the 2-m strips. Where the samples were collected in 10-m strips, the value shown for each 2-m strip is simply one-fifth of the 10-m strip value.
- The Matlab program assigns 1 (one) to the first column or row of a matrix. The plots strips are therefore numbered 1-14 instead of 0-13.
- The plots are organized as four Quad Plots per page for easier comparison of the four trucks.
- The scaling increment for each Quad Plot is done automatically in Matlab and is based on the maximum and minimum measured sample weight of that test. The colors patterns and assignment with sample weights will therefore vary for each test. Attempts to standardize the color patterns for a particular test resulted in greatly reduced visualization of material distribution.
- The Quad Plot title format is the test number in the following format: Spreader-Material-Spread rate (lb/lnmi)-Lane configuration (C-center, A-All, L-left, R-right – Date of test (month-date). In the example shown in Figure 8, the title identifies the test of the Epoke spreader, spreading sand material at a rate of 1200 lb/lnmi to the right lanes on July 21.

Many photos of the spread patterns were taken looking south at the resulting spreader test run. Figure 9 shows a rectified and rotated image of the photo taken of the Epoke test in the Quad Plot in Figure 8. Patterns of the plotted results can be seen on the ground at this heavy spread rate.

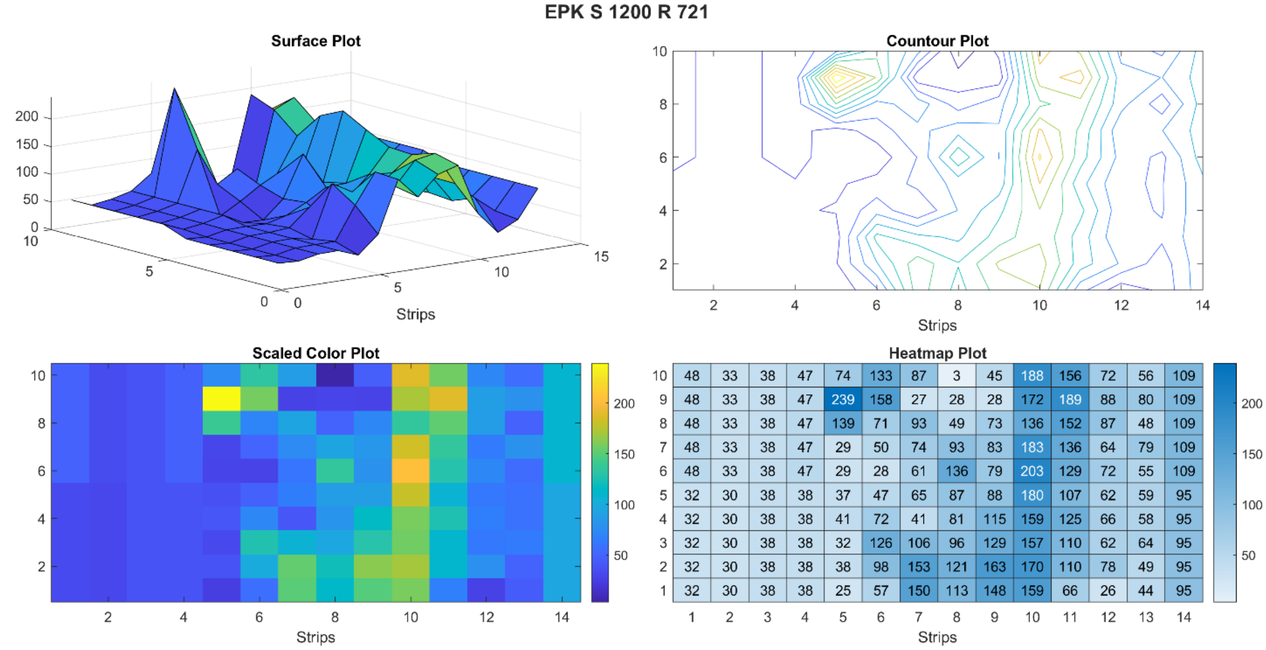


Figure 8: Example of a Quad Plot EPK S 1200 R 721

Figure 9: Rectified/rotated image (left) of photo for EPK S 1200 R 721 (right)

Tables and Graphs

The objective of the testing was to determine and compare the effectiveness of spreaders in distributing material. Table 4 shows the two most basic characteristics that can be used to compare the machines:

A. Sum of Sand/Ice Slicer Weight in Area - The value is the sum of the weight in all strips 0 to 13. This sum measures the auger feed rate out of the hopper and is the simplest comparison between machines. Some losses resulted during the vacuuming process and due to the loss of sand over the walls. The value for the sum of weight of all samples in each test is increased to account for the 7.3% sand or 7.5% Ice Slicer missed. The sum of weight is represented as the percentage of the nominal sum of weight, and the mean of each test is converted to a percentage of the nominal value. The adjusted nominal is used for each test.

B. Sum of Sand/Ice Slicer Weight in Target Strips Fraction of Material in Target - This second value (column 2a and 2b) defines the fraction of sand that landed in the 'targeted' lanes. The spinner speed and height directly affect this value. Ideally all the sand is deposited in equal amounts in each of the target strips that make up the lanes being targeted. This value does not account for the distribution within each target lane. It is used as a gross comparison and is included in Table 4.

Table 4: Basic comparison of spreaders using the mean of all tests

A. Ratio of the sum of sand weight in area divided by the nominal sum				
	MEAN	**STDEV.P**	**MIN**	**MAX**
FSH	67%	24%	25%	95%
Epoke	78%	9%	51%	96%
2018 FRS	101%	20%	58%	140%
2020 FRS	104%	29%	48%	165%
B. Fraction of sand in target				
	MEAN	**STDEV.P**	**MIN**	**MAX**
FSH	66%	14%	41%	82%
Epoke	71%	16%	39%	93%
2018 FRS	77%	18%	39%	97%
2020 FRS	81%	14%	53%	97%

A. Ratio of the sum of Ice Slicer weight in area divided by the nominal sum				
	MEAN	**STDEV.P**	**MIN**	**MAX**
FSH	65%	24%	18%	97%
Epoke	98%	18%	71%	136%
2018 FRS	66%	21%	25%	96%
2020 FRS	46%	27%	15%	103%
B. Fraction of Ice Slicer in target				
	MEAN	**STDEV.P**	**MIN**	**MAX**
FSH	63%	19%	25%	90%
Epoke	73%	12%	57%	92%
2018 FRS	71%	19%	42%	96%
2020 FRS	70%	19%	37%	94%

Sand Distribution Plots

The example sand distribution plots in Figure 10 were generated for each of the tests.

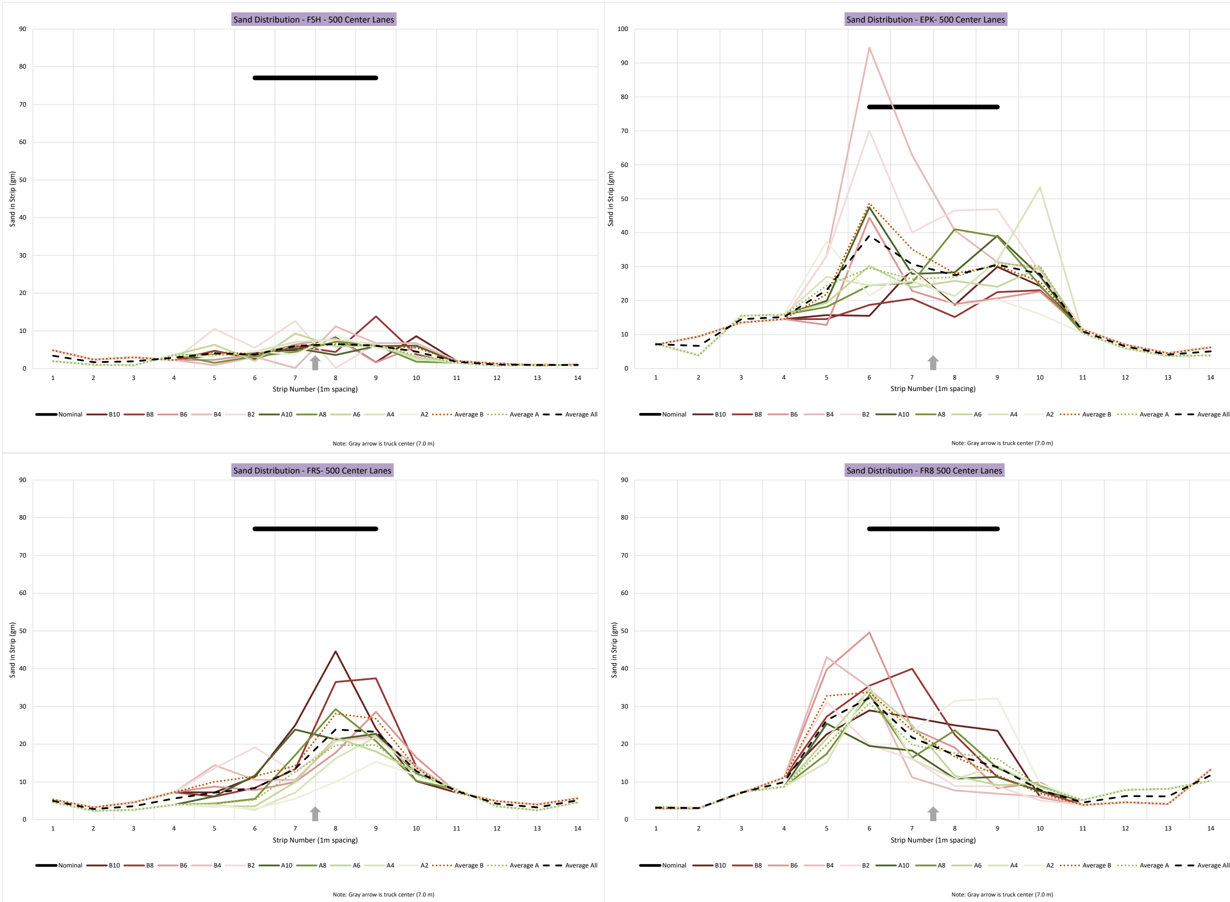


Figure 10: Example sand distribution results from four CENTER Lanes tests

These results were combined in mean material distribution plots like those in Figure 11 that average all the tests for each material and lane configuration.

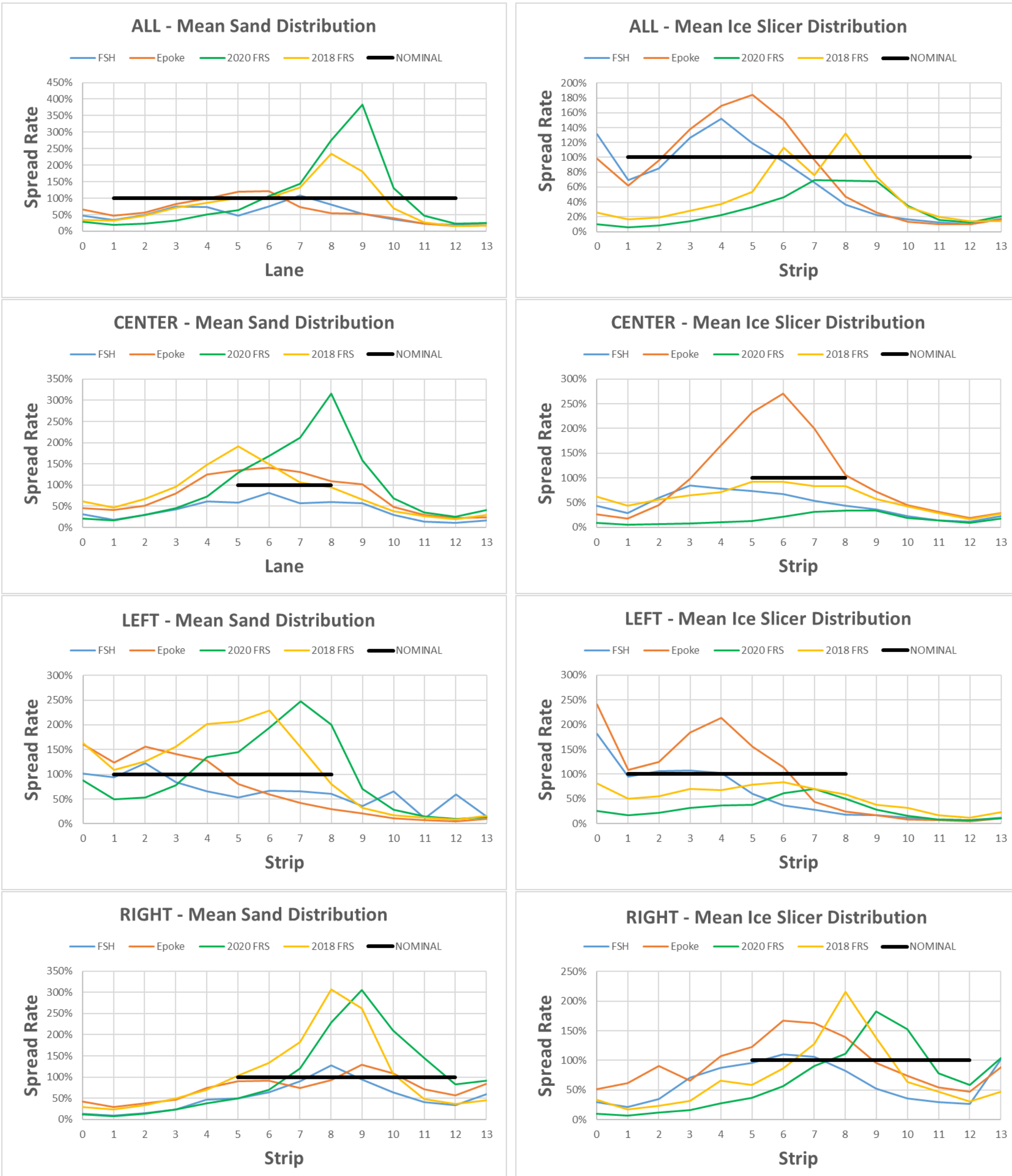


Figure 11: Plots averaging results from all tests

The testing with Ice Slicer was the least useful. In several of the tests, the Henderson machines placed very little material on the track. For future testing, sand is recommended.

F1-Score

A machine learning concept, the F1 score, was used to quantitatively compare the machines. An ideal model considers not just the amount of material that is dropped on the testing grid but also its location. To distinguish between an acceptable and non-acceptable collection, different thresholds needed to be met depending on location. For tests involving directed spreads (Right, Left, Center), there were target strips and non-target strips (gutters) where the spreader was expected to concentrate the spread of material or avoid it. The F1 scoring ideally provides a single value that assesses the spreader performance.

A binary classification was used. Each 2-m sample of each strip was considered True (1) if it passed its threshold and False (0) if it did not. To determine whether each 2-m sample passed or failed, a comparison between actual collections was made against the predicted parameters (spread rate). The first attempt simply assigned minimum values for samples in the target strips and maximum values for samples outside of it. Figure 12 shows an example of a heat map and an associated binary classification for the FRS-S-1200-C-811 test. As previously noted, the strip numbering is changed to work in the Matlab routines.

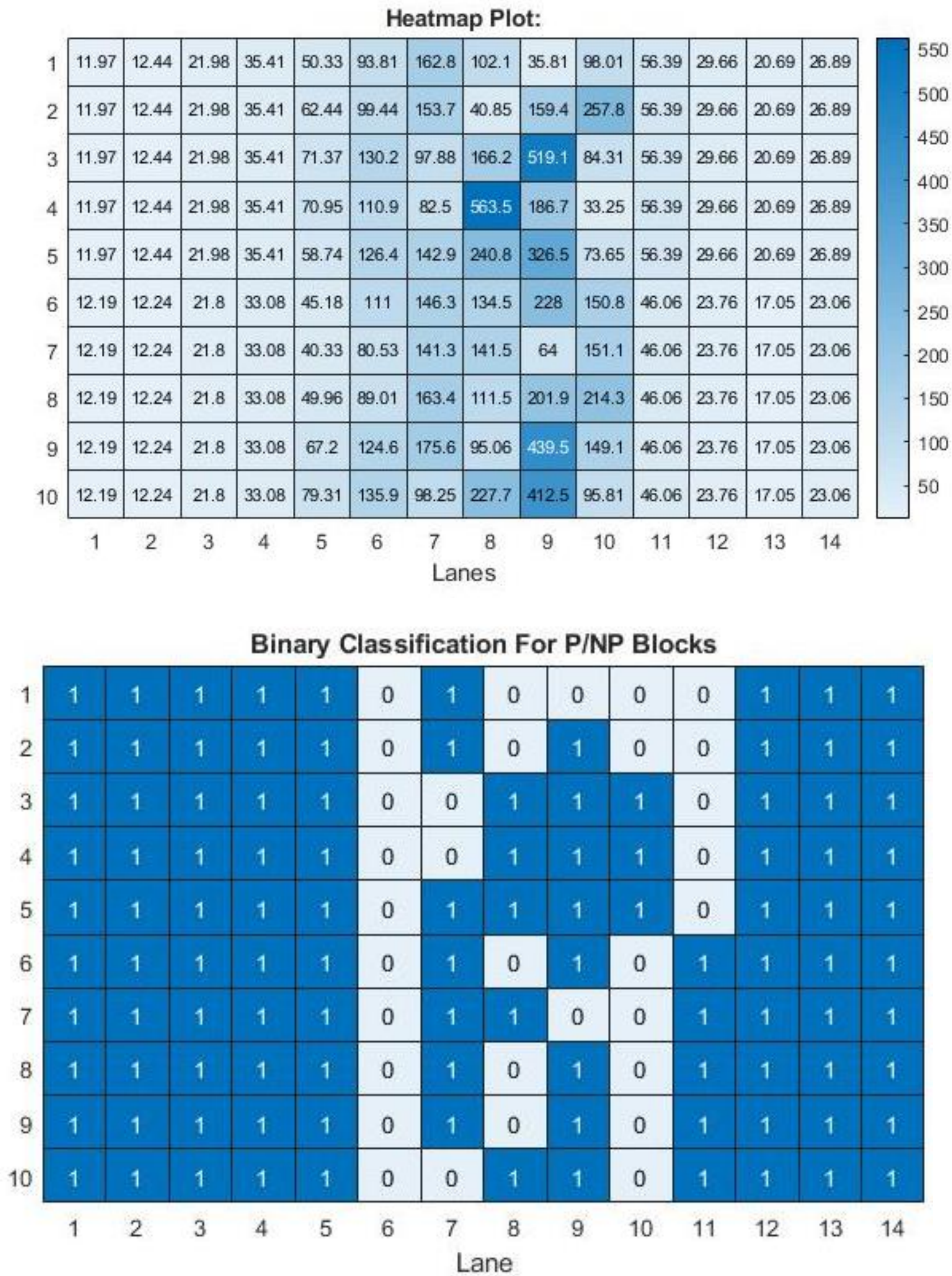


Figure 12: Example of heat map and resulting binary classification

In our application of machine learning, the prediction is the desired nominal material distribution. The machine learning terminology and calculations are described next.

Accuracy is one metric that could be used when evaluating classification models. Accuracy is the fraction of correct predictions over the total predictions in our model. While this was an acceptable initial approach to quantify the success of each body/weight/spread, accuracy was not measuring what proportion of positive identifications our model actually got correct (precision) or what proportion of actual positives was correctly identified (recall).

Commonly used in machine learning when working with binary classification datasets, precision and recall are both calculated for the positive class. Precision, also known as positive predicted value (PPV), is used as a performance metric when the goal is to limit the number of false positives, while recall is used to identify all positive samples and avoid false negatives [3].

The formulas to calculate precision and recall are:

$$Precision = \frac{TP}{TP + FP} \qquad\qquad Recall = \frac{TP}{TP + FN}$$

where

TP = number of true positives for class X
TN = number of true negatives for class X
FP = number of false positives for class X
FN = number of false negatives for class X

Precision and recall were useful metrics in the analysis of the testing because they ensured that the model was not biased to produce false positives (enables high precision) and avoid false negatives (is sensitive). Precision and recall are useful measures; however, both must be considered to provide comparable results.

The *F1-score, f-score,* or *f-measure* combines precision and recall of a classifier by taking their harmonic mean into a single metric.

$$F1 = 2 * \frac{Precision * Recall}{Precision + Recall}$$

By using the F1-score as a balance between precision and recall, each test receives a score between 0 and 1. A score of 1 means that the trial was 100% correctly predicted by our model, or in this case, each 2-m strip had the correct amount of material.

In the initial scoring attempts, the full grid pattern was used in the score. The example in Figure 12 shows the large number of True (1) values beyond the target strips. The F1 scoring method reduces the effect of the large number of samples outside the target on the overall score.

The final scoring was modified to further reduce the effect of the number of samples outside the target strips. A maximum and minimum value were assigned to each sample as shown in Table 5. In each row, all the material outside of the target row was summed and assigned to the associated single sample next to the target, which was equivalent to moving the walls inward to the outer edge of the gutter strip.

Table 5: Parameters assignment used in F1 scoring (values as %)

CENTER	0	1	2	3	4	5	6	7	8	9	10	11	12	13
MAX					**80**	100	150	150	100	**80**				
MIN					**0**	**50**	75	75	**50**	**0**				

RIGHT	0	1	2	3	4	5	6	7	8	9	10	11	12	13
MAX					**80**	100	150	150	150	150	150	150	100	**80**
MIN					**0**	**50**	75	75	75	75	75	75	**50**	**0**

LEFT	0	1	2	3	4	5	6	7	8	9	10	11	12	13
MAX	**80**	100	150	150	150	150	150	150	100	**80**				
MIN	**0**	**50**	75	75	75	75	75	75	**50**	**0**				

ALL	0	1	2	3	4	5	6	7	8	9	10	11	12	13
MAX	**80**	100	150	150	150	150	150	150	150	150	150	150	100	**80**
MIN	**0**	**50**	75	75	75	75	75	75	75	75	75	75	**50**	**0**

Target strip samples were expected to be between 75% and 150% of the nominal spread rate. The strip bordering the target strips (gutter) was expected to be less than 80% of the nominal spread rate.

The classification model values were as follows:

TP: block target values that were from 75% to 150% nominal spread rate.
TN: block target values that were less than 75% or more than 150% of the nominal spread.
FP: block gutter values higher than 80% nominal.
FN: block gutter values 80% or less than the nominal.

F1-score results for all tests were computed and graphed using Matlab and Excel. A minimum value F1-score of 0.02 was assigned. Plots of the average F1-score for each spread rate are included in Appendix C.

