Characterization of Florida Landfills with Elevated Temperatures

2019

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STARS Citation

Joslyn, Ryan, "Characterization of Florida Landfills with Elevated Temperatures" (2019). *Electronic Theses and Dissertations*. 6323.
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CHARACTERIZATION OF FLORIDA LANDFILLS WITH ELEVATED TEMPERATURES

by

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B.S. University of Central Florida, 2017

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Spring Term
2019

Major Professor: Debra R. Reinhart

ABSTRACT

The occurrence of elevated temperatures within landfills is a very challenging issue for landfill operators to detect and correct. Little is known regarding the causes of elevated temperatures (ETs) and the number of landfills currently operating under such conditions. Therefore, the goal of this research was to determine which landfills within Florida have been impacted by ETs, and to develop a more complete understanding of the factors that may lead to these landfills becoming elevated temperature landfills (ETLFs).

Historical landfill gas wellhead data, waste deposition reports, and landfill site geometry were collected for 27 landfill cells through the FDEP OCULUS database and from landfill operators and owners. These data were evaluated to quantify the statistical characteristics that result in landfills becoming 'elevated' in temperature. Gas data included landfill gas temperatures, methane content, carbon dioxide content, and balance gas readings. Waste deposition information was gathered through solid waste reports for each landfill. Landfill site geometry was found through landfill permits, topographical landfill diagrams, and annual operation reports. Furthermore, landfill maps were created in ArcGIS to observe spatial distribution of ETs in landfills over time.

Upon analysis of the landfill gas wellhead data, it was discovered that 74% of studied landfill cells had ET readings; regulatory limits specify a maximum allowable gas temperature of 55°C (131°F). When studying the solid waste reports, it was discovered that 37% of landfill cells contained MSW ash; of these cells, 90% of them are considered ETLFs. Regarding site geometry, it was found that ETLF cells are on-average double the site area and approximately 20 feet deeper than the average non-ETLF cell. Furthermore, results suggest that heat propagation in most

landfills is limited; however, heat propagation is possible if gas wells are turned off for an extensive time period.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS/ABBREVIATIONS

ASP	Activated Sludge Process
Bal	Balance gas
°C	Degrees Celsius
CH_4	Methane
CO_2	Carbon Dioxide
ESRI	Environmental Systems Research Institute
ET	Elevated Temperature
ETLF	Elevated Temperature Landfill
°F	Degrees Fahrenheit
FDEP	Florida Department of Environmental Protection
ft	feet
GIS	Geographic Information System
IDW	Inverse Distance Weighting
LFGC	Landfill gas collection
LMOP	Landfill Methane Outreach Program
m	meter
MSW	Municipal solid waste
N_2	Nitrogen gas
NN	Natural Neighbor
Non-ETLF	Non-Elevated Temperature Landfill
NSPS	New Source Performance Standards
O_2	Oxygen

OK	Ordinary Kriging
OCULUS	Florida Department of Environmental Protection Electronic Document Management System
PAC	Powdered Activated Carbon
POTW	Publicly owned treatment works
SBR	Sequencing Batch Reactor
WTE	Waste-to-Energy

CHAPTER ONE: INTRODUCTION

Elevated temperatures (ETs) within municipal solid waste (MSW) landfills pose significant challenges to landfill operators and owners. Gas collection well temperatures greater than 131°F (55^{o}C) are considered elevated; these temperatures well exceed the range tolerable for micro-organisms and permit standards set by the Florida Department of Environmental Protection (FDEP) and regulations under the U.S. New Source Performance Standards (NSPS). Although most landfill operators receive variances allowing for the continued operation of their gas wells at temperatures greater than 131°F (in some cases getting variances for temperatures as high as 150-155°F), it is known that ETs can damage landfills in a variety of ways. For example, ETs can damage the structure of MSW landfill containment systems, impacting the hydraulic performance of composite clay liner systems (Aldaeef and Rayhani, 2014). In addition, ETs can impact the biological processes within landfills, inhibiting methanogenesis and thus the decomposition of waste (Øygard et al., 2005; Ruokojarvi et al., 1995). Other studies have reported increased leachate volume and leachate of greater organic strength. Furthermore, ETs can impair the gas extraction and leachate collection systems and contribute to problems such as slope instability and the release of toxic chemicals into the environment (Jafari et al., 2016).