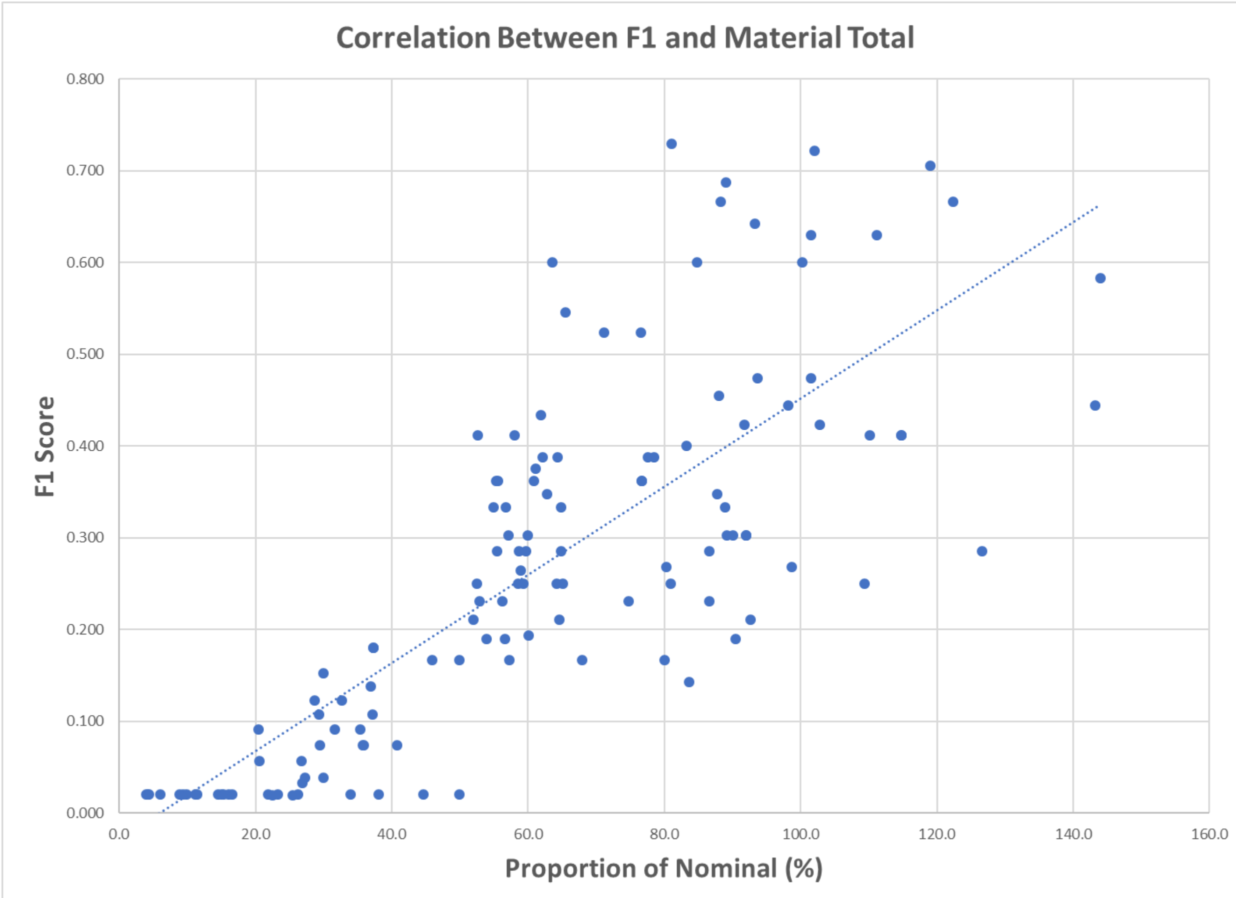


Figure 13: All F1-scores plotted against total material in the grid

In Figure 13, the F1 scores for all bodies and weights are plotted against the total material dispensed expressed as a percentage of the nominal. It shows a linear trend as expected. The points above the dotted line (linear fit) indicate that the material was better placed.

The plot in Figure 14 summarizes the mean F1-scores for all the spreaders. The results confirm that the FSH and FSR spreaders do not operate correctly at spread rates below 300 lb/lnmi.

Although the results of the F1 scoring are reasonable, it is not likely to be useful for evaluation of a spreader because it requires a large number of tests and samples to be used successfully. In addition, the factors leading to a F1-score cannot be understood without returning to the underlying data.

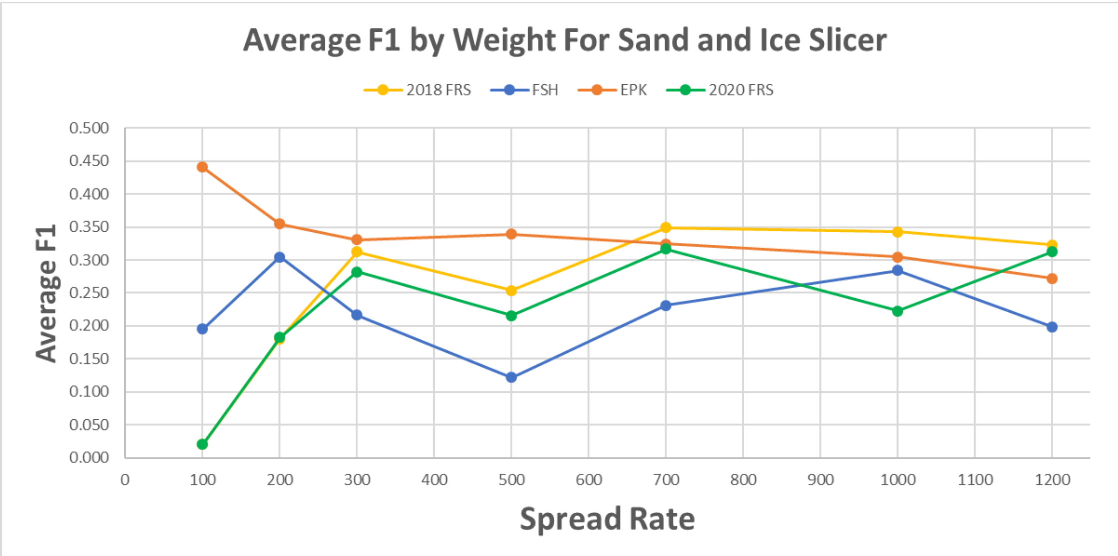


Figure 14: Plots summarizing the results across all the tests

Questions not answered

The wide variations observed in Quad Plots, F1-scores, and the sand distribution plots suggest that the spreaders' function is inconsistent at this scale of testing. Much longer lengths of grids or repeated runs over the existing grid will be needed to smooth out the results. Monitoring auger speeds and spinner speeds is required to better understand factors that might be causing the variations. Manufacturer technical information and support will be required. Operating the spreader on a chassis dynamo is likely necessary to efficiently perform the testing needed to fully understand the spreader operation.

Additional testing may be needed to answer the following questions:

- What is the spreader performance at different speeds?
- How does the spreader perform as its load is emptied?
- How does the spreader perform at freezing temperatures? Spreader operation and material properties will be affected by sub-freezing temperatures.
- What is the effect of increasing the distance between spreader start and the point at which it enters the grid? Based on observations, a very long advanced spreading run may be required to allow the spreader system to stabilize before entering the grid.
- What is the ideal test material? The material distribution is dependent on the size of the particles. The large particles are thrown farther. The Ice Slicer particles break down and are not an ideal material for general testing.

Chapter 5: Conclusions and Future Research

This research project completed the goal of testing spreaders using Ice Slicer and dry sand at application rates ranging from 100 to 1200 lb/lnmi for four lane configurations. The test methodology was based on Section 6.4.2 Dynamic Test Method of the EU standard CEN/TS 15597-2:2012.

A detailed display of material spread patterns was achieved by sampling at 1x2-m sections in much of the grid for 2021 testing. These results clearly identify the limitations of this type of testing to qualify a spreader design.

The testing provided a detailed understanding of the spreading capabilities and limitations of the modern spreader technology as demonstrated by the Henderson FSH, Henderson FRS and the Epoke designs. The following conclusions are made:

- Sampling at 2-m increments clearly shows a highly random distribution of material.
- Based on observations and test results, it is likely that air turbulence at the rear of the spreader is a significant factor in the resulting irregular material spread patterns.
- Sampling at the 2-m increments over much longer distances will be required to fully capture any patterns that might be used to understand the characteristics of the spreader operations, such as auger or spinner speed variations, which is likely to be impractical.
- Aggregated scoring based on all tests provides differentiation between the systems.
    - The Epoke spreader operates more consistently than the Henderson spreaders. This conclusion is based on the Epoke's low standard deviation value in Table 4A, which indicates that the auger feed rate is better controlled. It also has a good F1-score across the range of spread rates. The lower delivery rate can be adjusted by adjusting the calibration value.
    - The Henderson FRS had the best 'In target' scores, and the FSH had the worst.
- The FRS and FSH do not spread consistently below 300 lb/lnmi, which is a known characteristic confirmed by the vendor.
- Based on observations, it appears that the Henderson machines may require a longer operating distance before entering the grid. This change

in distance would allow the control system to stabilize the auger and spinner speeds.

- Significant in-house engineering and field support is required to maintain the capabilities of these spreaders. Vendor technical support is required. The lack of documented diagnostic information for in-house service personnel is a serious issue that all vendors need to address.

The following long-term actions are recommended for future spreader qualification testing:

- There is no significant apparent difference between the application of Ice Slicer and sand. Ice Slicer grains break apart easily, which changes the material properties. Testing with dry sand is recommended.
- Develop the basis for a testing specification that can be used in the purchase process and by customers to verify the capabilities of modern spreaders. Specification 15597 has been updated and is a contender for standardizing this process.
- Based on the results, sample sizes of 20 m or more should be considered to average out the effects of turbulence and spreader function variables.
- Develop simpler procedures for validating the spread patterns. The use of static spread patterns produced by keeping the spreaders stationary should be evaluated, which will be useful in the field calibration of spreaders.
- The calibration process for spreaders must be simple and convenient. The Muncie hydraulic system on both the Epoke and Henderson bodies can operate with an artificial speed setting while the vehicle is stationary. The stationary operation allows for convenient evaluation and calibration of the spread patterns. The Epoke spread rate is calibrated by collecting and weighing the deposited material while the vehicle is stationary. The Henderson spread rate calibration requires the use of scales that weigh the whole truck in order to measure the amount of deposited material. The Henderson body calibration method should be modified to be similar to the Epoke. Only a large trash can is needed to collect deposited material on the Epoke, but the Henderson may require some form of customized catch basin.

References

[1] W. A. White, "Sand spreader testing Fall 2018" (http://ahmct.ucdavis.edu/pdf/UCD-ARR-19-04-12-01.pdf). AHMCT Research Center, UC Davis, Test Report, Apr. 2019.

[2] Technical Specification CEN/TS 15597-2:2012: E, January 2012, Winter maintenance equipment – Spreading machines (gritting machines) – Part 2: Requirements for distribution and its test (https://www.document-center.com/standards/show/DD-CEN-15597-2), CEN European Committee for Standardization (this standard has been superseded)

[3] Andreas Christoph Müller and Sarah Guido. "Evaluation Metrics and Scoring." Introduction to Machine Learning with Python: A Guide for Data Scientists (https://www.oreilly.com/library/view/introduction-to-machine/9781449369880/), O'Reilly and Associates Inc., Beijing, 2016.

Appendix A: Quad Plots for All Tests

Quad Plots document the actual test sample weights and provides a visual detailed representation of the spread pattern:

- The measured weight in grams is shown for each of the 2-m strips. Where the samples were collected in 10-m strips, the value shown for each 2-m strip is simply 1/5th of the 10-m strip value.
- The Matlab program assigns 1 (one) to the first column or row of a matrix. The plots strips are therefore numbered 1-14 instead of 0-13.
- The plots are organized as four Quad Plots per page to compare the four trucks in each test configuration.
- The scaling increment for each Quad Plot is done automatically in Matlab and is based on the maximum and minimum measured sample weight of that test.
- The Quad Plot title format is the test number in the following format: Spreader-Material-Spread rate (lb/lnmi)-Lane configuration (C-center, A-All, L-left, R-right – Date of test (month-date)
- The Quad Plot titles refer to systems as follows:
    - o FSH: Henderson Vbody FSH14 spreader with Direct Cast (2019 model)
    - o EPK: Epoke S4900 with directional casting
    - o FRS: Henderson FRS with Direct Cast (2020 model)
    - o FR8: Henderson FRS with Direct Cast (2018 model)

Table A.1: Tabulation of nominal and adjusted spread rates

Spread Rate		Weight in 2-m^2 Sample Area (gm)		
lb/lnmi	**gm/m^2**	**Nominal**	**Adjusted Sand**	**Adjusted Ice Slicer**
100	7.7	15	-	14
200	15.4	31	-	28
300	23.1	46	43	42
500	38.5	77	71	-
700	53.9	108	100	-
1000	77.0	154	143	-
1200	92.4	185	171	-

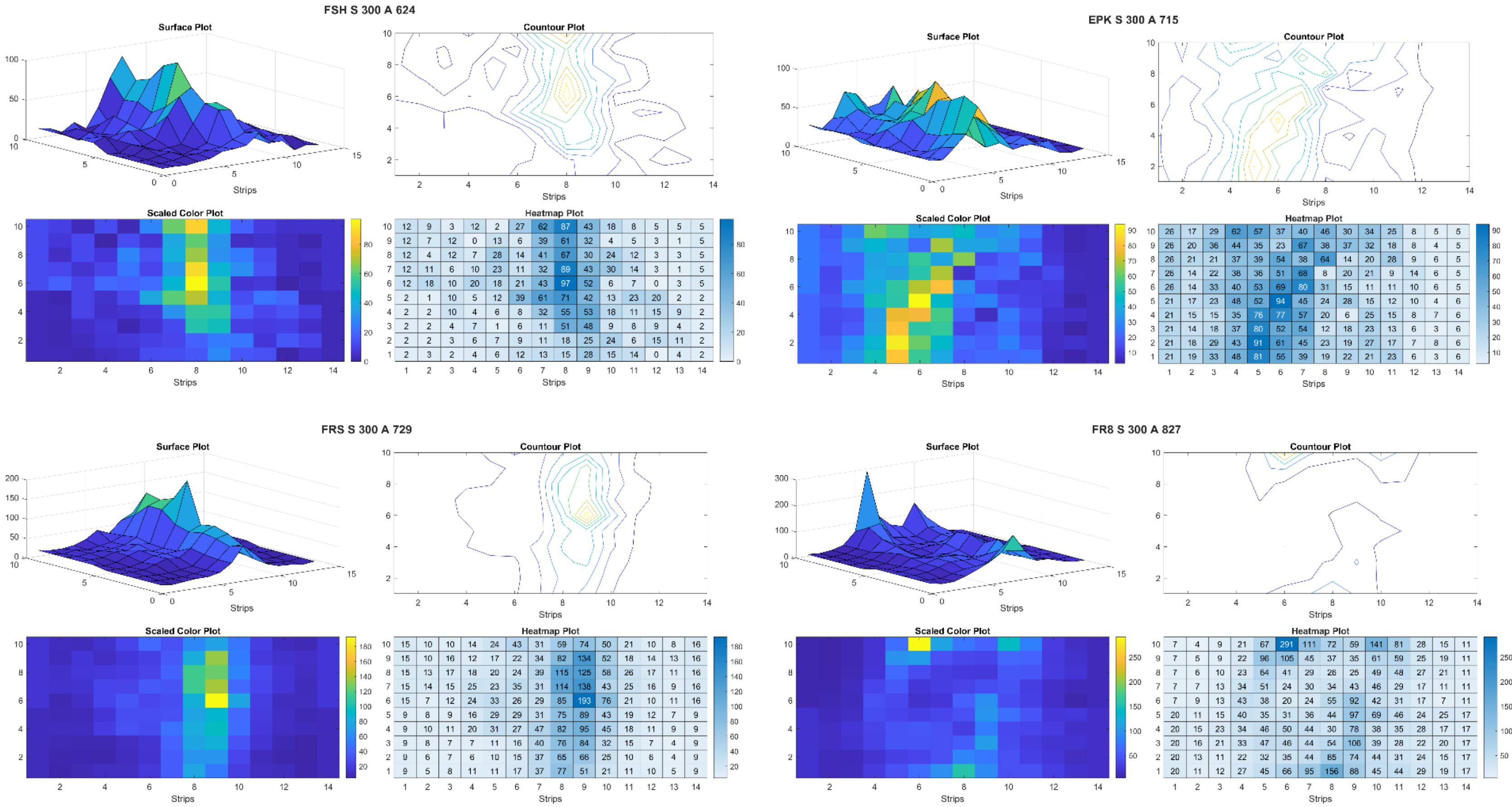


Figure A.1: Quad Plot Set 1 – Sand 300 lb/lnmi ALL, target strip 2-13, adjusted nominal 43 gm per 2 m²

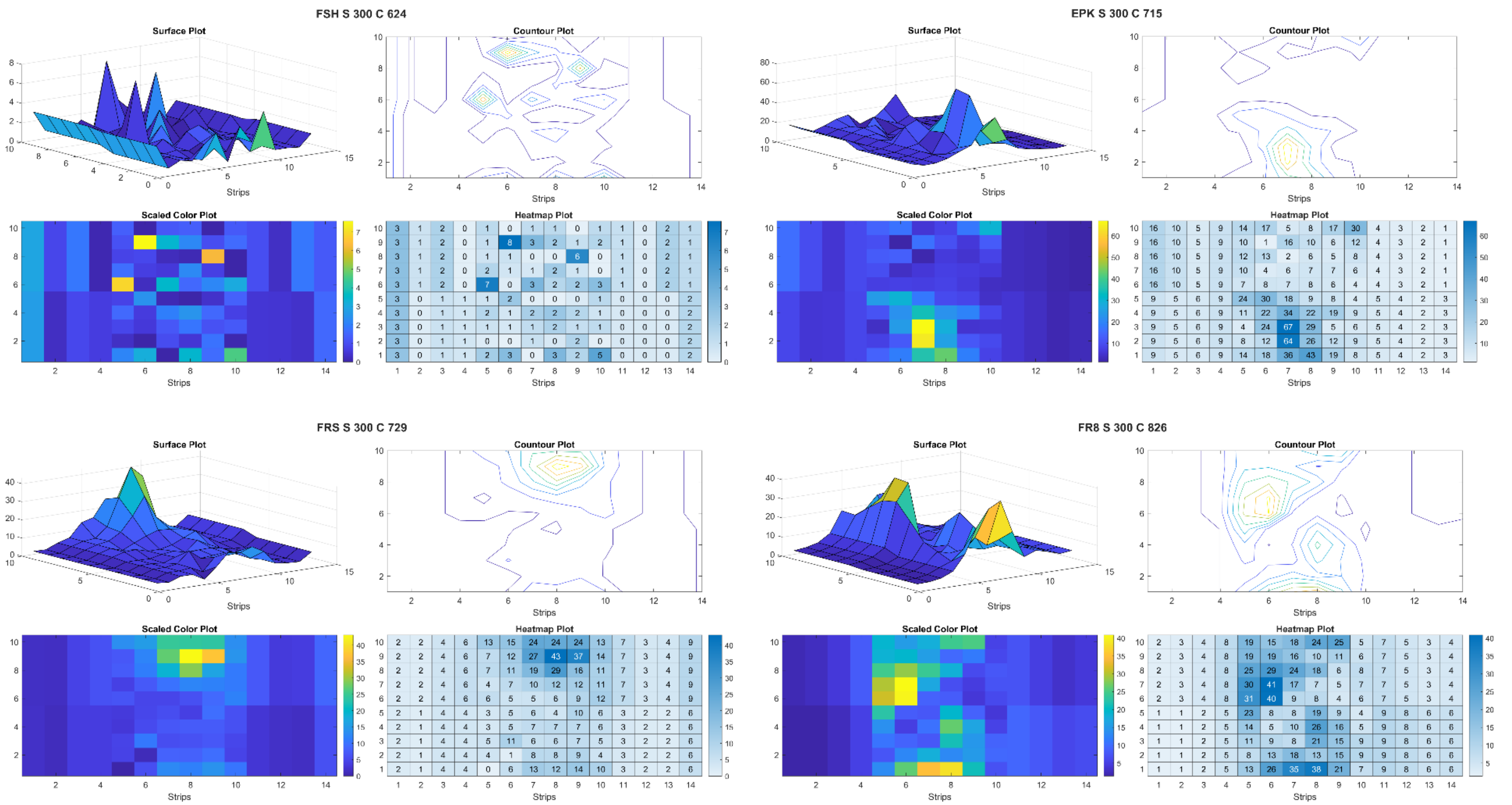


Figure A.2: Quad Plot Set 2 – Sand 300 lb/lnmi CENTER, target strip 6-9, adjusted nominal 43 gm per 2 m²

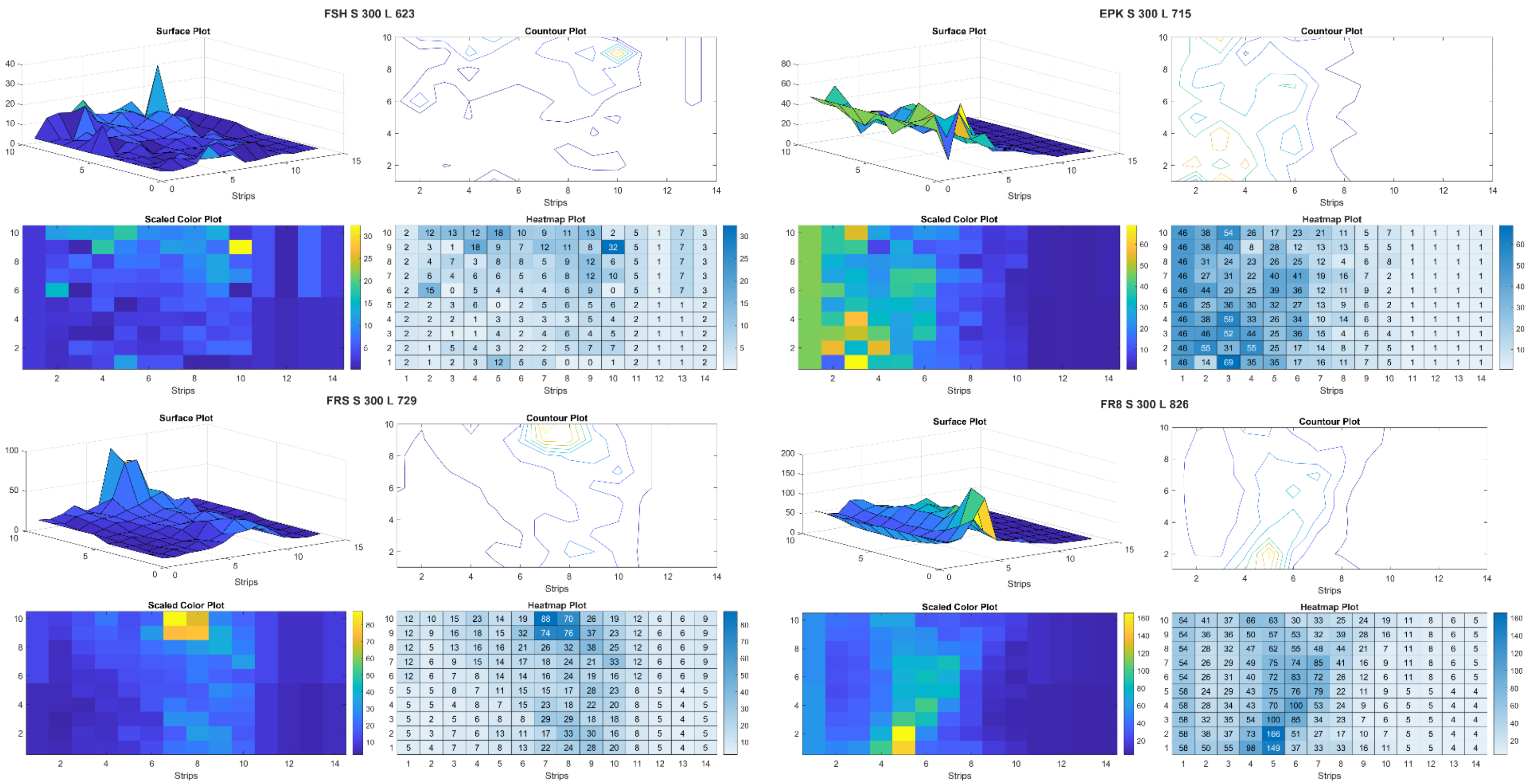


Figure A.3: Quad Plot Set 3 – Sand 300 lb/lnmi LEFT, target strip 2-9, adjusted nominal 43 gm per 2 m²

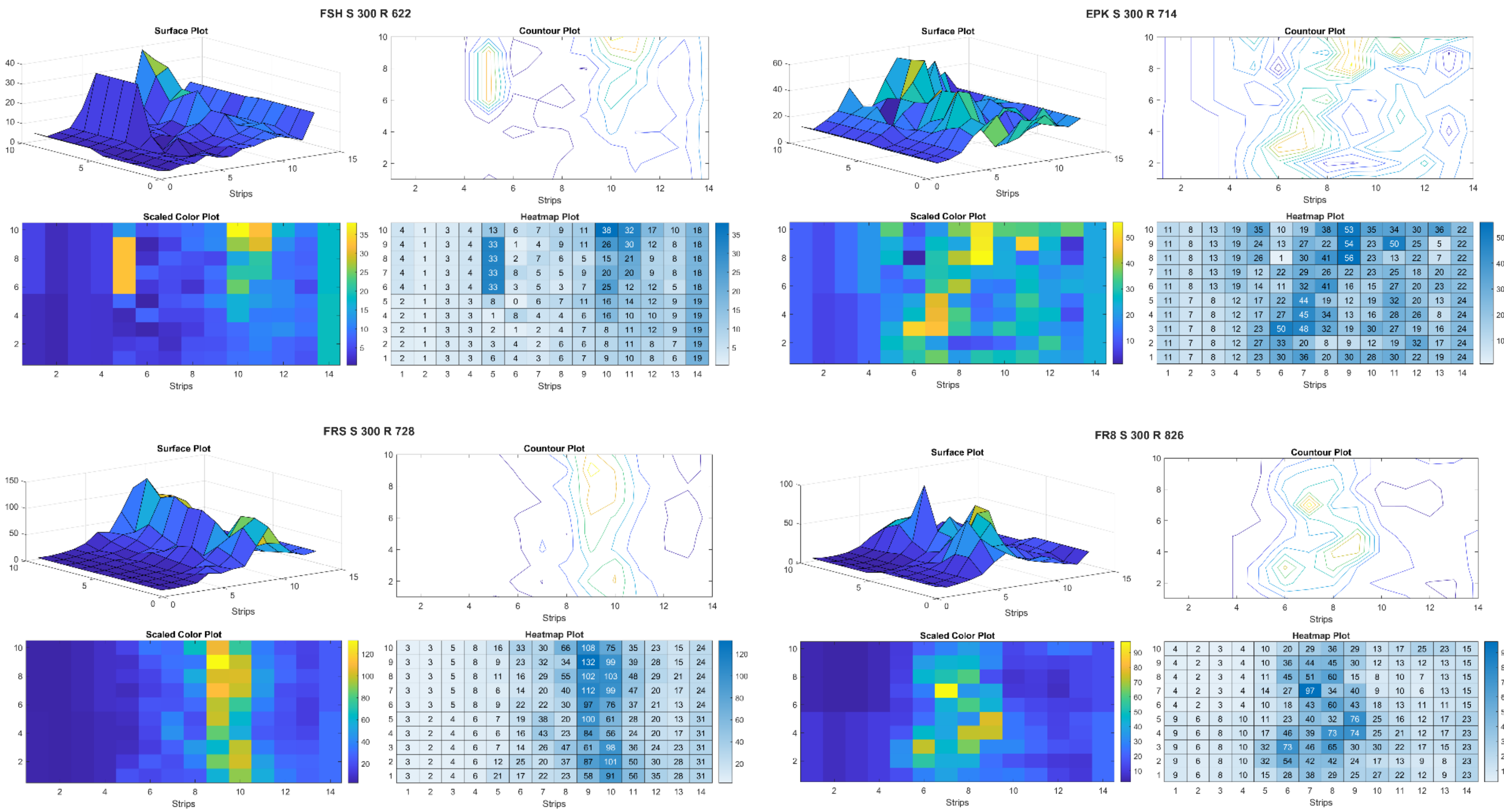


Figure A.4: Quad Plot Set 4 – Sand 300 lb/lnmi RIGHT, target strip 6-13, adjusted nominal 43 gm per 2 m²

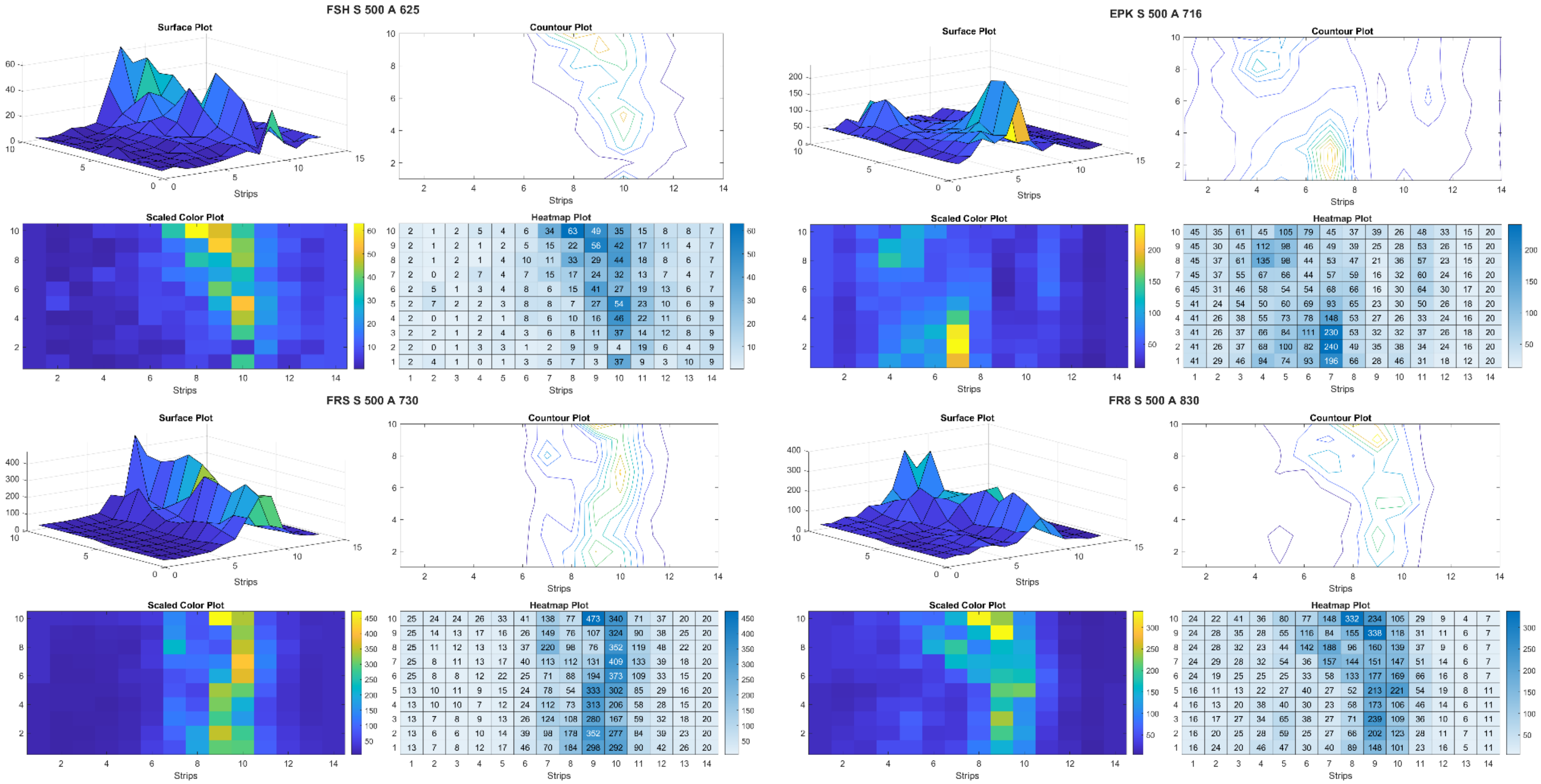


Figure A.5: Quad Plot Set 5– Sand 500 lb/lnmi ALL, target strip 2-13, adjusted nominal 71 gm per 2 m²

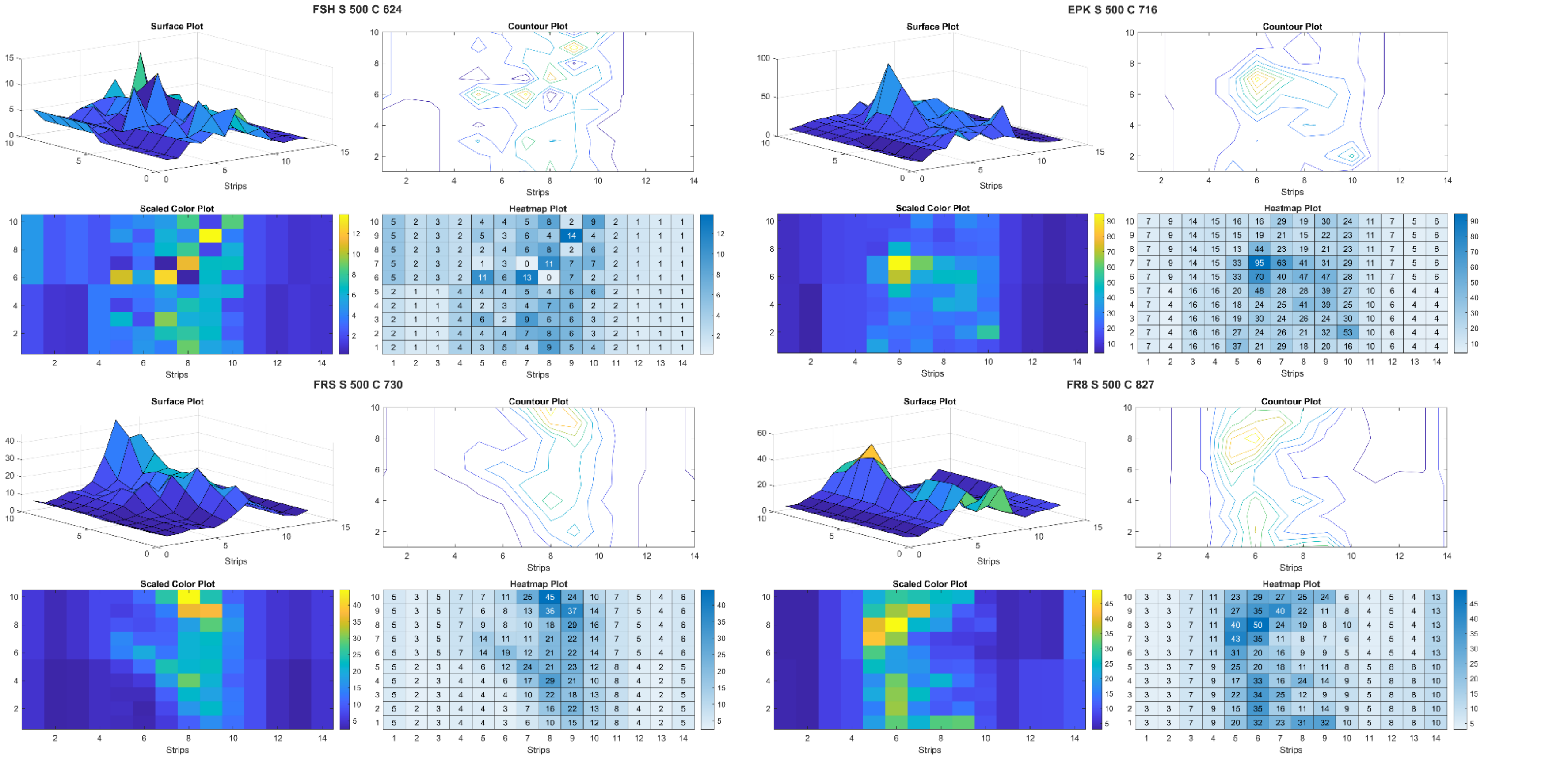


Figure A.6: Quad Plot Set 6– Sand 500 lb/lnmi CENTER, target strip 6-9, adjusted nominal 71 gm per 2 m²

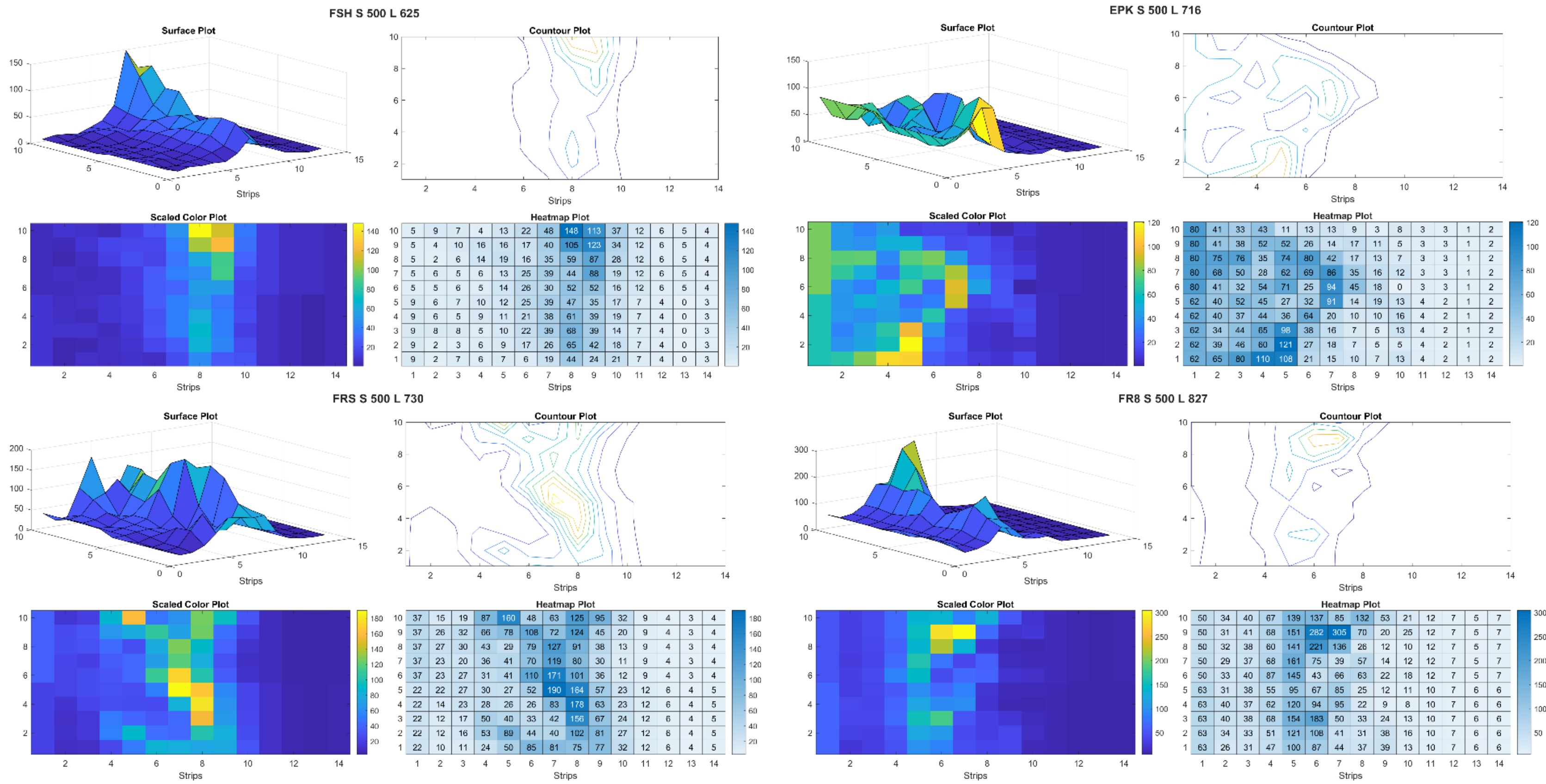


Figure A.7: Quad Plot Set 7– Sand 500 lb/lnmi LEFT, target strip 2-9, adjusted nominal 71 gm per 2 m²

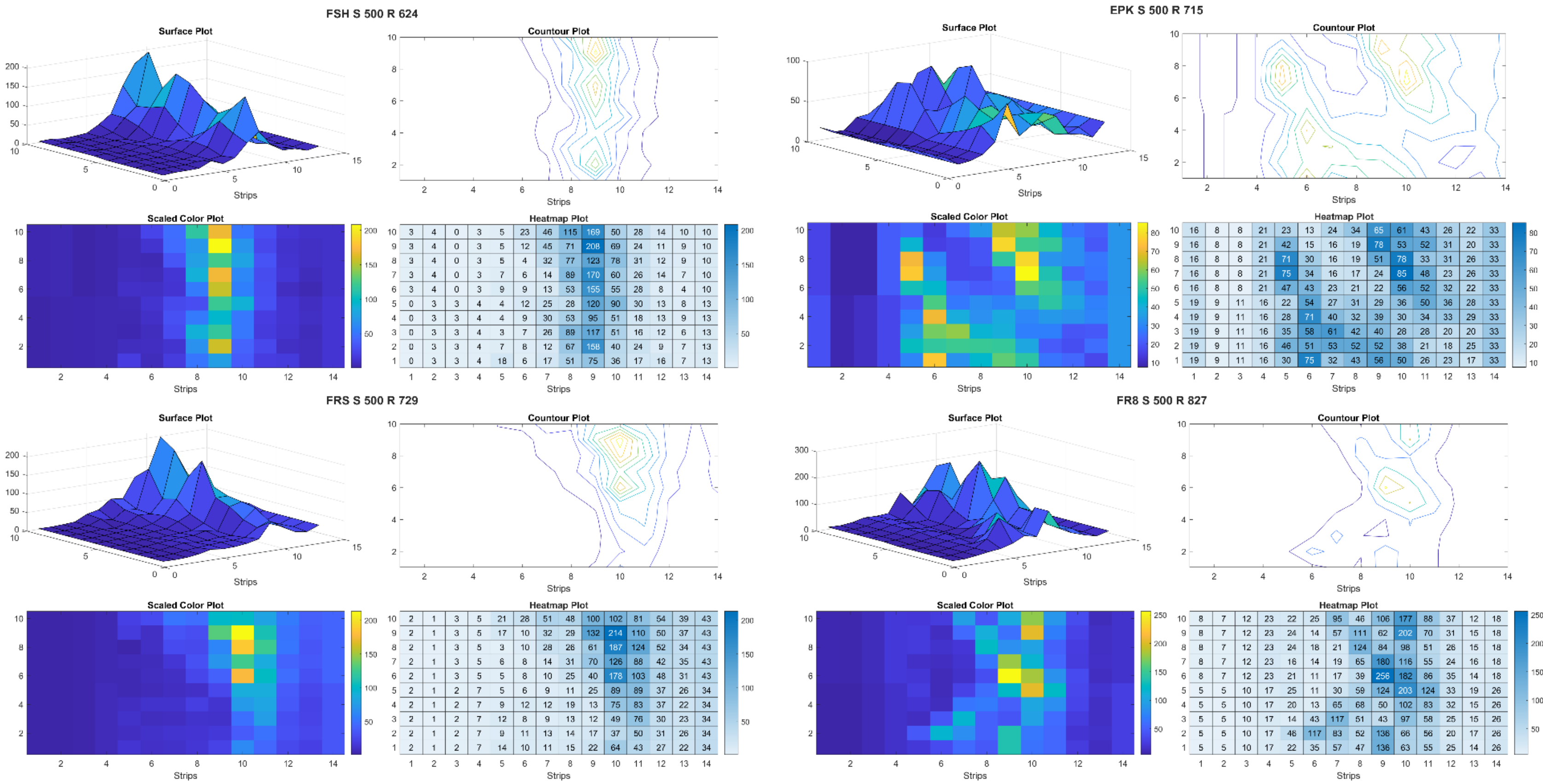


Figure A.8: Quad Plot Set 8– Sand 500 lb/lnmi RIGHT, target strip 6-13, adjusted nominal 71 gm per 2 m²

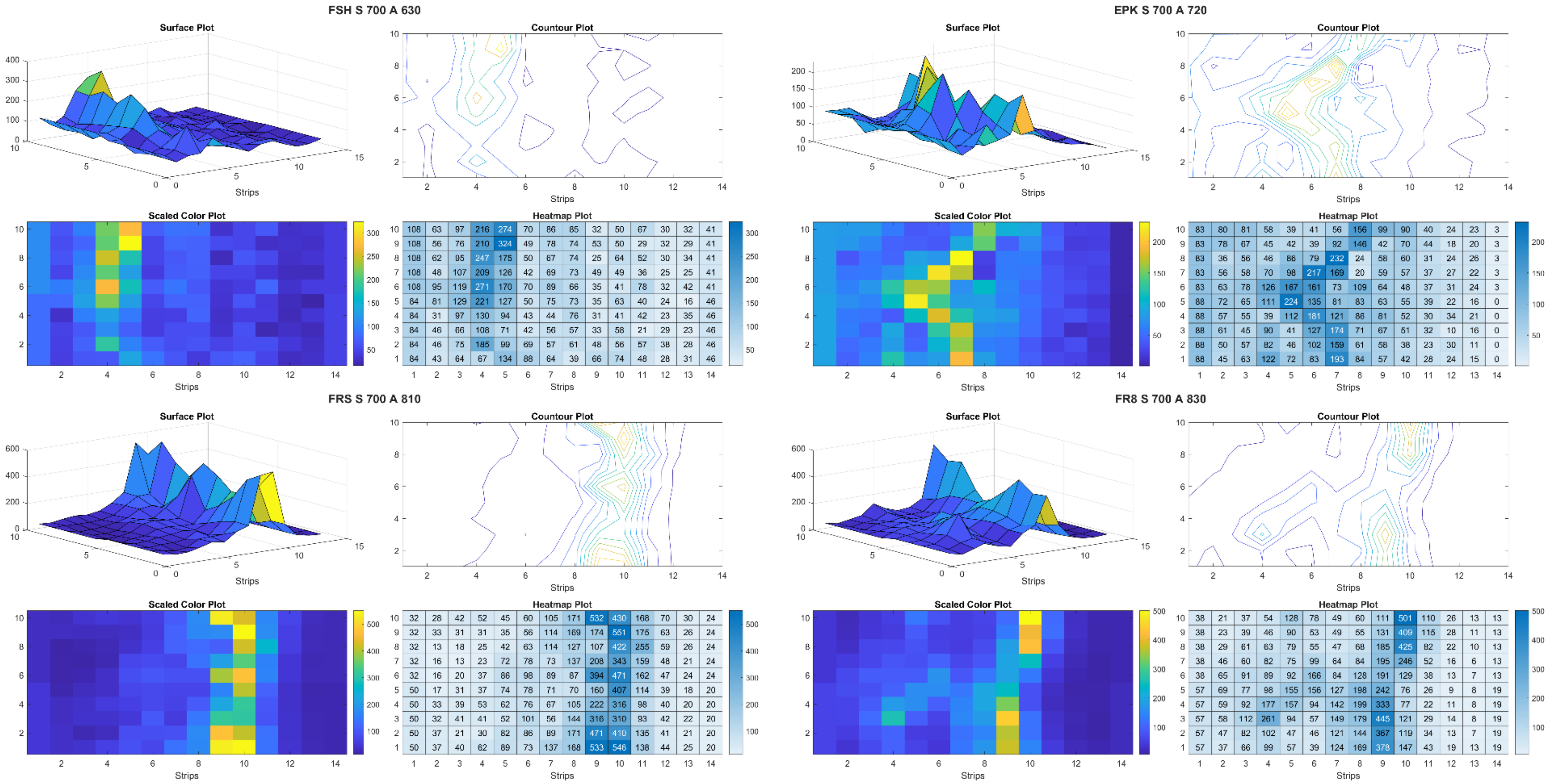


Figure A.9: Quad Plot Set 9– Sand 700 lb/lnmi ALL, target strip 2-13, adjusted nominal 100 gm per 2 m²