Certain properties and reactants are necessary to produce ET conditions within landfills. These include the availability of a fuel, moisture, and an energy input. Fuel is provided by disposed waste organic matter present within the landfill. Energy input can be from biotic oxidation in the presence of oxygen, chemical reactions, or hot loads. Although oxygen intrusion through excessive vacuum applied to the landfill gas extraction system is a potential cause for temperature increase within gas collection wells (Greenwalt, 2016), most landfill operators reported limited occurrences of oxygen intrusion. When they did occur, it was usually for a very short time span.

In addition, microbial decomposition is unlikely to be a significant heat contributor in elevated temperature landfills (ETLFs), as microbes rarely thrive at temperatures above 70-75° C (158-167°F) (Nozhevnikova et al., 1999 and Zinder et al., 1984). Anaerobic decomposition is also unlikely to be a significant heat contributor in ETLFs, as the exothermic heat released from methanogenic reactions is quite low when compared to the heat produced from chemical reactions such as anaerobic metal corrosion and ash hydration and carbonation (Hao et al., 2017).

Therefore, abiotic constituents are increasingly considered to be drivers of exothermic chemical reactions within the landfill; these reactions have the potential to produce the ET readings recorded by operators of the landfill gas wells. Aluminum and iron are of concern due to the availability of these two metals within landfills. These metals can be present in bulk form (as aluminum cans, foil, or car parts) or as a component of incinerated MSW ash (Calder and Stark, 2010). These metals can undergo corrosion reactions within the landfill, releasing substantial amounts of heat.

Currently, the detection methods for ETs within landfills are limited and include measuring waste and gas temperature, gas composition (methane to carbon dioxide ratio), and leachate composition, as well as visual occurrences such as smoke emissions (Jafari et al., 2016). However, models are being developed to better explore the causes of ETs, informed by laboratory experiments and field testing.

Thus, it is imperative to study and analyze the characteristics that may lead to the onset of ETs, considering design and waste acceptance. For this reason, this study aims to characterize Florida landfills with and without ETs, noting the potential features that may result in an onset of ETs.

CHAPTER TWO: LITERATURE REVIEW

Included in this literature review are sections entitled Background Information, Requisite Conditions Leading to Elevated Temperatures, and Microbial Decomposition. These sections provide a brief review regarding terms necessary to know in order to understand the occurrence of ETs. In addition, these sections provide a review of technical literature with respect to decomposition of waste and basic conditions needed to promote ET scenarios. Also included are sections entitled Aluminum and Iron Deposition and Additional Metal Deposition. These sections expand on the impact that certain disposed materials may have on the creation of ET conditions through a mixture of equations and previous studies. The literature review ends with a segment on ArcGIS interpolation methods, which were utilized to create temperature contour maps.

Background Information

Between 2004 and 2010, there were approximately 840 landfill fires in the United States, occurring at MSW landfills throughout the country. Of these 840 fires, approximately 400 of them occurred at landfills with an active gas collection system, with many of these landfills reporting multiple fire incidents during the timespan (Powell et al., 2016). Landfill fires can occur at surface and subsurface depths (depths > 20 m); however, subsurface fire events are of importance because of their long duration and potential impact to the landfill liner and leachate structures (Jafari et al., 2016).

Understanding the complex occurrence of ETs requires definition of relevant terms (Reinhart, 2014):

- **Smoldering** – slow, low temperature (<100°C), flameless combustion, low oxygen concentration. Heat generation is sufficient to dry waste; polymer degradation and char oxidation drive combustion.
- **Ignition** – rapid temperature transition; exothermic and self-sustained combustion, followed by thermal explosion. The presence of heat, oxygen, and fuel leads to sustained combustion if auto-ignition temperature is reached.
- **Fire** – exothermic combustion initiated by a heat source sufficient to reach ignition temperatures.
- **Induction time** – time before fire initiation.
- **Pyrolysis** – destruction of chemicals by heat alone; includes hydrolysis, dehydration, depolymerization, and aromatization.
- **Combustion** –reactions of exposed fuel molecules at the solid surface with gas phase species.

Requisite Conditions Leading to Elevated Temperatures

Requisite conditions for ETs include the availability of a fuel (waste), moisture, and an energy input; the latter of which can be provided by biotic oxidation in the presence of oxygen, chemical reactions, or hot loads. The steps toward combustion include an increase in the temperature of the waste mass due to biotic degradation, pyrolytic decomposition of waste materials (e.g., paper), the escape of volatile compounds from the waste surface, diffusion of the pyrolyzed compounds from the solid surface into the gas phase, and gaseous and heterogeneous reactions at the waste surface (Buggeln and Rynk, 2002). The sources of heat, then, include chemical oxidation or decomposition into simpler molecules (biotic or abiotic); aerobic or anaerobic biotic degradation of waste; oxygen adsorption, chemical reactions, oxidative degeneration of fuel (slow pyrolysis), or oxidation of pyrolytic byproducts; and condensation of evaporated water (Yesiller et al., 2005). Abiotic oxidation yields more heat than biotic reactions but occurs at higher temperatures (Cossu and Stegmann, 2019).

Microbial Decomposition

In many cases the introduction of air is thought to cause elevated landfill temperatures as a result of aerobic decomposition of waste which releases considerable heat. Air may be introduced during the placement of MSW, but the oxygen within the air is quickly consumed near the landfill surface. Also, the open landfill cover allows for significant heat loss. A more likely source of air intrusion can be attributed to excess vacuum applied to the landfill gas collection system (Greenwalt, 2016). However, microbial decomposition is likely to be a limited heat provider in ETLFs, as the growth rate of microbes is inhibited at temperatures exceeding 70-75^{o}C (158-167°F) (Nozhevnikova et. al, 1999 and Zinder et al., 1984).

Anaerobic decomposition is also unlikely to be a significant source of heat because the exothermic heat released from methanogenic reactions is quite low when compared to the heat produced from aerobic decomposition, anaerobic metal corrosion, and ash hydration and carbonation (Hao et al., 2017).

Aluminum and Iron Deposition

Abiotic constituents are increasingly considered as drivers of chemical reactions within the landfill. Landfills receive aluminum and iron in elemental form from MSW and special wastes as containers, foil, car parts, and other processing waste. In addition, aluminum can enter a landfill from incinerated MSW, industrial waste (private industries), and from aluminum production facilities (as aluminum dross) (Calder and Stark, 2010). These two metals undergo corrosion reactions within the landfill, both of which release substantial amounts of heat. Corrosion reactions for elemental aluminum and iron deposition are shown in Equations 1 and 2 (Hao et., al 2017).

Elemental Aluminum:

$$Al + 3H_2O \rightarrow Al(OH)_3 + 3/2\ H_2 \qquad \Delta H = -15922\ \frac{kJ}{kg\ Al} \qquad (1)$$

Elemental Iron:

$$Fe + CO_2 + H_2O \rightarrow FeCO_3 + H_2 \qquad \Delta H = -1268\ \frac{kJ}{kg\ Fe} \qquad (2)$$

The extent of corrosion, and thus heat release, is a function of the surface area of the metal and the protective coatings surrounding the metal; therefore, the actual heat produced may depend on the waste and the environmental conditions present at each landfill (Hao et al., 2017). Although a large amount of aluminum metal is oxidized in incinerators, the baghouse dust/fines from an incinerator have a larger, more reactive surface area, as the protective coating surrounding the metal may be reduced or burned off completely (Calder and Stark, 2010). The amphoteric reaction of aluminum with alkaline water at a pH ≥ 8, is shown in Equation 3 (Calder and Stark, 2010).

$$Al + (OH)^{-1}{}_{aq} + 3H_2O \rightarrow Al(OH)_4{}^{-1} + 3/2\ H_2 \qquad (3)$$

As shown in Equation 3, alkaline co-reactants $(OH)^{-1}$ are needed for corrosion to occur. These are often present in landfills in the form of calcium carbonate ($CaCO_3$) and calcium oxide (CaO). $CaCO_3$ is found in much of the MSW disposed, including paper, cardboard, and construction materials. CaO is found in the lime added to the MSW incinerator process; thus, CaO is present in the fly ash that is disposed in the landfills (Calder and Stark, 2010). This provides another potential source for chemical reactions within the landfill, as the CaO reacts with water to form slaked lime ($Ca(OH)_2$). This slaked lime reacts with the abundant carbon dioxide (CO_2)

present in landfill gas to form $CaCO_3$. The production of slaked lime and calcium carbonate are also exothermic in nature, emitting heat with each reaction. The chemical equations for these two reactions are shown in Equations 4 and 5 (Hao et al., 2017).