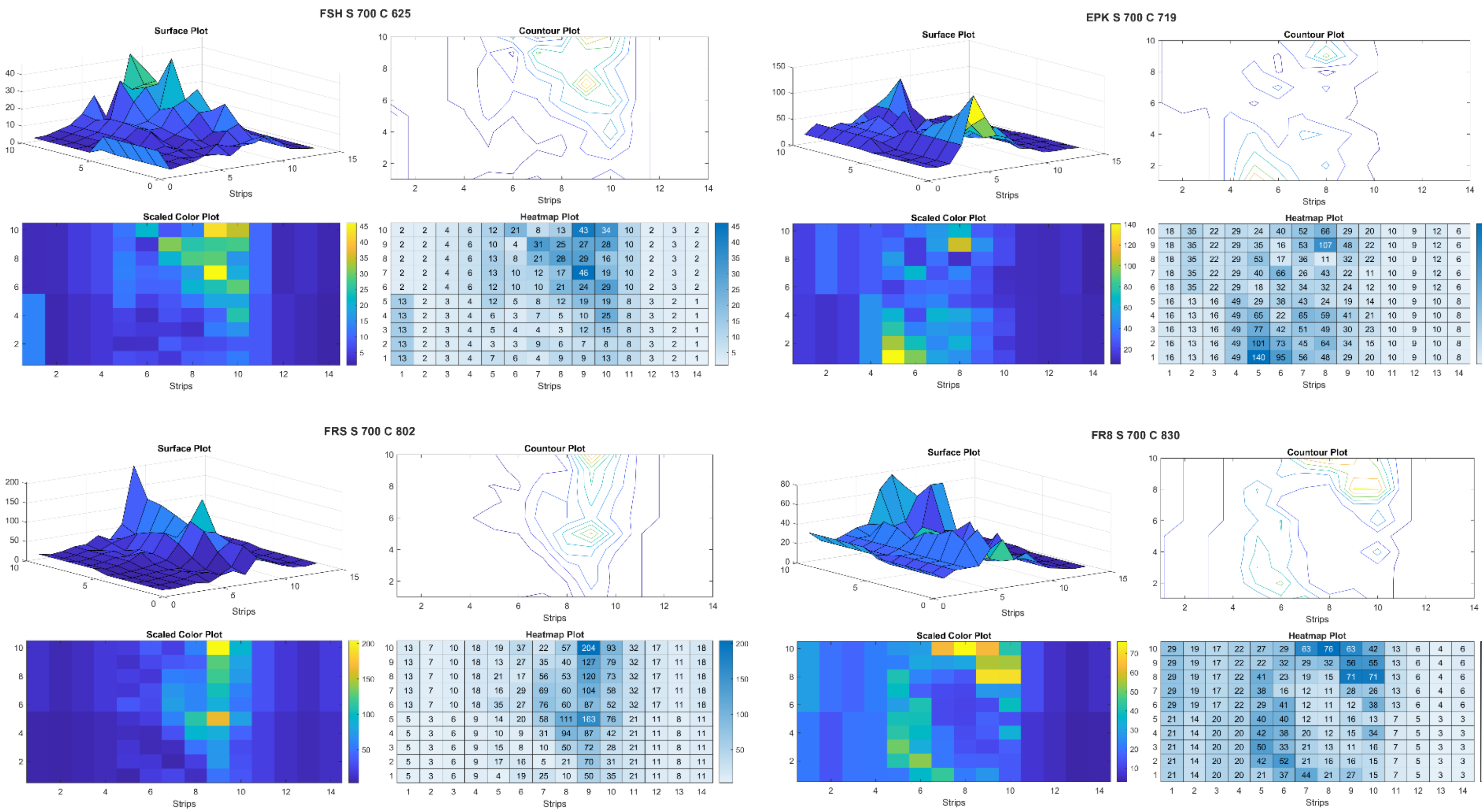


Figure A.10: Quad Plot Set 10– Sand 700 lb/lnmi CENTER, target strip 6-9, adjusted nominal 100 gm per 2 m²

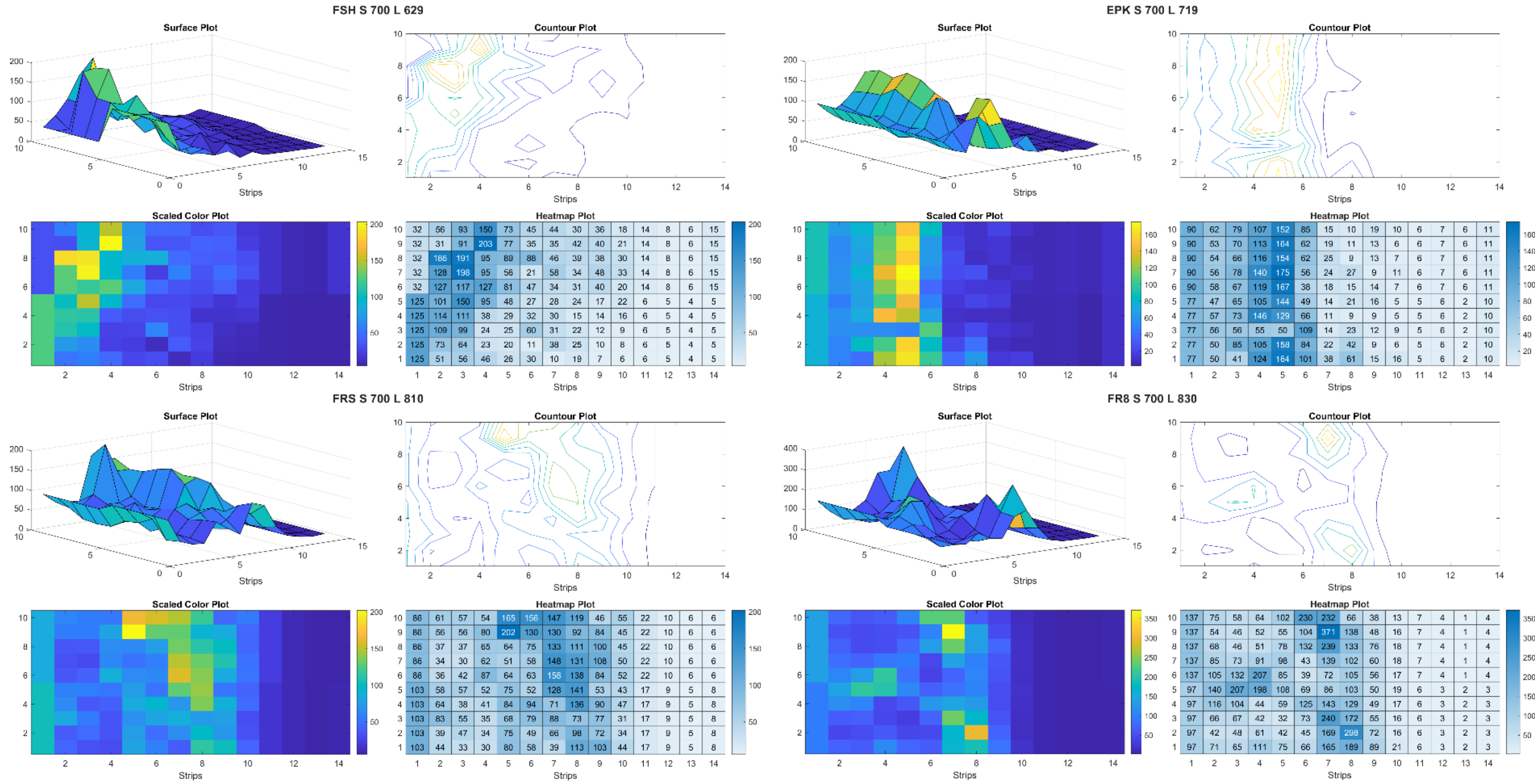


Figure A.11: Quad Plot Set 11– Sand 700 lb/lnmi LEFT, target strip 2-9, adjusted nominal 100 gm per 2 m²

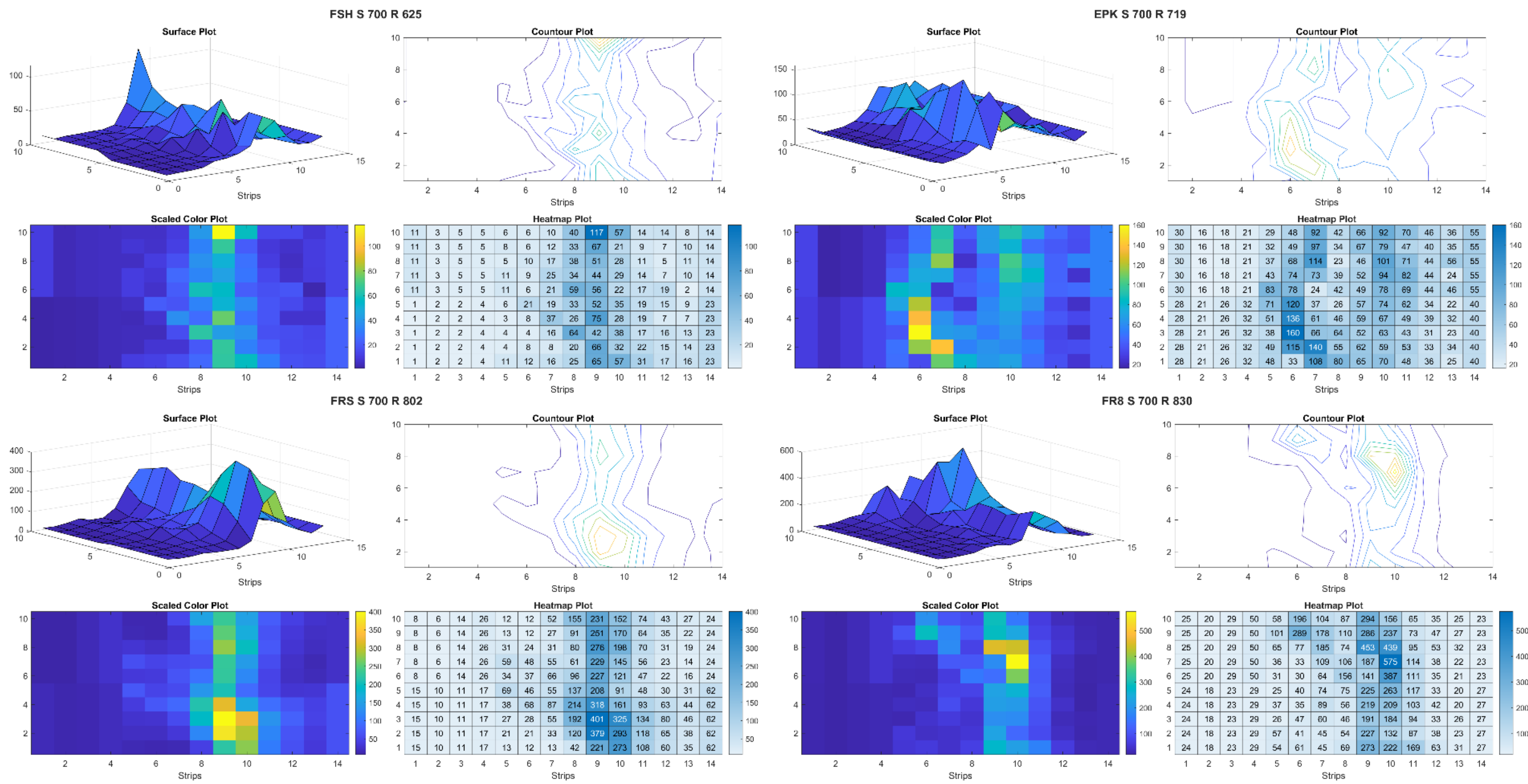


Figure A.12: Quad Plot Set 12– Sand 700 lb/lnmi RIGHT, target strip 6-13, adjusted nominal 100 gm per 2 m²

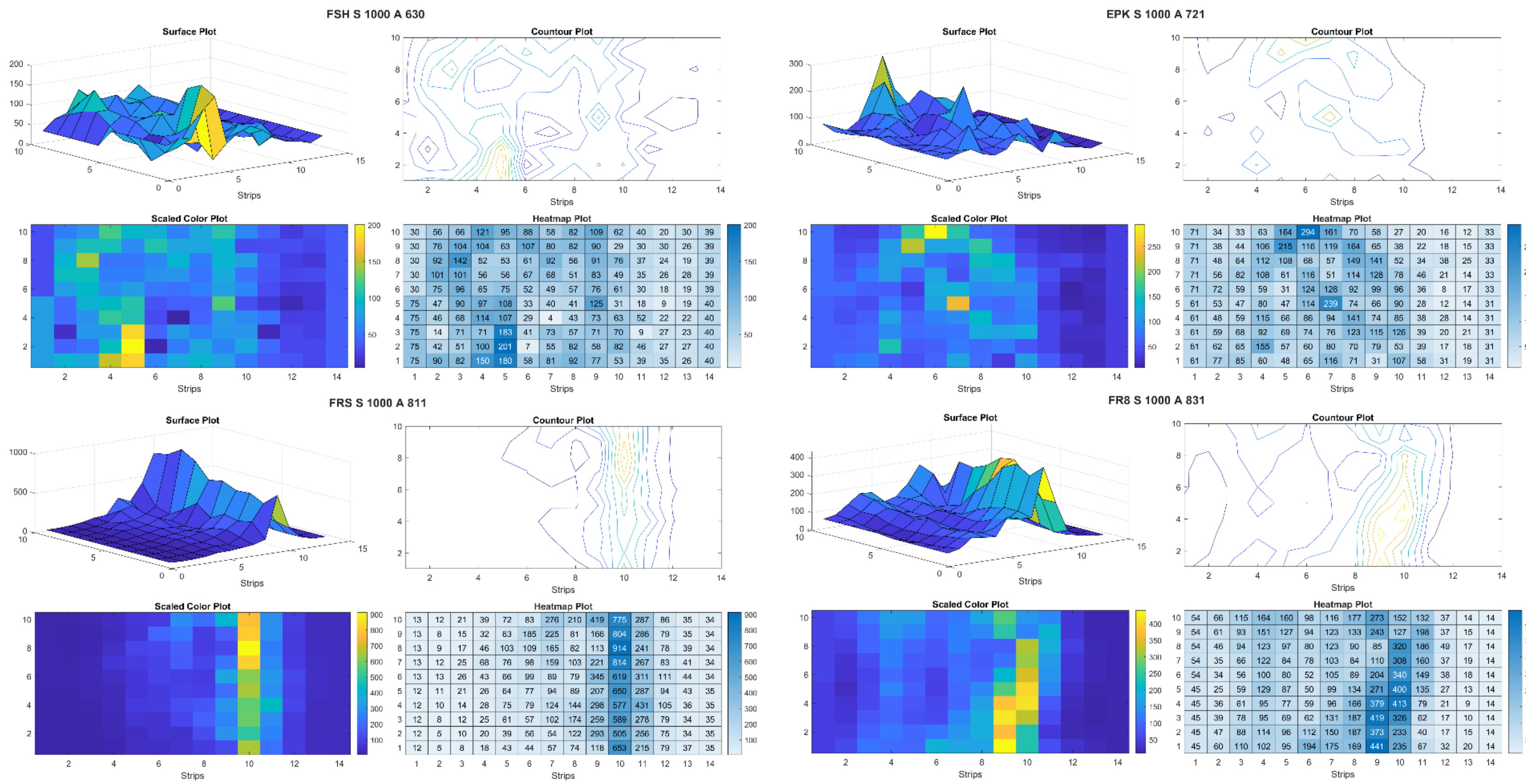


Figure A.13: Quad Plot Set 13– Sand 1000 lb/lnmi ALL, target strip 2-13, adjusted nominal 143 gm per 2 m²

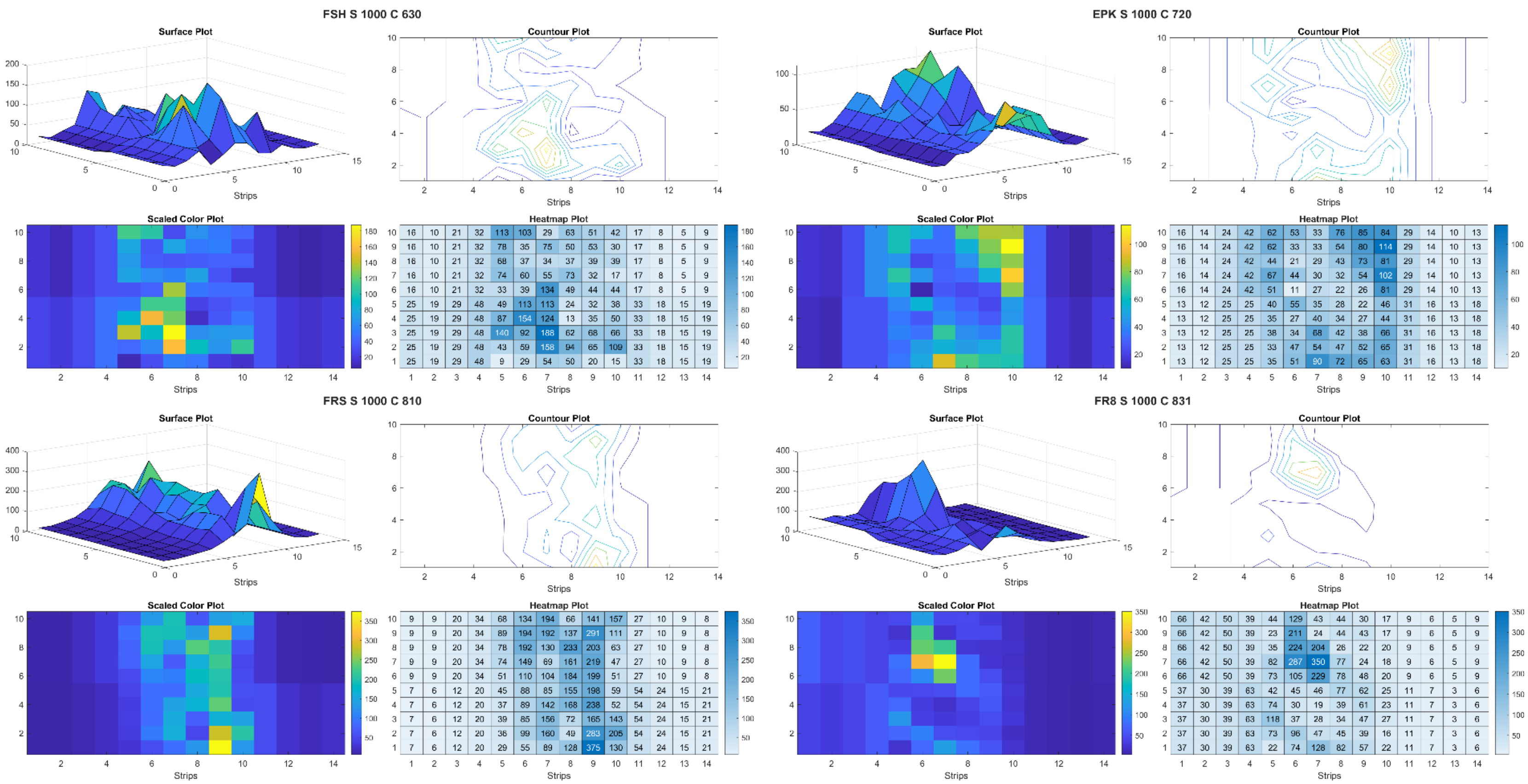


Figure A.14: Quad Plot Set 14– Sand 1000 lb/lnmi CENTER, target strip 6-9, adjusted nominal 143 gm per 2 m²

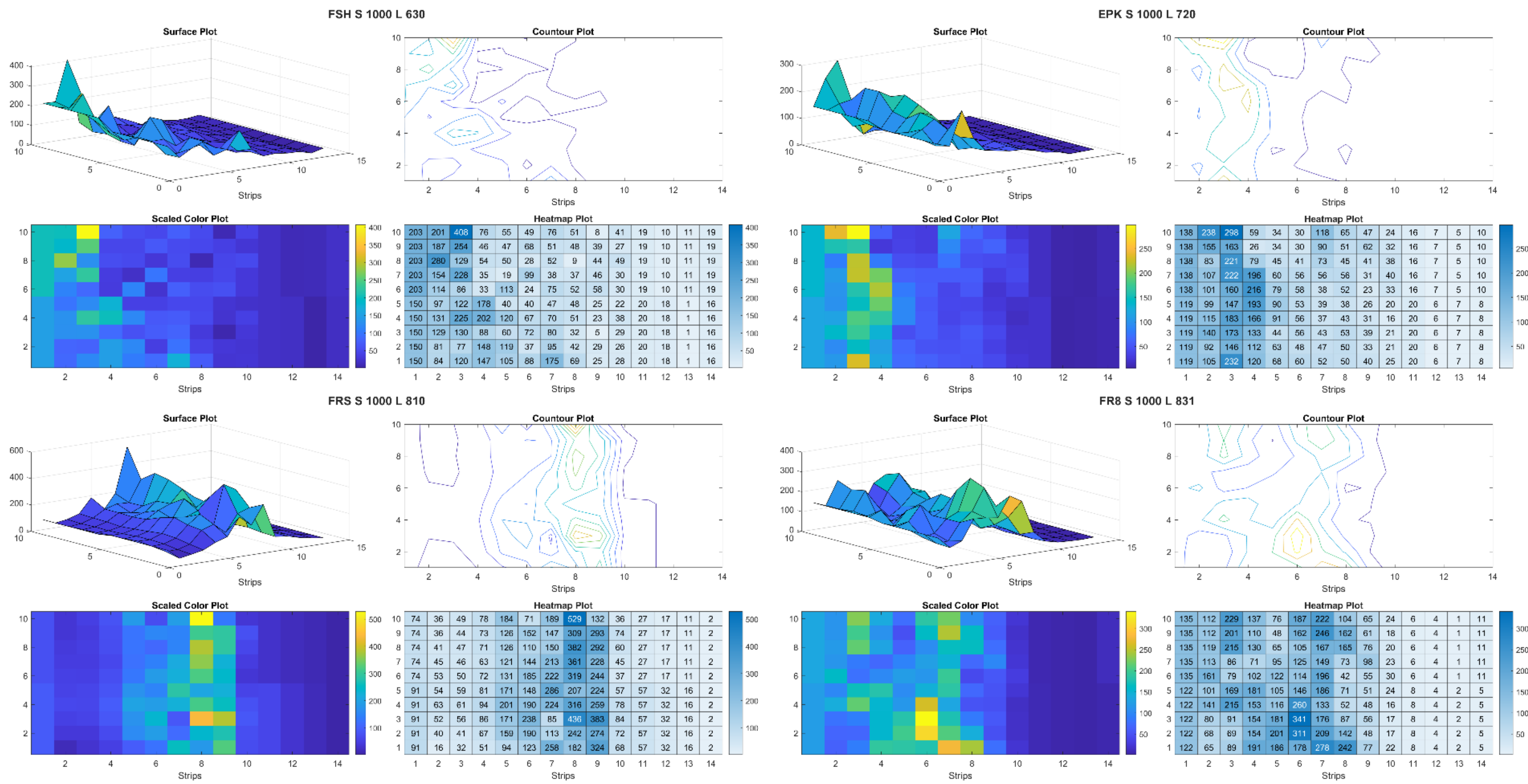


Figure A.15: Quad Plot Set 15– Sand 1000 lb/lnmi LEFT, target strip 2-9, adjusted 143 nominal gm per 2 m²