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{4}$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{5}$$

The production of $CaCO_3$ increases the hydroxide content of water that it comes into contact with, causing the water to become alkaline. Therefore, when MSW ash is disposed in a landfill, the alkaline sources from this ash may lead to additional reactions with aluminum. In addition, even without the presence of CaO, if other metal oxides, such as magnesium oxide (MgO), sodium oxide (Na_2O), potassium oxide (K_2O), or aluminum oxide (Al_2O_3) are present in the ash, these oxides could hydrolyze when contacted with water to form their appropriate hydroxide forms. The hydroxide forms of the ash could then react with the aluminum disposed in the landfill. If the metal oxides do not hydrolyze with water, they could react with CO_2 to produce carbonates (Calder and Stark, 2010). This would still result in alkaline products, which could function as a reactant for the amphoteric reaction of aluminum to occur (Equation 3). For this reason, studies determining the impact of incinerator ash on ETs in landfills continue to be needed.

Iron reacts much slower in neutral or alkaline pH and does not produce water soluble reaction products. Consequently, iron does not have the same potential to produce substantial exothermic temperatures in most MSW landfills. Considering that CO_2 is a reactant for iron oxidation, as shown in Equation 2, and iron-containing MSW is prevalent, exothermic temperatures produced from iron oxidation could still occur even without the presence of incinerator ash (Calder and Stark, 2010).

In addition, as noted by Equations 1 and 2, hydrogen (H_2) is a byproduct of metal corrosion, which can be converted to methane (CH_4) by hydrogenotrophic methanogens using CO_2 present in the landfill gas. This reaction presents a significant problem for landfills, as it produces significantly more heat than aluminum corrosion. Due to the availability of CO_2 in landfill gas, this reaction has the potential to occur in landfills that receive substantial quantities of elemental aluminum and iron as special waste. Methane production by hydrogenotrophic methanogens reaction is shown in Equation 6 (Chynoweth, 1996).

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \Delta H= -20625\,\frac{kJ}{kg\ H2} \qquad (6)$$

Some additional examples of exothermic chemical reactions from aluminum and iron deposition are shown in Equations 7-12 (Moqbel et al., 2010):

Rust and hydrogen sulfide, oxidation of FeS:

$$2FeO(OH) + 3H_2S = 2FeS + S + 4H_20 \qquad (7)$$

$$4FeS + 7O_2 \rightarrow 2\ Fe_2O_3 + 4SO_2 \qquad (8)$$

Scrap iron and carbonates:

$$2H_2O + 5CO_2 + 4Fe \rightarrow 4FeCO_3 + CH_4 \qquad (9)$$

Aluminum dross:

$$2H_2O + 5CO_2 + Al_4C_3 + 12H_2O = 4\ Al(OH)_3 + 3CH_4 \qquad (10)$$

$$AlN + 3H_2O = Al(OH)_3 + NH_3 \qquad (11)$$

$$AlP + 3H_2O = Al(OH)_3 + PH_3\ 4Fe \rightarrow 4FeCO_3 + CH_4 \qquad (12)$$

It should be noted that almost every chemical reaction regarding aluminum and iron deposition requires water and some require CO_2 as reactants. Reducing pooling within a landfill is one preventative method that could affect these chemical reactions. In addition, for landfills accepting both MSW and MSW incinerator ash, leachate recirculation may exacerbate ETs, as leachate increases the ability for potentially alkaline water and metals to interact within the landfill (Calder and Stark, 2010).

Additional Metal Deposition

Beyond aluminum and iron, there are other elements found in MSW incinerator ash that may contribute to ETs. MSW that enters an incinerator contains a combination of organic materials (primarily kitchen waste), wood, paper, glass, and construction materials. The majority of organic substances are burned in the incinerator. Inorganic substances within the MSW ash includes silicon, metal oxides, aluminum, iron, calcium, and magnesium (Sun et al., 2016). In addition, smaller concentrations of heavy metals may be present, although often only in bottom ash (Dugenst et al., 1999). A study by Rendek et al. (2007) found that MSW bottom ash was composed of between 30-48% silicon oxide, 15-23% calcium oxide, and smaller traces of sodium and magnesium oxides. A study conducted by Anthony et al. (1999) found that coal combustion fly ash contains large quantities of calcium oxide, sulfur trioxide (SO_3) and silicon dioxide (SiO_2) (36-42%, 16-19% and 11-14%, respectively). Therefore, metal composition of incinerated ash samples differs depending on the source of the ash and the process by which it was generated. Regardless, hydrolysis reactions with the metal oxides present in both types of ash could generate significant energy, producing CO_2 and H_2 (Calder and Stark, 2010).

Furthermore, if certain reduced metals are exposed to acids present within landfill leachate or pooling water, an exothermic reaction can occur in which the metal forms a metallic salt by stripping the hydrogen from the acid. This results in hydrogen gas as a byproduct, and, as stated earlier, emits significant heat. Reduced metals that are present in MSW include aluminum, zinc, chromium, iron, cadmium, cobalt, nickel, tin, and lead (Environmental Protection Agency, 2014).

For this reason, it is imperative to understand the characteristics of the ash disposed within each landfill, as well as the characteristics of the landfill itself.

ArcGIS Interpolation Methods

ArcGIS software was utilized in this study to determine whether heat generation and propagation (heat movement) occurs in ETLFs. Similarly, methane to carbon dioxide (CH_4 to CO_2) ratio was analyzed to determine the impact that ETs may have on CH_4 and CO_2 quality. Landfill maps were created to visually show these changes in temperature and CH_4 to CO_2 ratio over time. To accomplish this, interpolations were conducted in the Environmental Systems Research Institute's (ESRI's) ArcGIS software using average annual temperatures and CH_4 to CO_2 ratios compiled for each landfill to exhibit the temperatures and CH_4 to CO_2 ratios experienced at each section of a landfill.

ArcGIS contains multiple interpolation techniques as part of its "Spatial Analyst Tools" menu, which is found in ArcCatalog. Interpolation techniques in this menu include: Inverse-Distance Weighting (IDW), Ordinary Kriging (OK), Natural Neighbor (NN), and Spline. Each of these methods are programmed to interpolate data between points differently. Thus, before temperature contour maps could be generated, the appropriate interpolation mechanism had to be selected.

Following an extensive environmental engineering literature review, we discovered that few tests have been conducted using geographic information systems (GIS) to map and interpolate landfill gas well temperatures over time. Rather, most studies utilized GIS to map groundwater monitoring data to determine both the depth of groundwater and the potential pollution risks that exist at each groundwater source.

A few studies were conducted over ten years ago regarding the design and mapping of landfill gas systems and their temperature and gas characteristics. One particular study assessed the spatial variability of greenhouse gas emissions from landfills using ArcGIS (Perera et al., 2004). This study applied the Ordinary Kriging interpolation technique on a 2-D horizontal plane to locate potential "hotspots" of gas emissions at a landfill, measuring and modeling gas concentrations at the surface of the landfill. Thus, "hotspots" in this study indicated high strength areas of landfill gas (in terms of flow) rather than the temperature of landfill gas. Another study conducted by Börjesson et al. (2000) utilized Ordinary Kriging to map methane emissions from landfill surfaces.

However, as stated earlier, most studies conducted groundwater modeling analysis using GIS. One study tested eight spatial interpolation models to replicate the groundwater levels in the Wuwei oasis, which is located in northwest China. This study concluded that Ordinary Kriging was the optimal interpolation technique, although it did mention some drawbacks due to the "smoothing effect" associated with Ordinary Kriging (Yao et al., 2014). This smoothing effect refers to the fact that Ordinary Kriging often overestimates small values and underestimates large values (Yao et al., 2014).

Another study conducted by Noori et al. (2013) tested the spatial variability of groundwater levels in the Saveh-Nobaran aquifer during different meteorological periods. This study tested four interpolation techniques (Kriging and IDW included), evaluating their effectiveness based on root mean square error (RMSE), mean absolute error (RAE), and the R-squared (R^2) value. Upon completing the groundwater-level maps (composed of 59 groundwater wells) and interpolating the maximum, average, and minimum water levels for the different meteorological periods at each well, it was found that the Kriging was much more effective than IDW, and very similar in effectiveness to Co-Kriging, which is not an option in ArcGIS (Noori et al., 2013).