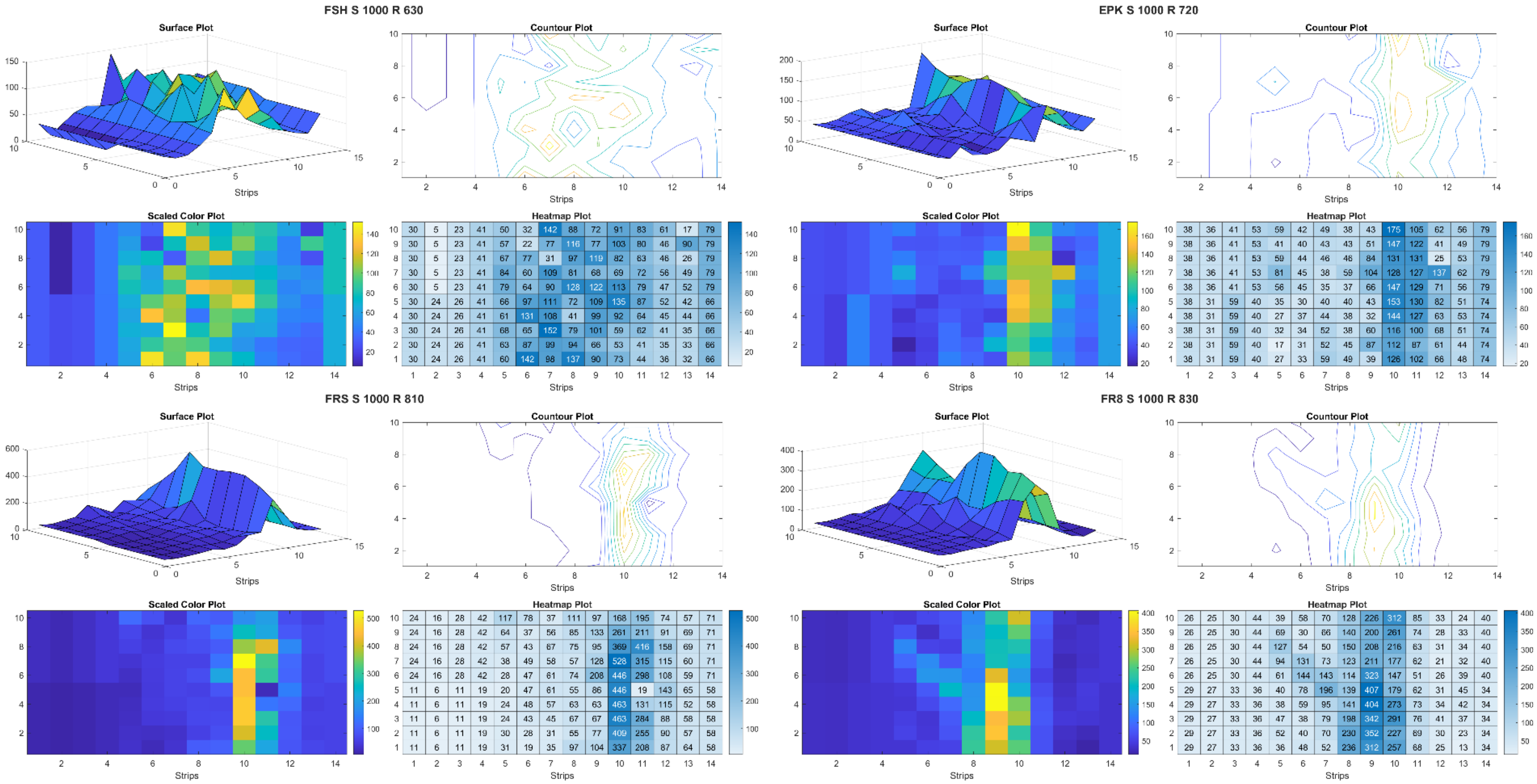


Figure A.16: Quad Plot Set 16– Sand 1000 lb/lnmi RIGHT, target strip 6-13, adjusted 143 nominal gm per 2 m²

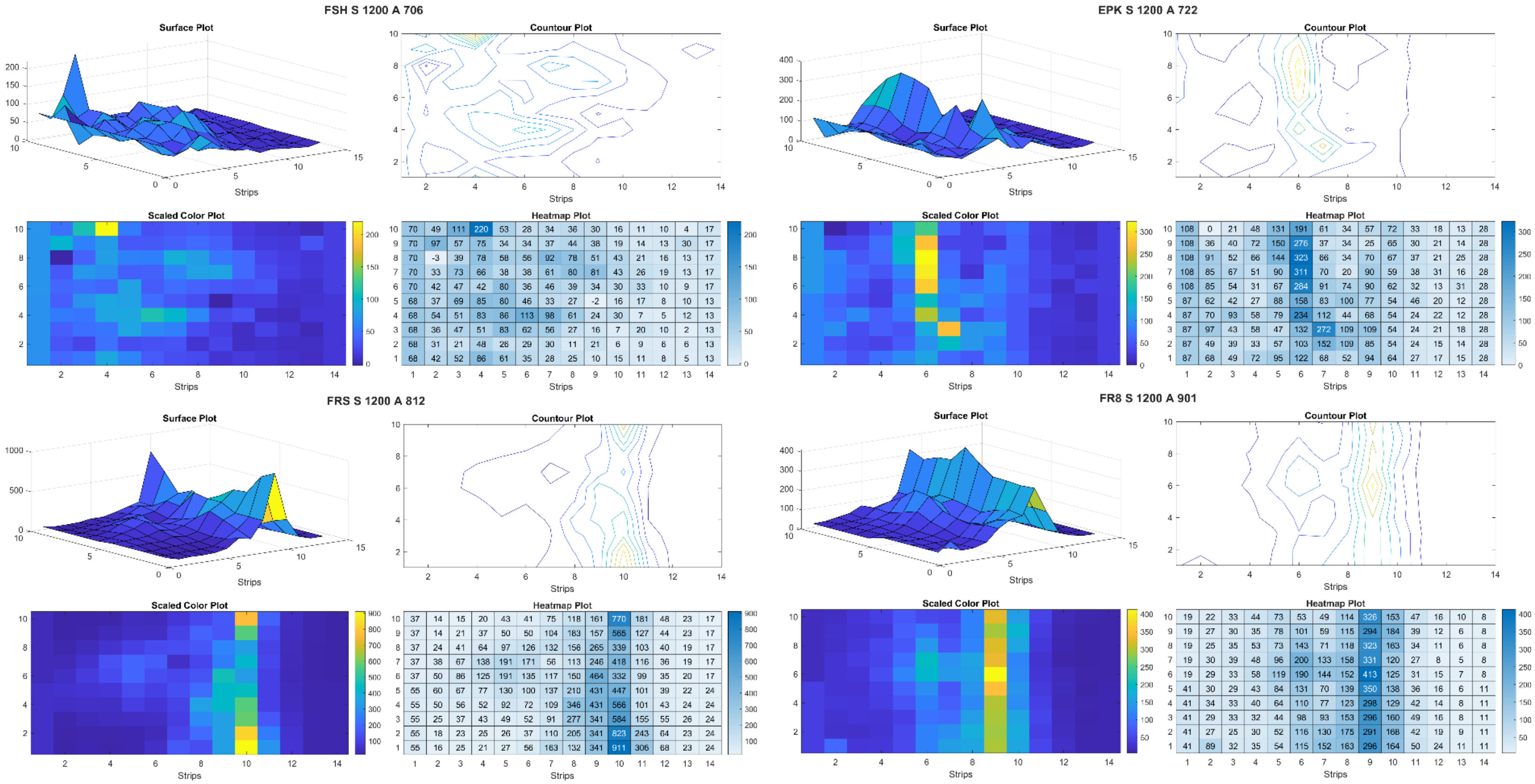


Figure A.17: Quad Plot Set 17– Sand 1200 lb/lnmi ALL, target strip 2-13, adjusted nominal 171 gm per 2 m²

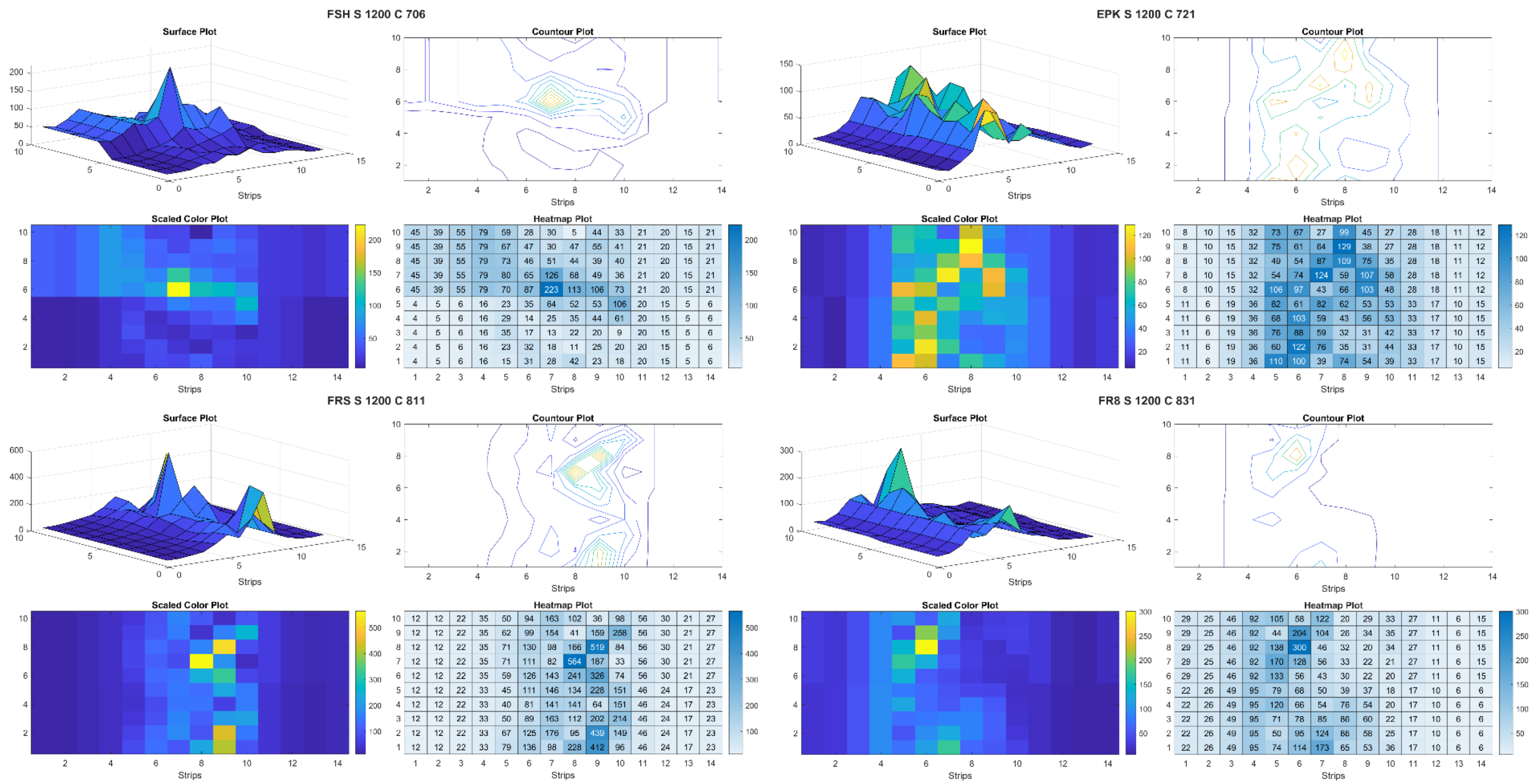


Figure A.18: Quad Plot Set 18– Sand 1200 lb/lnmi CENTER, target strip 6-9, adjusted nominal 171 gm per 2 m²

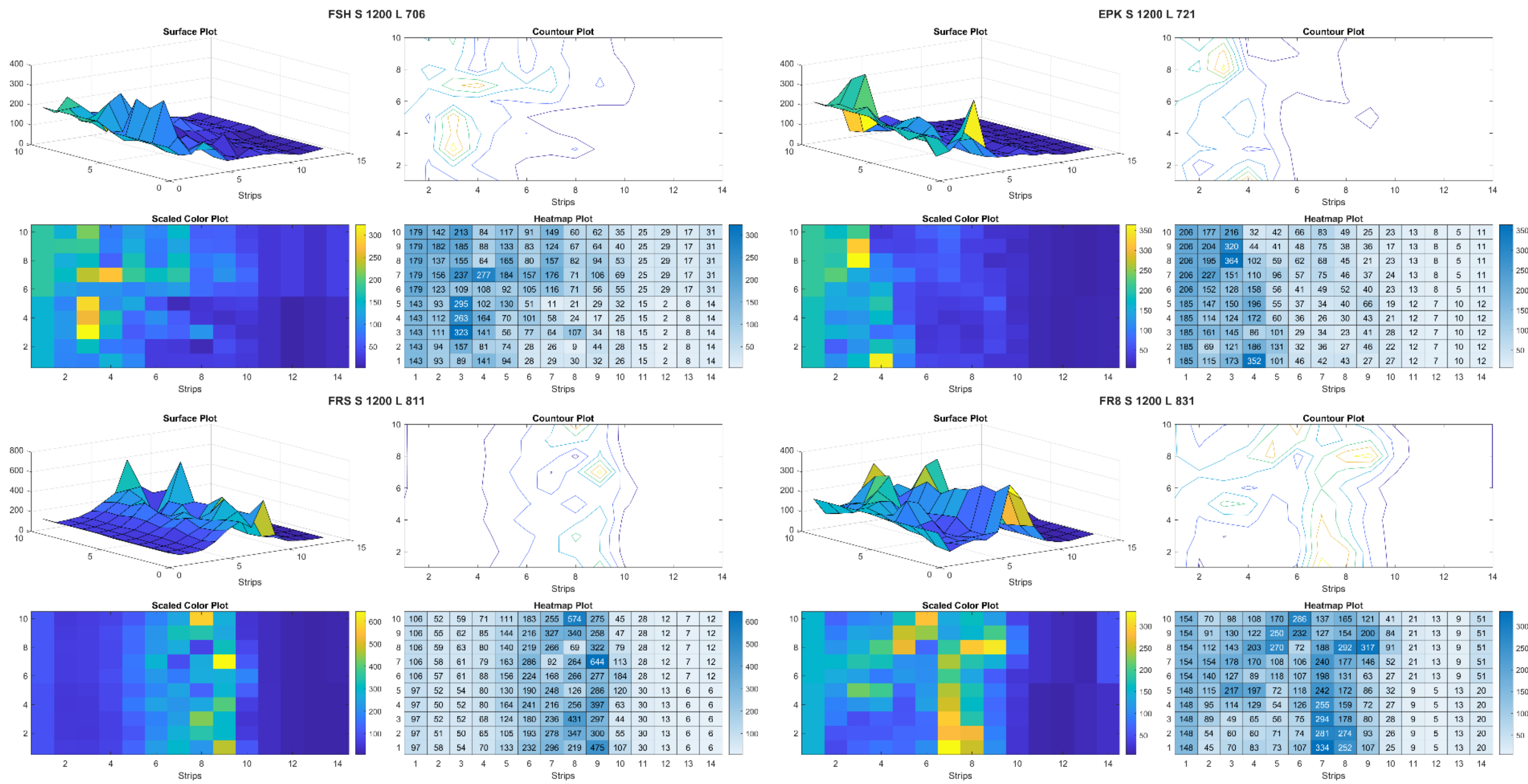


Figure A.19: Quad Plot Set 19– Sand 1200 lb/lnmi LEFT, target strip 2-9, adjusted nominal 171 gm per 2 m²

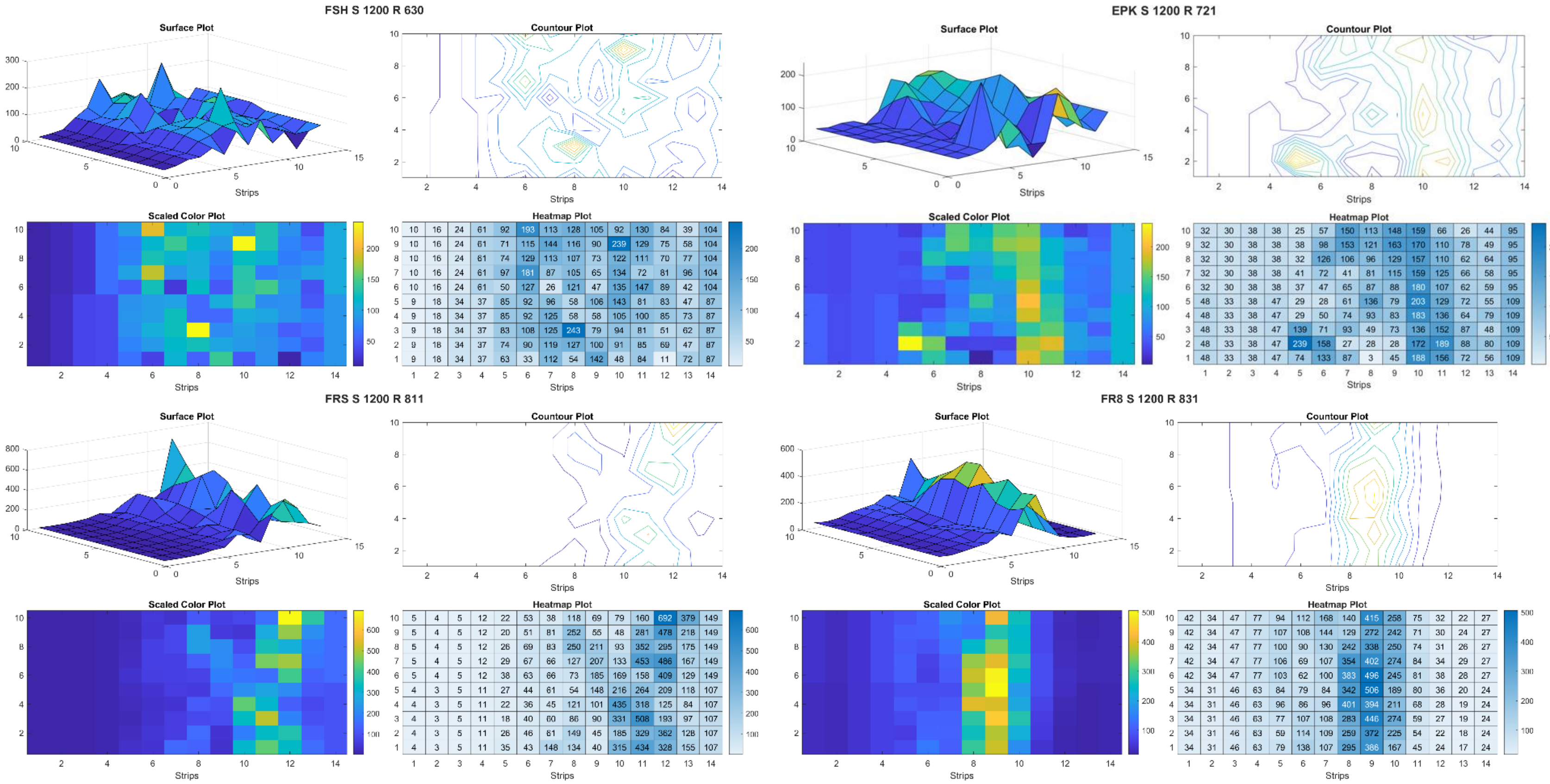


Figure A.20: Quad Plot Set 20– Sand 1200 lb/lnmi RIGHT, target strip 6-13, adjusted nominal 171 gm per 2 m²

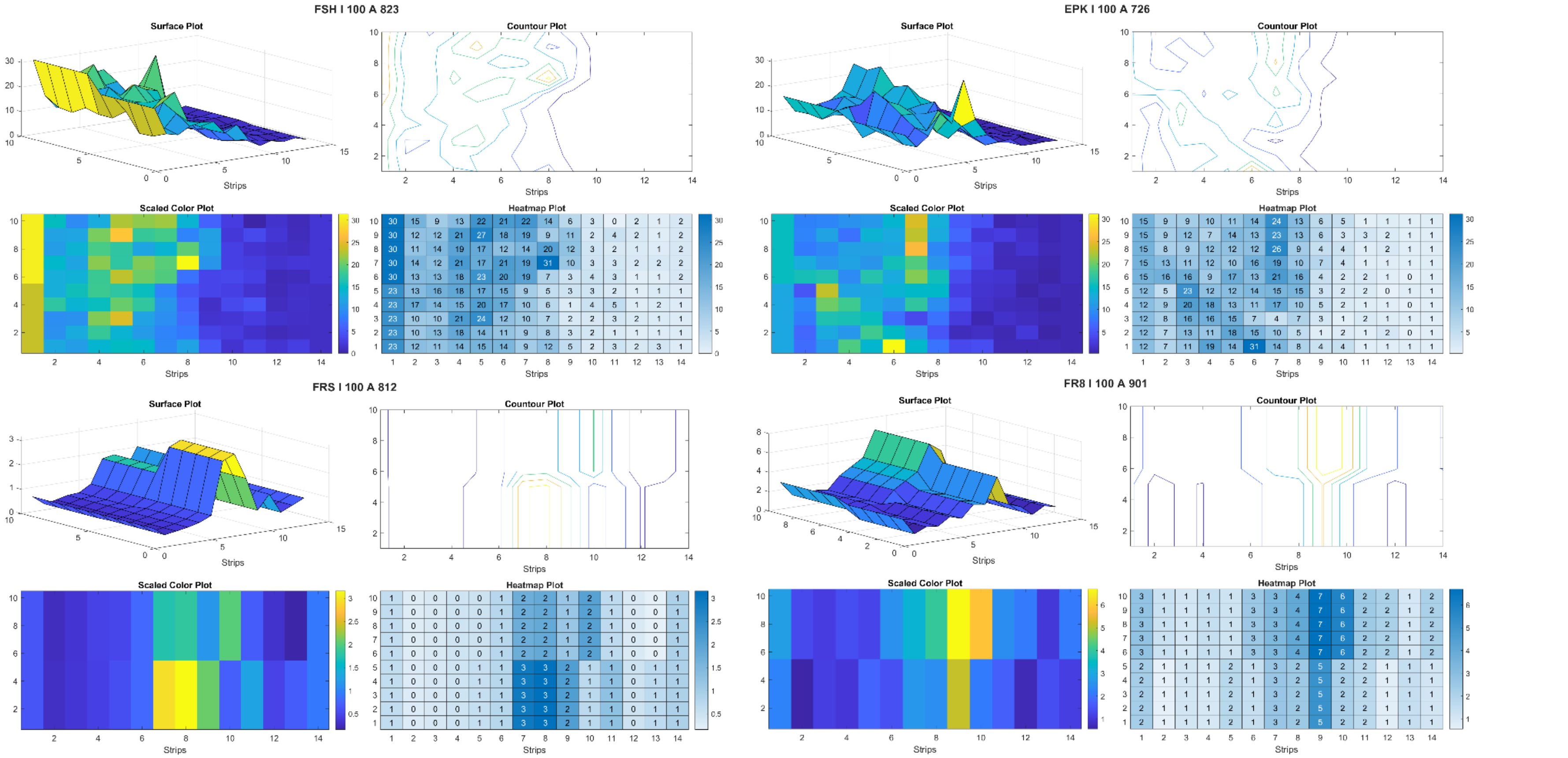


Figure A.21: Quad Plot Set 21– Ice Slicer 100 lb/lnmi ALL, target strip 2-13, adjusted nominal 14 gm per 2 m²