As stated earlier, risk assessment tests were also conducted for groundwater sources using different spatial representation tools. A study conducted by Rabah et al. (2011) tested the accuracy of spatial representation tools (IDW, Kriging, and Spline) with reference to chloride concentrations found at groundwater wells located in the Gaza Strip. Using regression analysis and other statistical methods, it was found that Kriging produced the most accurate model to predict groundwater level and chloride concentration within the groundwater wells (Rabah et al., 2011).

Therefore, with these studies in mind, Ordinary Kriging was selected as the interpolation technique used to create the temperature contour maps and CH_4 to CO_2 ratio contour maps. A step-by-step description of the process conducted to create the interpolations maps is found in the Methodology.

Summary

Information regarding the causes of ETs in landfills is accumulating through current studies and technical literature; however, observational research regarding the number of landfills operating under such conditions is limited. Little research has been conducted on ETLFs on a statewide-level, comparing the differences between landfill design, solid waste acceptance, leachate treatment, and landfill gas reports and the impacts that these landfill characteristics may have on the initiation of ETs. Therefore, the goal of this study was to determine which landfills within Florida have exhibited ETs, and to develop a more complete understanding of the factors that may lead to ETs.

Furthermore, literature regarding the spatial distribution of temperatures and gas quality over time within a landfill is limited. For this reason, temperature contour maps and CH_4 to CO_2 ratio contour maps were created for four ETLFs throughout Florida.

Therefore, past literature provided important knowledge regarding conditions that may lead to ET generation in landfills, as well as chemical and biological reactions that create heat within landfills. Some of these, such as aluminum and iron deposition proved important to this study.

CHAPTER THREE: METHODOLOGY

Overview

This thesis focuses on ash as a probable cause of ETs because of the relatively common practice of combusting waste and disposing of the ash in landfills. In Florida, the most recent waste data provided on the Florida Department of Environmental Protection (FDEP) website included the following statistics for 2017: over 45 million tons of MSW were collected and managed; over 21 million tons of this waste (48%) was landfilled, while 42% of the waste was recycled. The remaining 10% of waste was combusted within Florida's 12 incinerators, which accounted for over 4.7 million tons of waste. Thus, the majority of waste is landfilled (58%), as combusted MSW is often placed in Class I landfills or disposed of in an ash monofill.

The amount of MSW managed has significantly increased on a yearly basis between 2012 and 2017. For example, 38% more MSW was collected and managed in 2017 than in 2012. Due to the increase of MSW collected, the total tonnage landfilled has also sharply increased; 37% more waste was landfilled in 2017 as opposed to 2012. Recycling has also increased due to more MSW being managed; between 2012 and 2017, almost 50% more in recycling tonnage was reported. In contrast, MSW combustion has stayed relatively constant, fluctuating minimally in tonnage combusted in most years. Year-by-year tonnage numbers regarding Florida MSW management practices are shown in Figure 1.