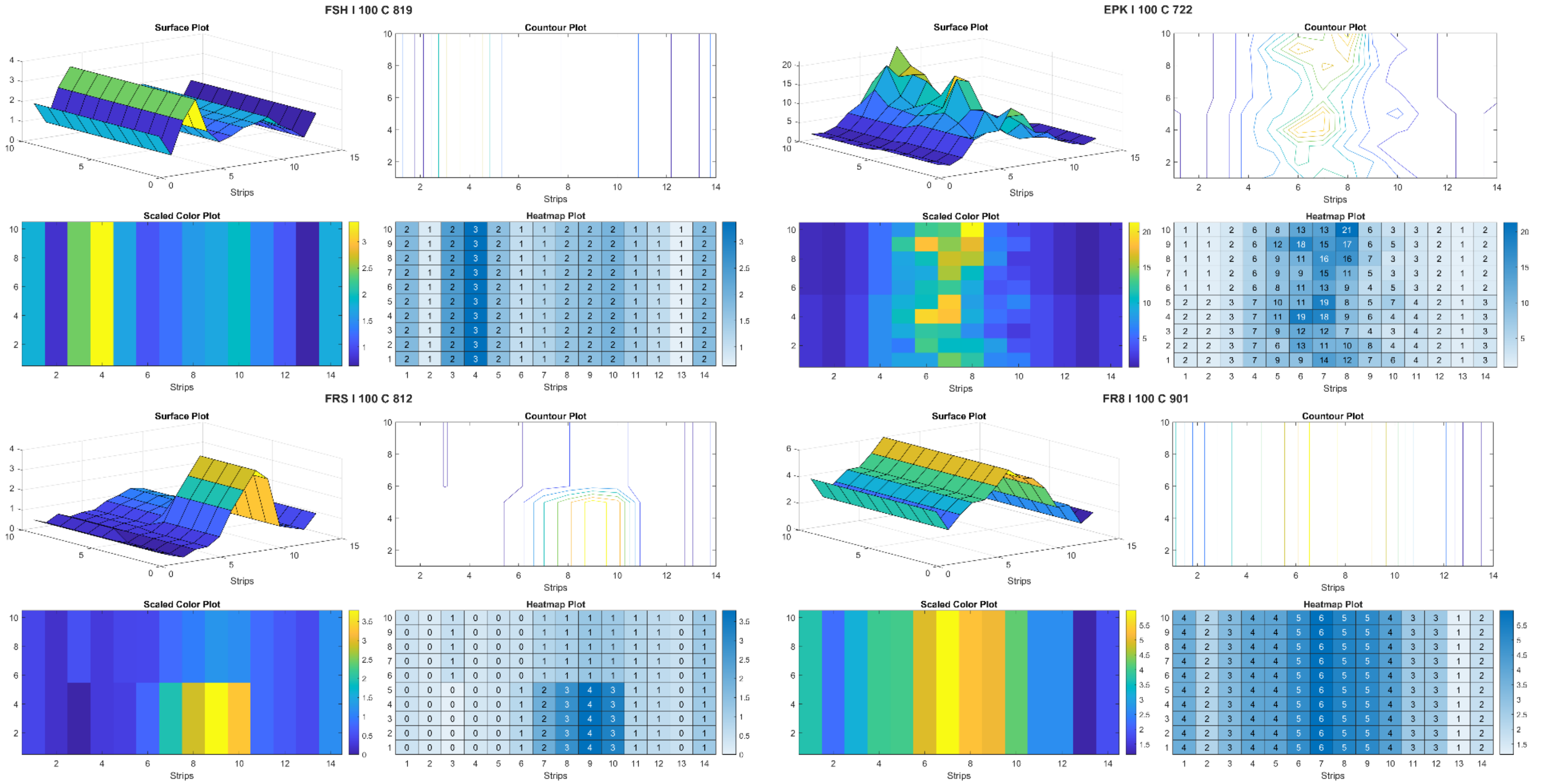


Figure A.22: Quad Plot Set 22– Ice Slicer 100 lb/lnmi CENTER, target strip 6-9, adjusted nominal 14 gm per 2 m²

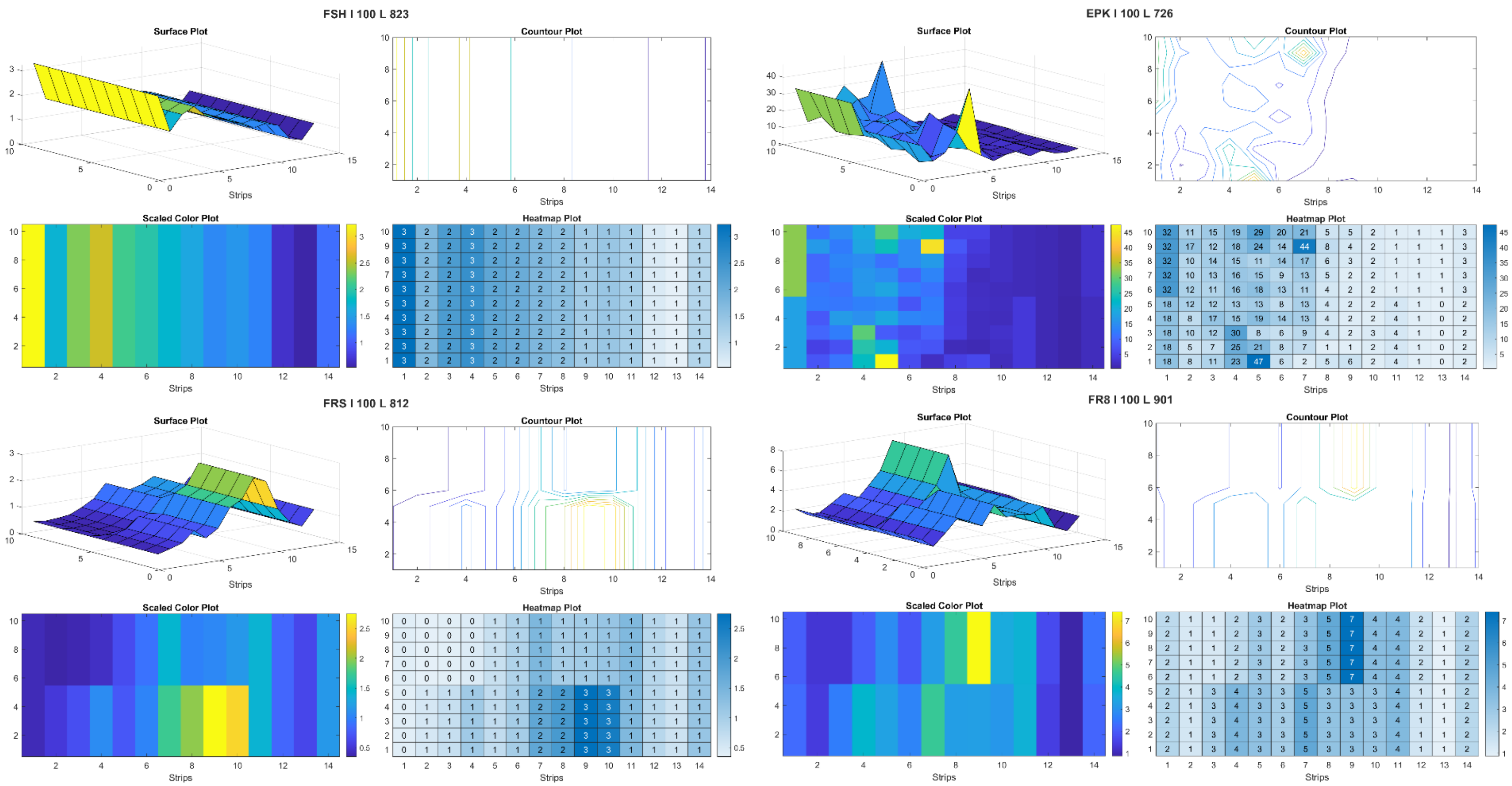


Figure A.23: Quad Plot Set 23– Ice Slicer 100 lb/lnmi LEFT, target strip 2-9, adjusted nominal 14 gm per 2 m²

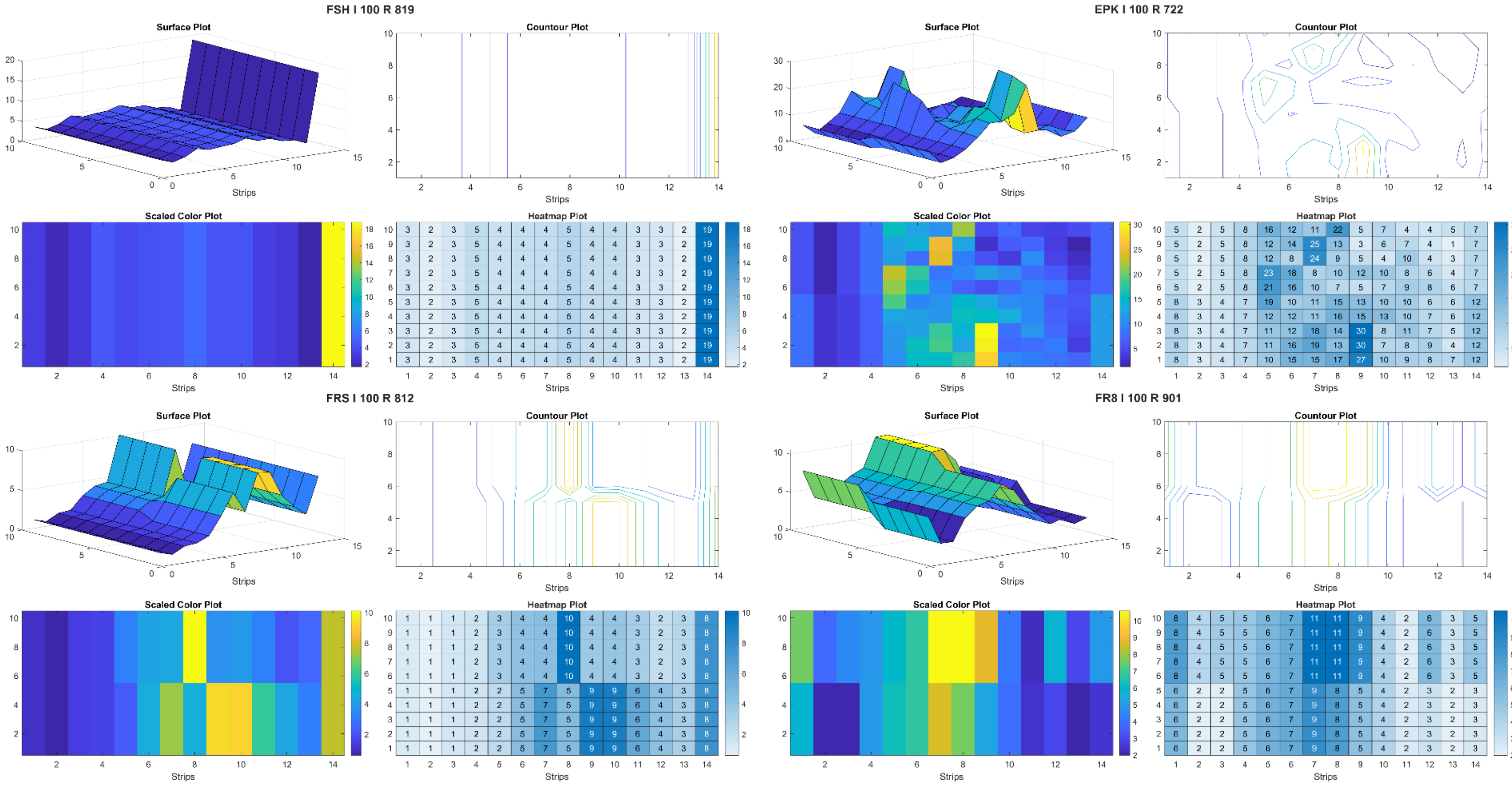


Figure A.24: Quad Plot Set 24– Ice Slicer 100 lb/lnmi RIGHT, target strip 6-13, adjusted nominal 14 gm per 2 m²

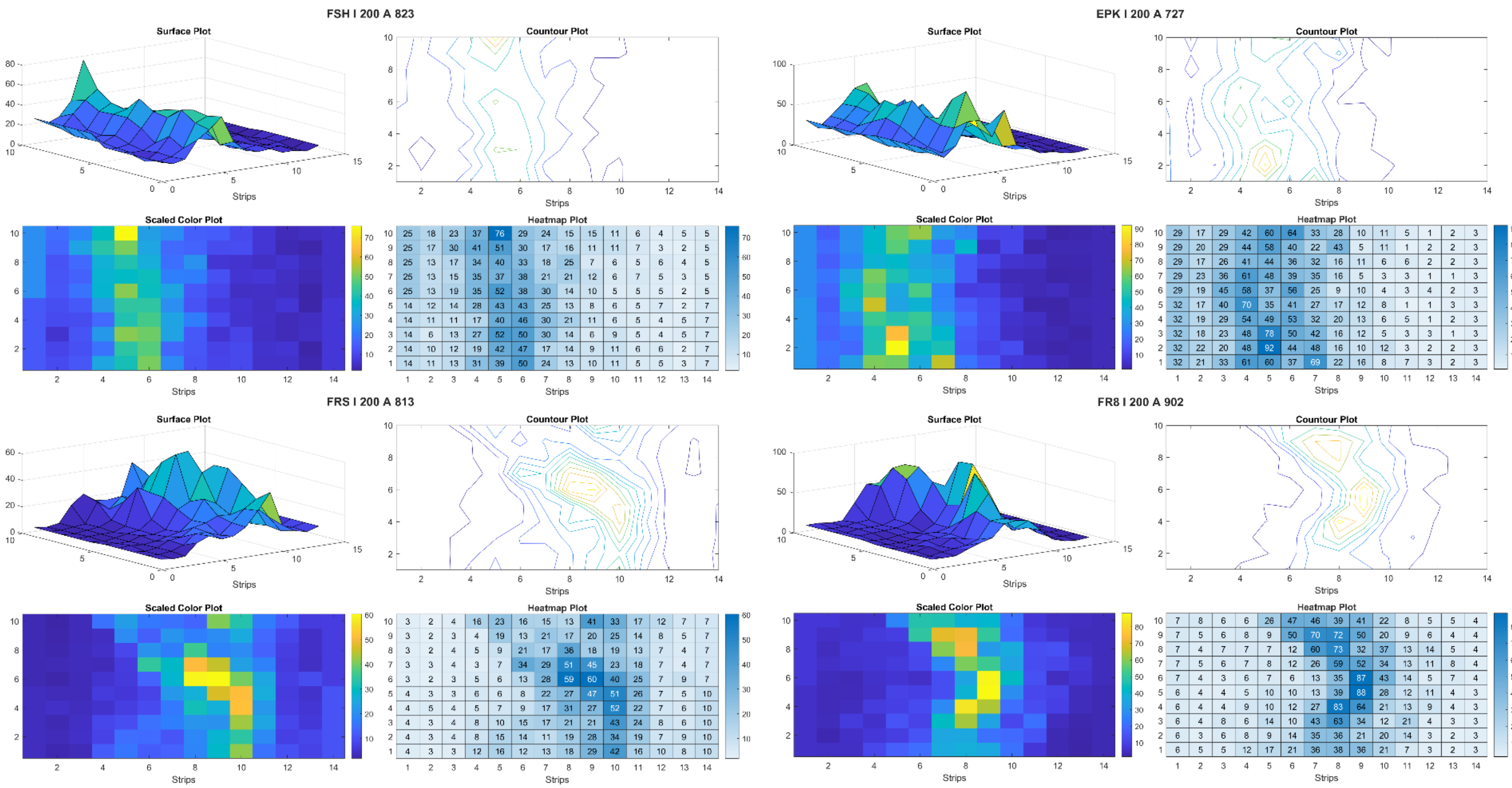


Figure A.25: Quad Plot Set 25– Ice Slicer 200 lb/lnmi ALL, target strip 2-13, adjusted nominal 28 gm per 2 m²

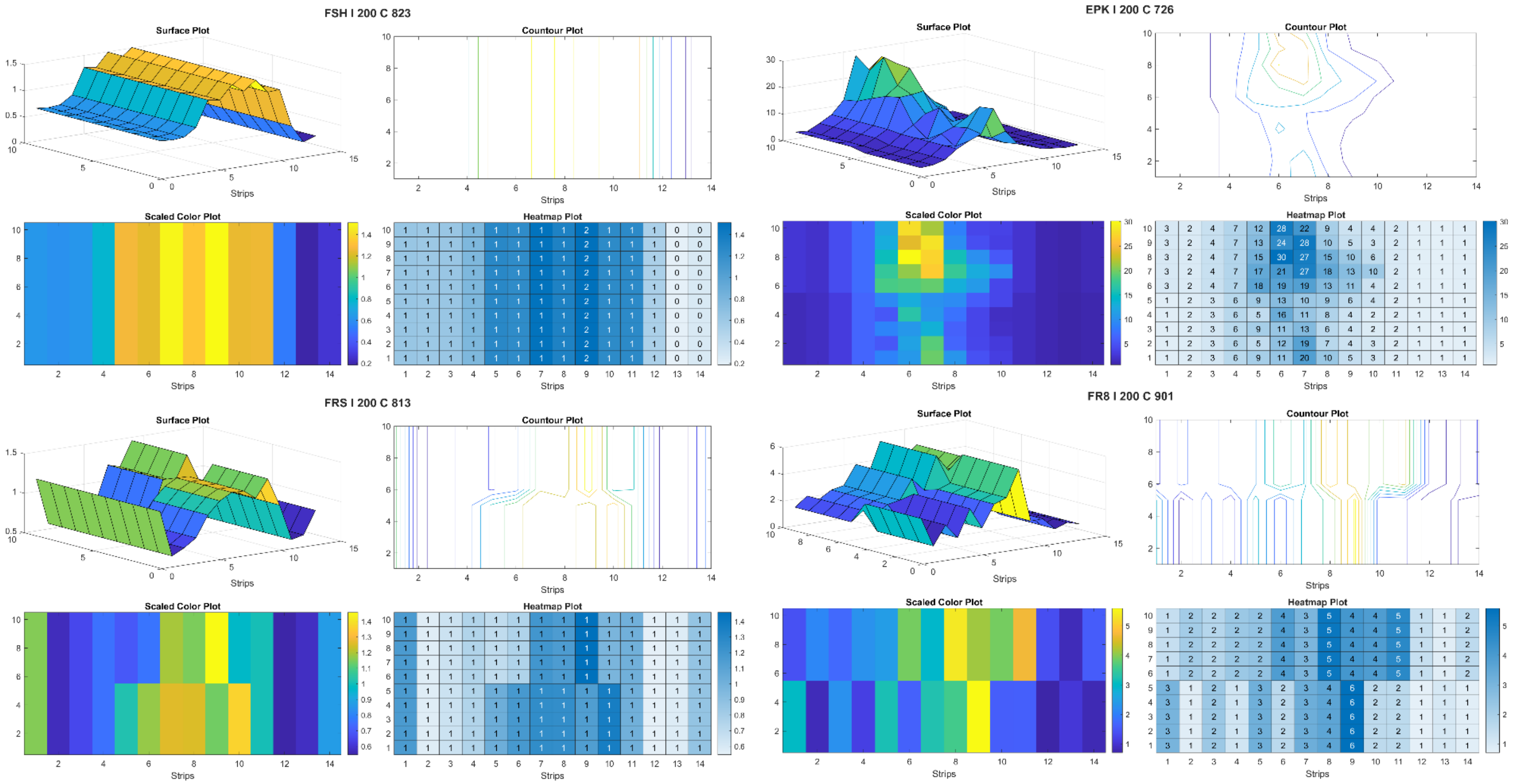


Figure A.26: Quad Plot Set 26– Ice Slicer 200 lb/lnmi CENTER, target strip 6-9, adjusted nominal 28 gm per 2 m²

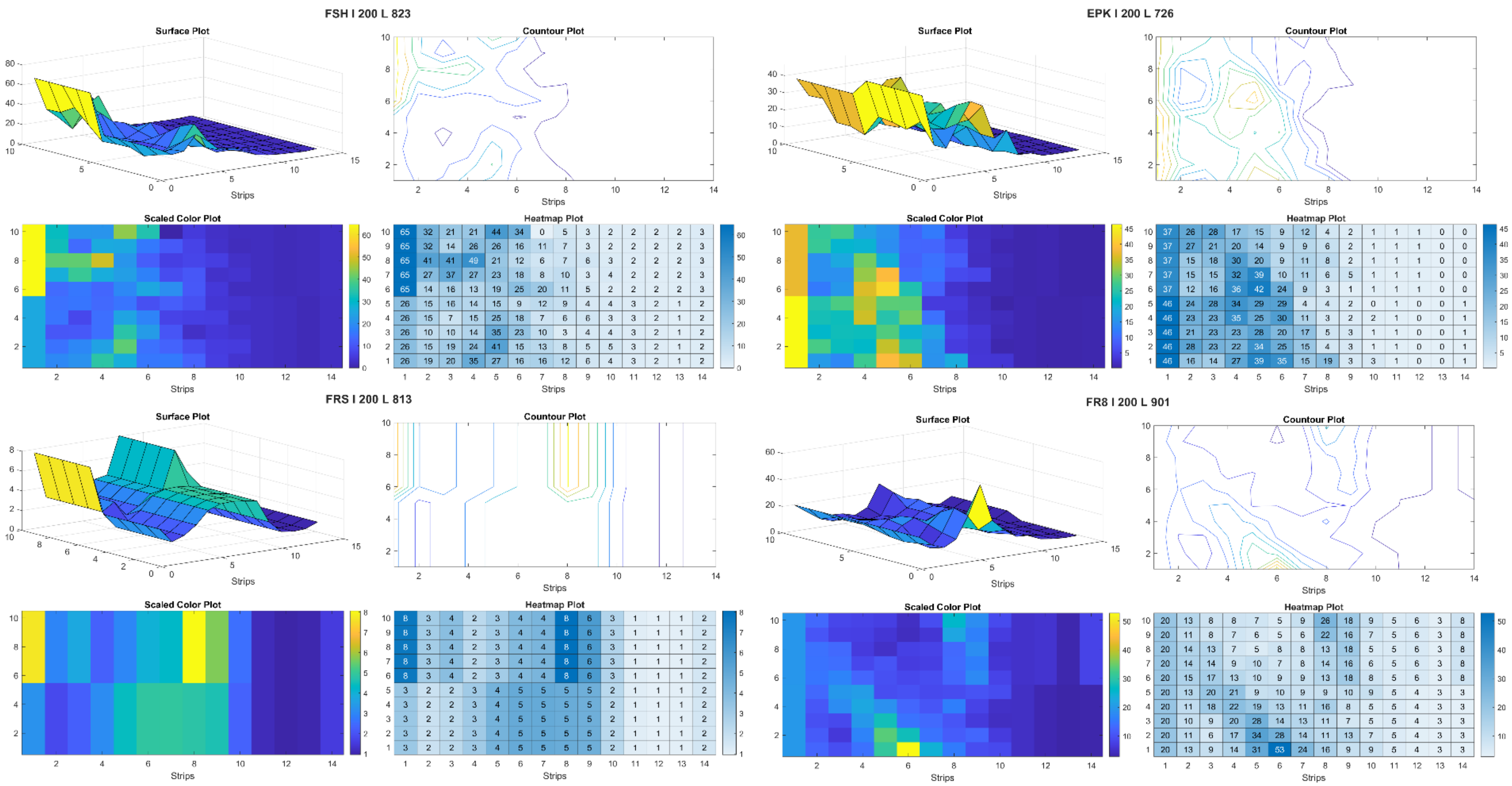


Figure A.27: Quad Plot Set 27– Ice Slicer 200 lb/lnmi LEFT, target strip 2-9, adjusted nominal 28 gm per 2 m²

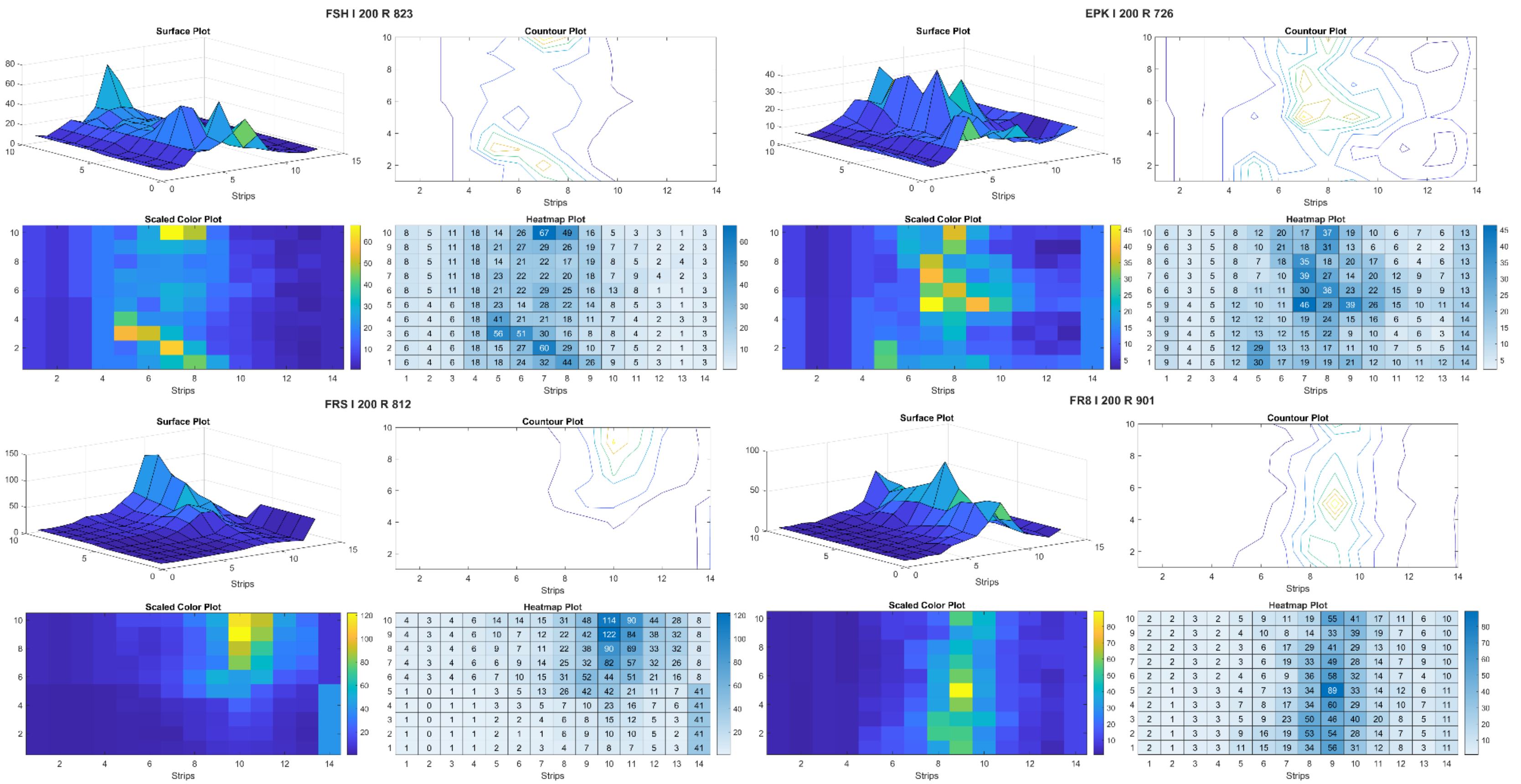


Figure A.28: Quad Plot Set 28– Ice Slicer 200 lb/lnmi RIGHT, target strip 6-13, adjusted nominal 28 gm per 2 m²

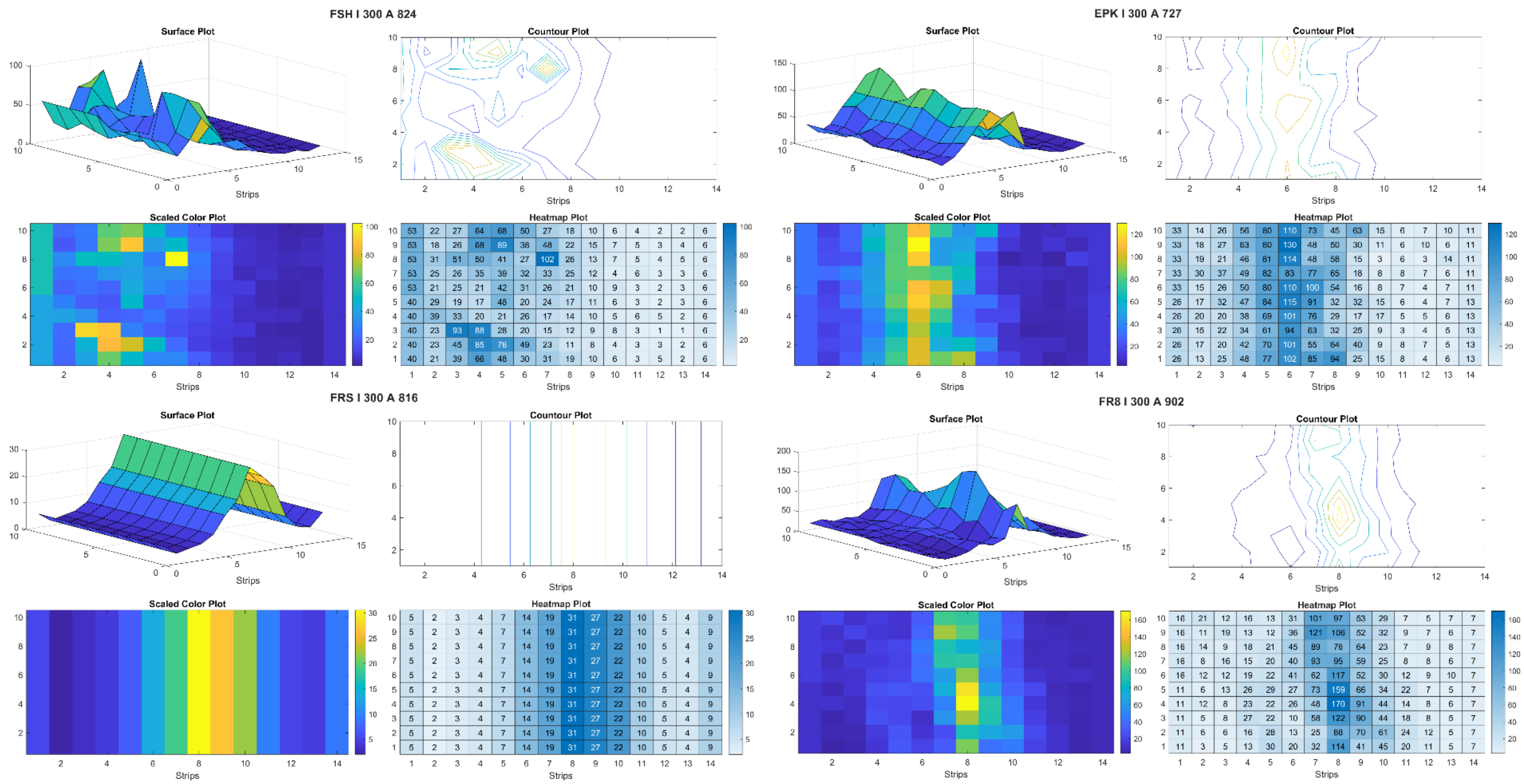


Figure A.29: Quad Plot Set 29– Ice Slicer 300 lb/lnmi ALL, target strip 2-13, adjusted nominal 43 gm per 2 m²

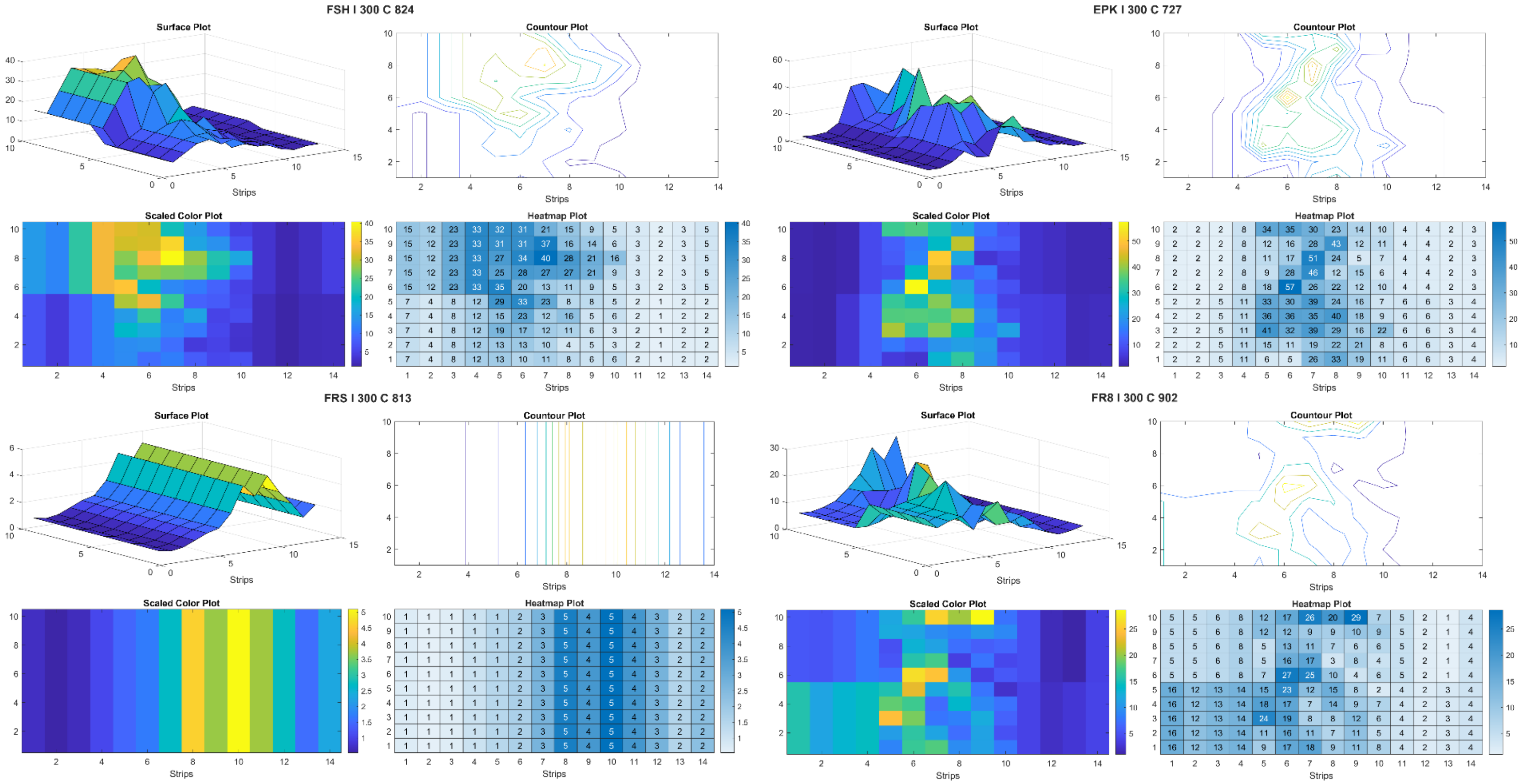


Figure A.30: Quad Plot Set 30– Ice Slicer 300 lb/lnmi CENTER, target strip 6-9, adjusted nominal 43 gm per 2 m²

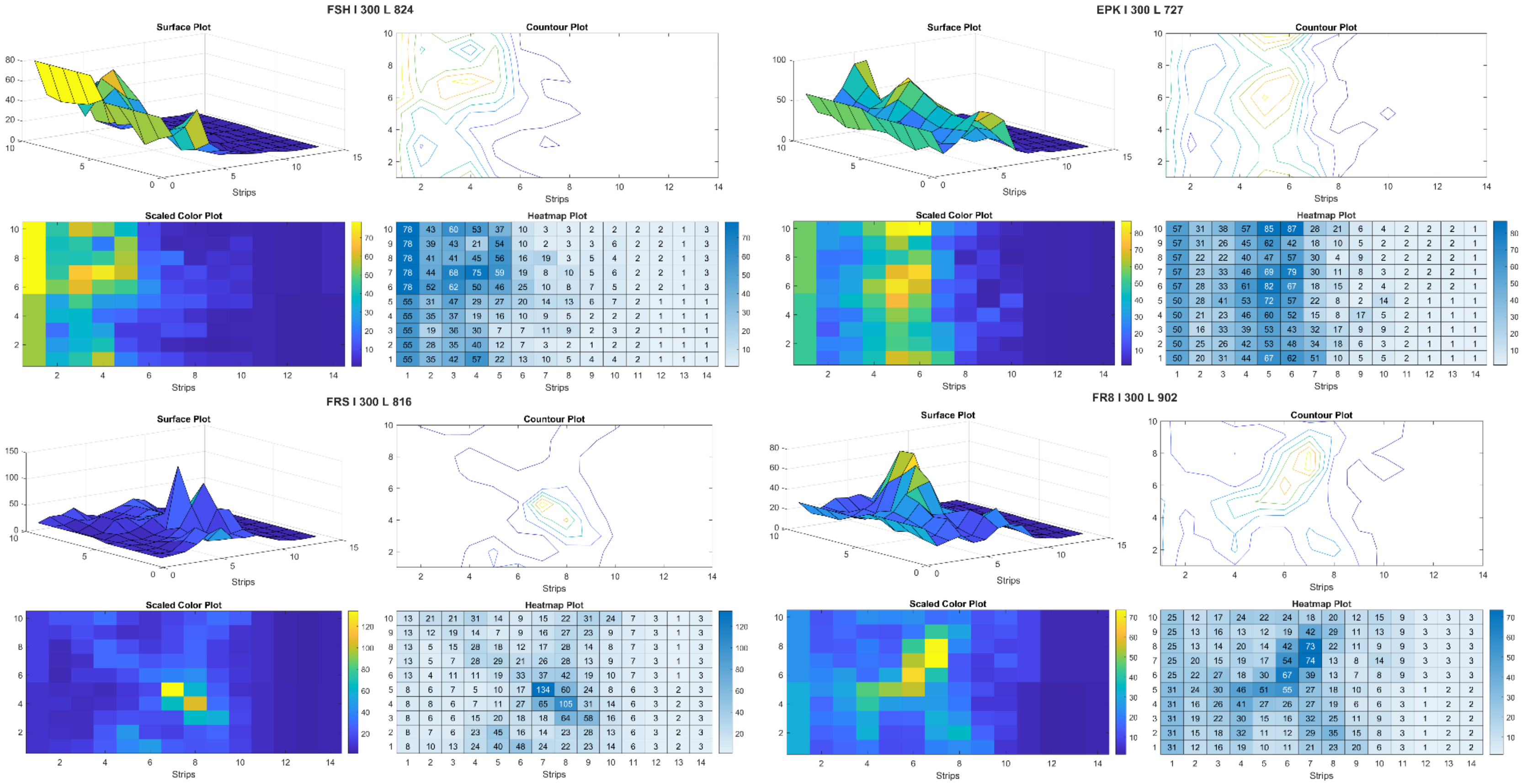


Figure A.31: Quad Plot Set 31– Ice Slicer 300 lb/lnmi LEFT, target strip 2-9, adjusted nominal 43 gm per 2 m²

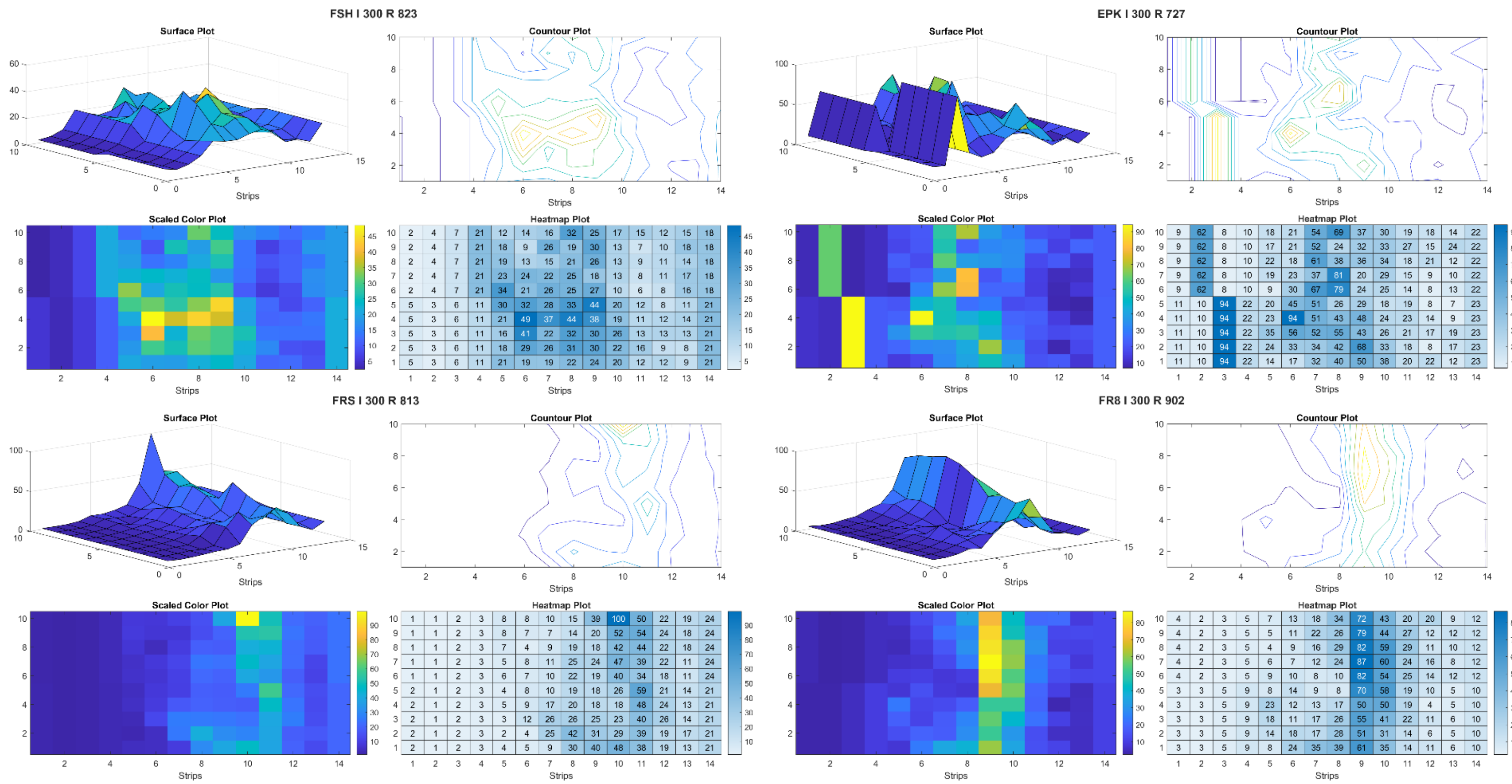


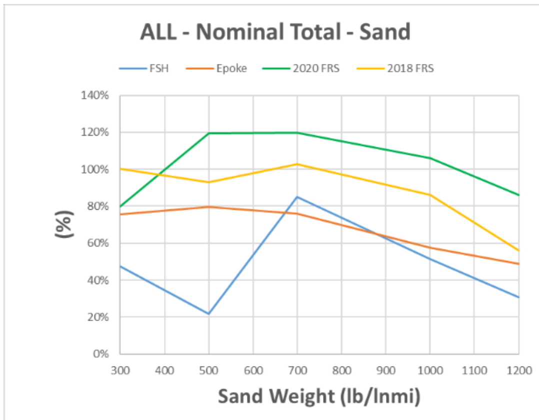
Figure A.32: Quad Plot Set 32– Ice Slicer 300 lb/lnmi RIGHT, target strip 6-13, adjusted Nominal 43 gm per 2 m²

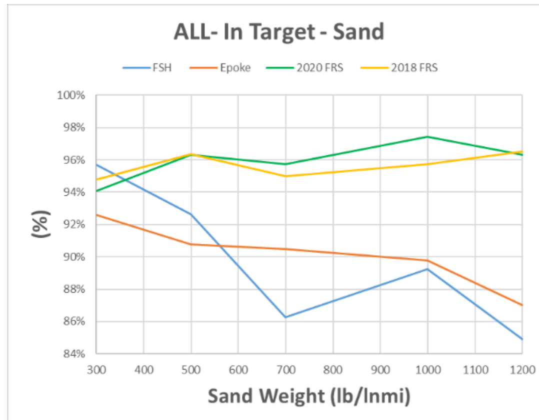
Appendix B: Tables and Plots of Test Results

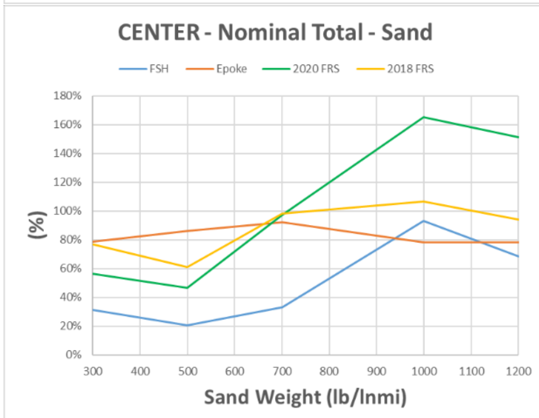
Table B.1: Percent material distributions

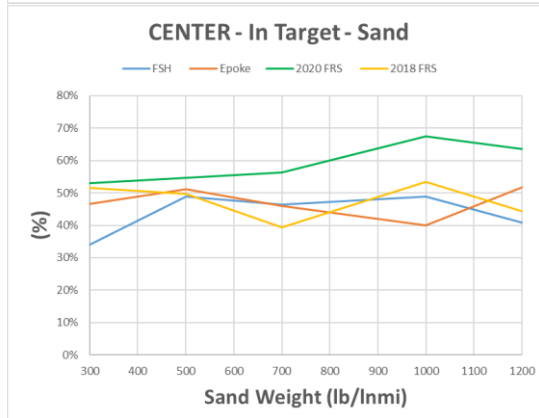
% of Nominal Total by Truck										
Sand							Ice Slicer			
All	**300**	**500**	**700**	**1000**	**1200**		***All***	***100***	***200***	***300***
FSH	47%	22%	85%	52%	31%		**FSH**	87%	74%	67%
Epoke	76%	80%	76%	57%	49%		**Epoke**	71%	94%	97%
2020 FRS	80%	119%	120%	106%	86%		**2020 FRS**	15%	63%	63%
2018 FRS	100%	93%	103%	86%	56%		**2018 FRS**	25%	63%	84%
Center	**300**	**500**	**700**	**1000**	**1200**		***Center***	***100***	***200***	***300***
FSH	31%	20%	33%	93%	69%		**FSH**	39%	18%	97%
Epoke	79%	86%	92%	78%	78%		**Epoke**	136%	80%	98%
2020 FRS	56%	46%	97%	165%	151%		**2020 FRS**	29%	18%	25%
2018 FRS	77%	61%	98%	107%	94%		**2018 FRS**	90%	36%	74%
Left	**300**	**500**	**700**	**1000**	**1200**		***Left***	***100***	***200***	***300***
FSH	23%	84%	77%	93%	81%		**FSH**	27%	85%	80%
Epoke	73%	73%	76%	78%	72%		**Epoke**	144%	82%	99%
2020 FRS	61%	96%	100%	126%	118%		**2020 FRS**	19%	26%	68%
2018 FRS	130%	114%	117%	107%	101%		**2018 FRS**	39%	70%	72%
Right	***300***	***500***	***700***	***1000***	***1200***		***Right***	***100***	***200***	***300***
FSH	38%	66%	34%	75%	77%		**FSH**	53%	82%	62%
Epoke	84%	74%	81%	74%	80%		**Epoke**	112%	78%	117%
2020 FRS	115%	75%	115%	107%	114%		**2020 FRS**	53%	103%	69%
2018 FRS	84%	104%	138%	103%	111%		**2018 FRS**	67%	89%	75%
Mean of Values							**Mean of Values**			
FSH	35%	38%	57%	78%	64%		**FSH**	52%	65%	77%
Epoke	78%	63%	81%	72%	70%		**Epoke**	116%	84%	103%
2020 FRS	78%	67%	108%	126%	117%		**2020 FRS**	29%	53%	56%
2018 FRS	98%	74%	114%	101%	90%		**2018 FRS**	55%	64%	76%

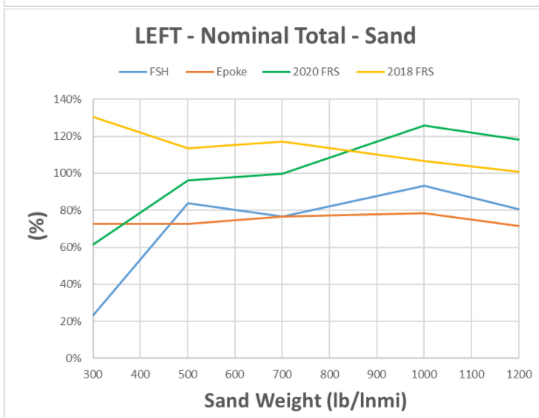
% in Target by Truck										
Sand							Ice Slicer			
All	**300**	**500**	**700**	**1000**	**1200**		**All**	**100**	**200**	**300**
FSH	96%	93%	86%	89%	85%		**FSH**	81%	90%	84%
Epoke	93%	91%	90%	90%	87%		**Epoke**	87%	90%	92%
2020 FRS	94%	96%	96%	97%	96%		**2020 FRS**	89%	94%	91%
2018 FRS	95%	96%	95%	96%	97%		**2018 FRS**	87%	96%	95%
Center	**300**	**500**	**700**	**1000**	**1200**		**Center**	**100**	**200**	**300**
FSH	34%	49%	46%	49%	41%		**FSH**	25%	43%	42%
Epoke	47%	51%	46%	40%	52%		**Epoke**	57%	61%	61%
2020 FRS	53%	55%	56%	67%	64%		**2020 FRS**	49%	37%	39%
2018 FRS	52%	50%	39%	54%	44%		**2018 FRS**	42%	44%	43%
Left	**300**	**500**	**700**	**1000**	**1200**		**Left**	**100**	**200**	**300**
FSH	69%	55%	78%	73%	76%		**FSH**	65%	71%	71%
Epoke	36%	37%	29%	78%	29%		**Epoke**	79%	75%	81%
2020 FRS	72%	87%	78%	85%	85%		**2020 FRS**	56%	72%	83%
2018 FRS	81%	84%	85%	86%	81%		**2018 FRS**	64%	70%	79%
Right	**300**	**500**	**700**	**1000**	**1200**		**Right**	**100**	**200**	**300**
FSH	64%	92%	83%	71%	74%		**FSH**	46%	65%	69%
Epoke	94%	43%	50%	67%	39%		**Epoke**	50%	69%	62%
2020 FRS	86%	85%	86%	85%	89%		**2020 FRS**	73%	76%	85%
2018 FRS	80%	85%	84%	81%	81%		**2018 FRS**	62%	88%	84%
Mean of Values							**Mean of Values**			
FSH	66%	72%	73%	70%	69%		**FSH**	54%	67%	66%
Epoke	67%	55%	54%	69%	52%		**Epoke**	68%	74%	74%
2020 FRS	76%	81%	79%	84%	84%		**2020 FRS**	67%	70%	74%
2018 FRS	77%	79%	76%	79%	76%		**2018 FRS**	64%	75%	75%

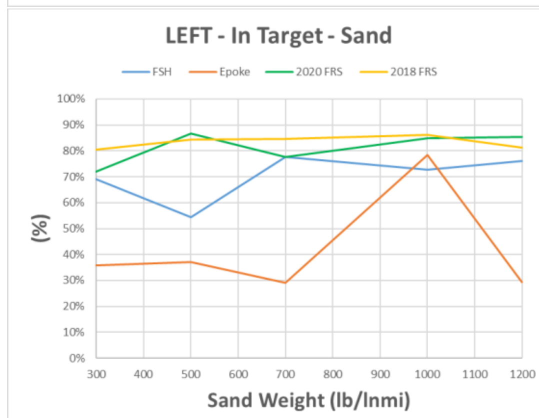

ALL - Nominal Total - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

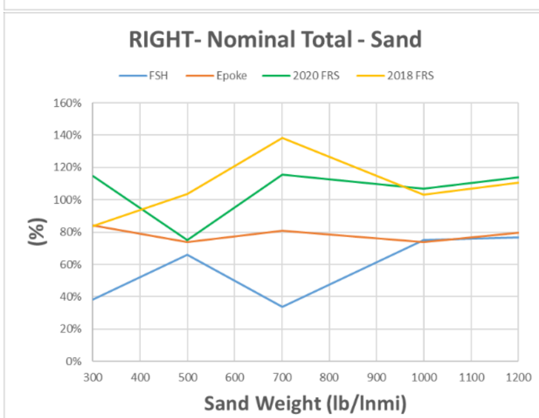

ALL- In Target - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

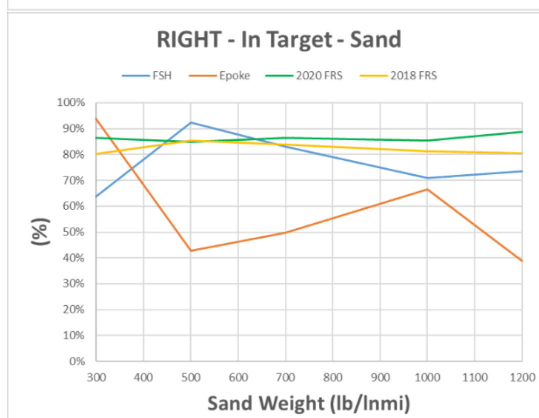

CENTER - Nominal Total - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

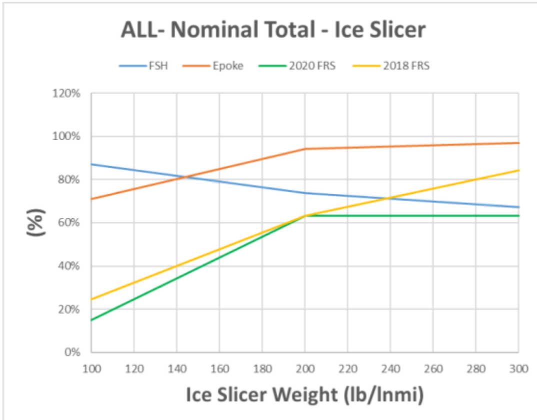

CENTER - In Target - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

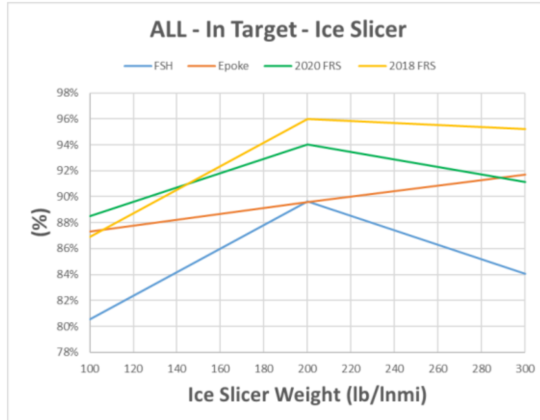

LEFT - Nominal Total - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

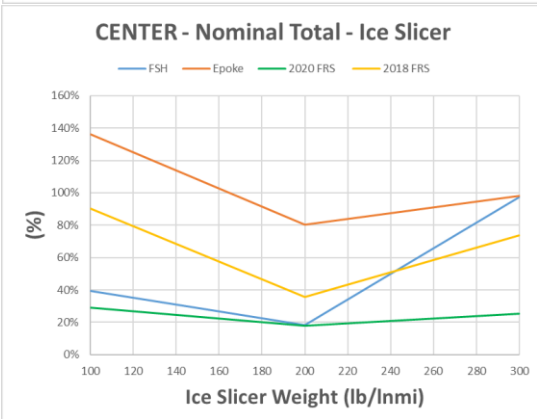

LEFT - In Target - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

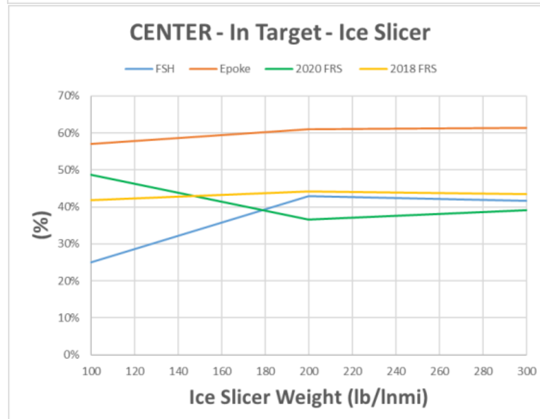

RIGHT- Nominal Total - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

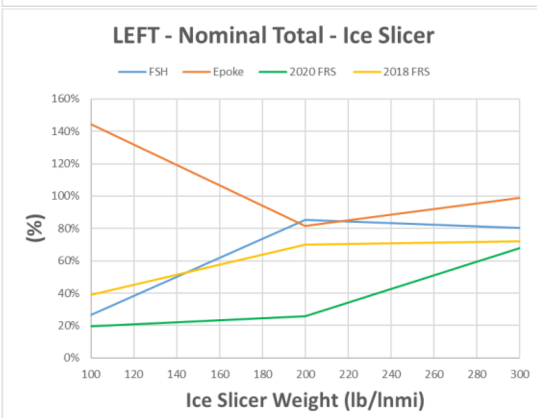

RIGHT - In Target - Sand
FSH
Epoke
2020 FRS
2018 FRS
(%)
Sand Weight (lb/lnmi)

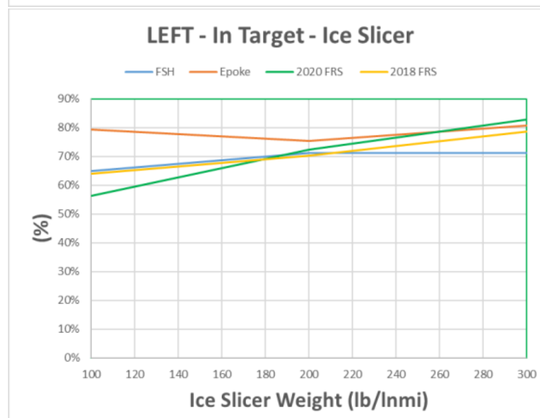

ALL- Nominal Total - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
120%
100%
80%
60%
40%
20%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

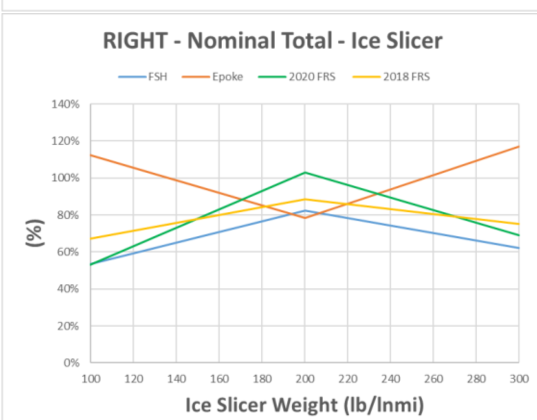

ALL - In Target - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
78%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

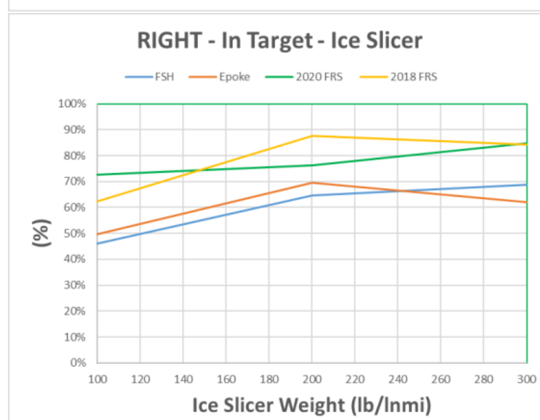

CENTER - Nominal Total - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
160%
140%
120%
100%
80%
60%
40%
20%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)


CENTER - In Target - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
70%
60%
50%
40%
30%
20%
10%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

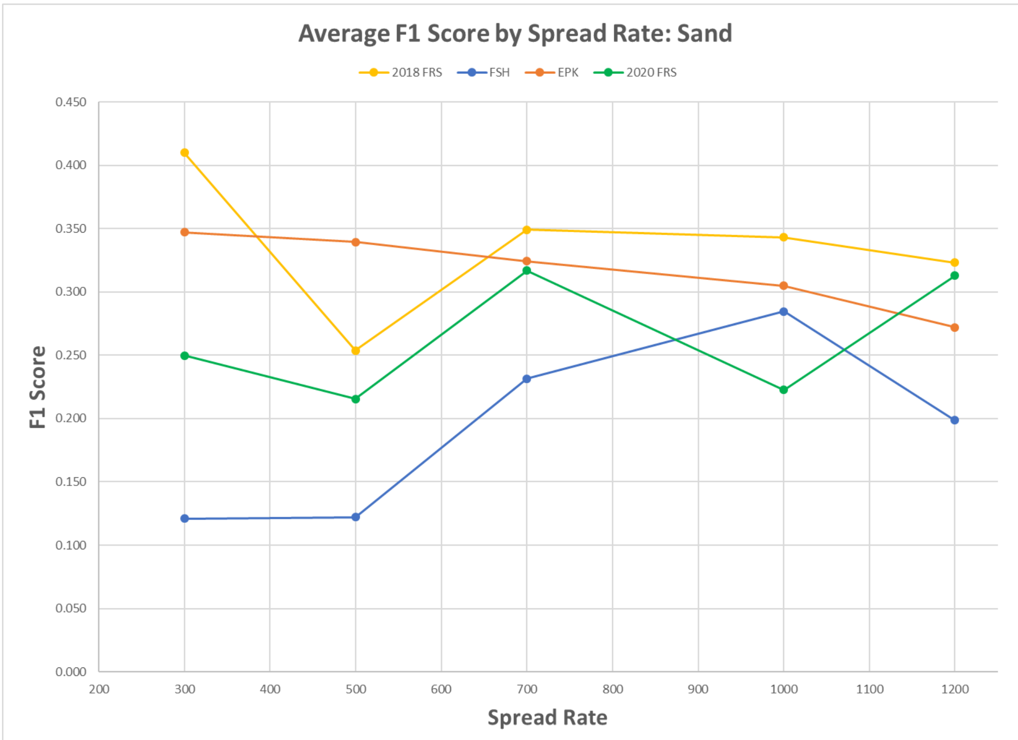

LEFT - Nominal Total - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
160%
140%
120%
100%
80%
60%
40%
20%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

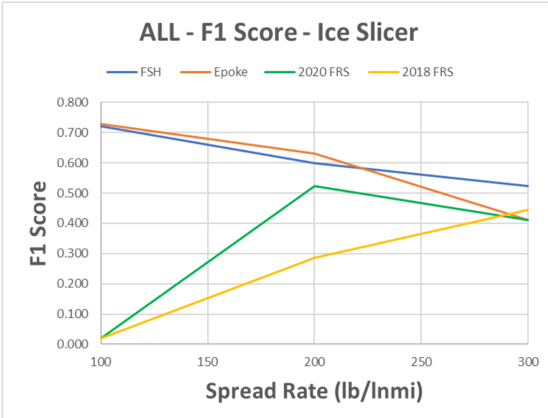

LEFT - In Target - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

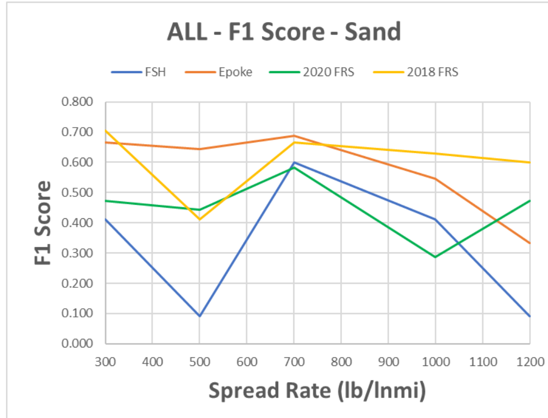

RIGHT - Nominal Total - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
140%
120%
100%
80%
60%
40%
20%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

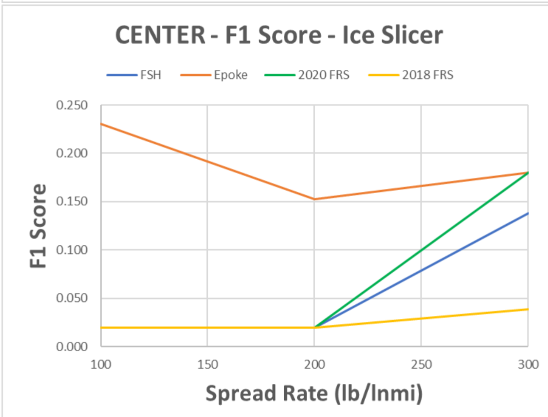

RIGHT - In Target - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(%)
100 120 140 160 180 200 220 240 260 280 300
Ice Slicer Weight (lb/lnmi)

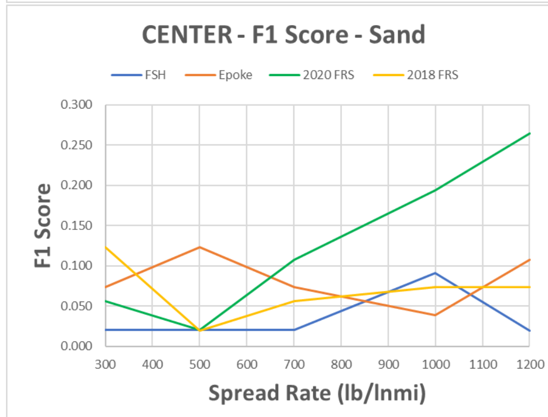
Appendix C: Plots of F1 scoring and spread rate

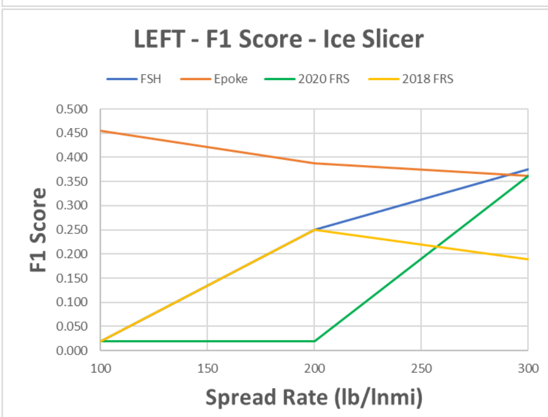


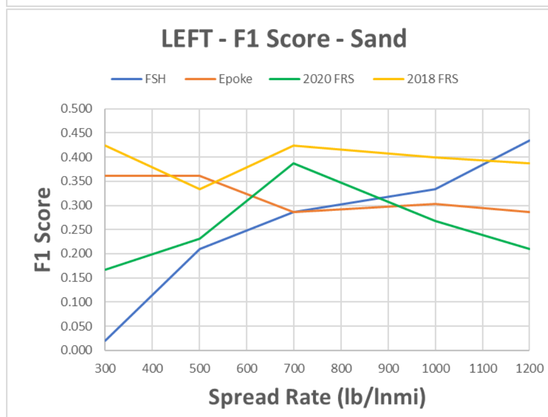

ALL - F1 Score - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
100
150
200
250
300
Spread Rate (lb/lnmi)

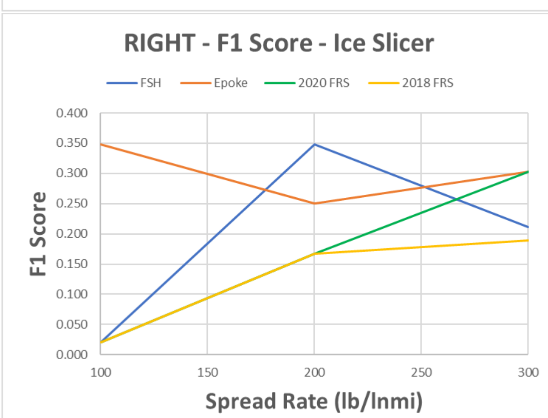

ALL - F1 Score - Sand
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
300
400
500
600
700
800
900
1000
1100
1200
Spread Rate (lb/lnmi)

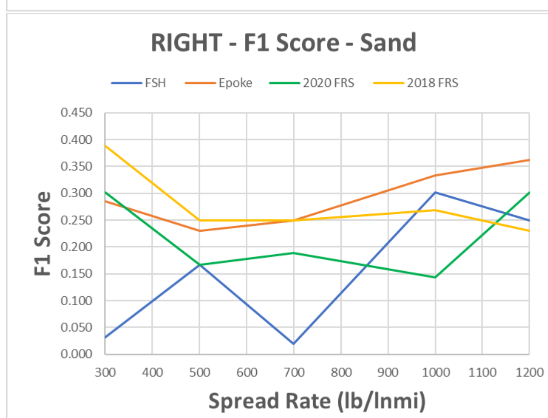

CENTER - F1 Score - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.250
0.200
0.150
0.100
0.050
0.000
100
150
200
250
300
Spread Rate (lb/lnmi)


CENTER - F1 Score - Sand
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.300
0.250
0.200
0.150
0.100
0.050
0.000
300
400
500
600
700
800
900
1000
1100
1200
Spread Rate (lb/lnmi)


LEFT - F1 Score - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.500
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
100
150
200
250
300
Spread Rate (lb/lnmi)


LEFT - F1 Score - Sand
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.500
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
300
400
500
600
700
800
900
1000
1100
1200
Spread Rate (lb/lnmi)


RIGHT - F1 Score - Ice Slicer
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
100
150
200
250
300
Spread Rate (lb/lnmi)


RIGHT - F1 Score - Sand
FSH
Epoke
2020 FRS
2018 FRS
F1 Score
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
300
400
500
600
700
800
900
1000
1100
1200
Spread Rate (lb/lnmi)