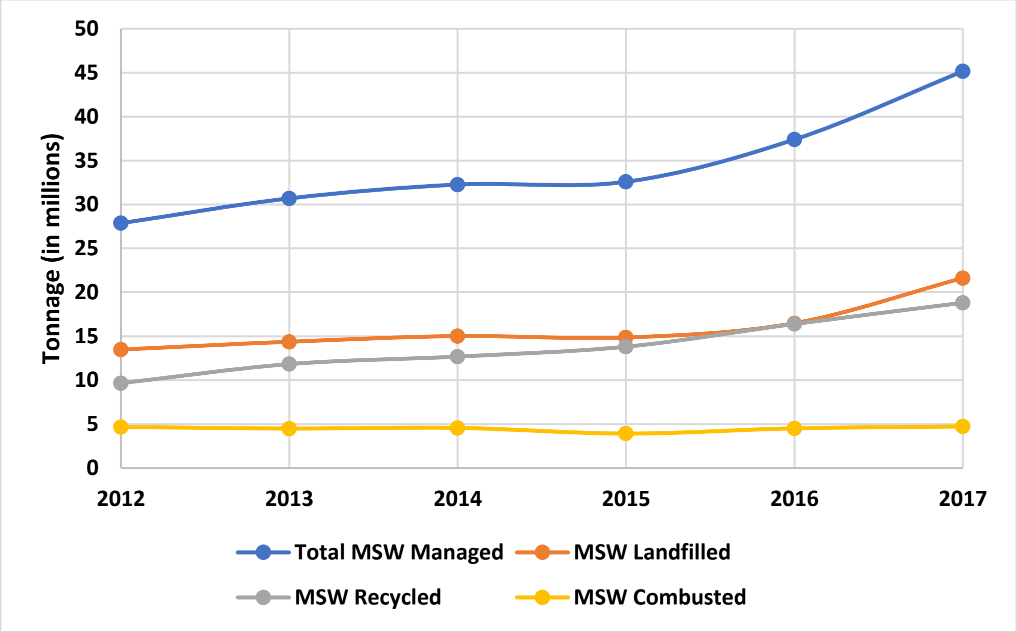


Figure 1: Florida MSW Management Practices

The percent of MSW managed with each disposal method (landfilling vs. recycling or combustion) was also calculated on a yearly basis; results of this are exhibited in Figure 2. Using this criterion, it appears that the percent of MSW recycled is increasing, while the percent of MSW landfilled has stayed relatively constant between 2012 and 2017, with slight decreases between 2014-2016. In contrast, combustion has decreased significantly when compared to the other disposal methods. This is probably because there are limited combustion facilities in Florida, and new combustion facilities are rarely constructed. Thus, the amount of tonnage combusted may be similar year-by-year; however, the percent of MSW combusted has decreased as the total amount of MSW being managed has increased on a yearly basis.

However, the amount of waste combusted in Florida is greater than the national average. A study conducted by the Environmental Research and Education Foundation (EREF) in 2016 concluded that approximately 347 million tons of MSW was managed in the United States by MSW management facilities in 2013. Most MSW was directly landfilled, accounting for 64% of total waste, whereas recycling accounted for 21% of waste management. About 9% of waste was combusted in waste-to-energy (WTE) facilities (EREF, 2016). This is much less than what was reported for Florida in 2013 (14.6%); thus, it appears that MSW is combusted to a greater degree in Florida when compared to the national average.

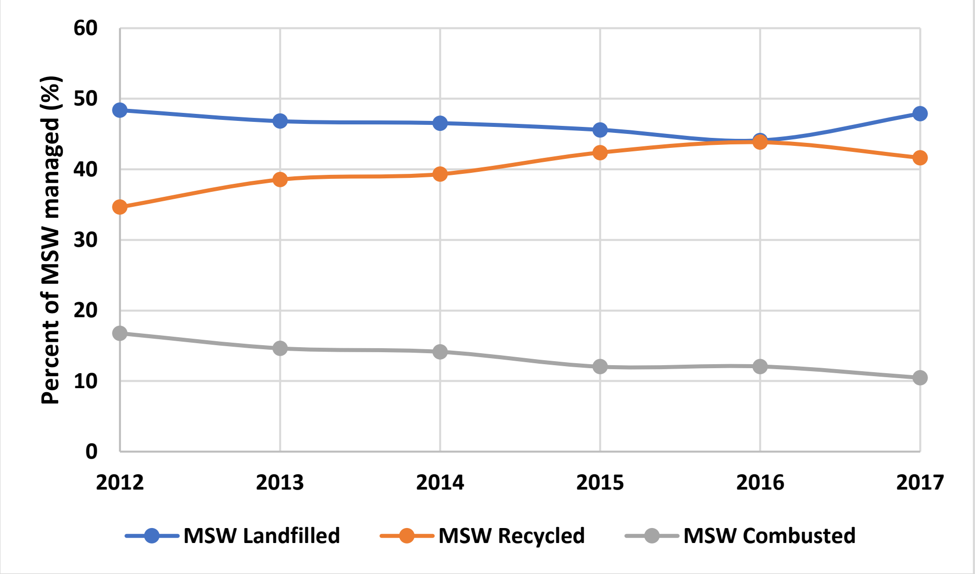


Figure 2: Percent of Florida MSW managed with each disposal method

Historical leachate, gas temperature, and gas composition data were examined for 22 landfill cells located throughout the state of Florida. Temperature exceedances were also compiled for 5 additional landfills; however, gas composition data was not available for those landfills. For the 22 landfill cells, the following information was gathered: (1) wellhead temperatures and wellhead gas composition (methane, carbon dioxide, balance gas, and oxygen) readings, (2) quantity of MSW and ash residue disposed, (3) landfill design characteristics (total landfill area, landfill depth, and waste-in-place), (4) leachate treatment methods, and (5) heat propagation over time. Overall, this information can be used to identify potential differences between non-ETLFs and ETLFs and to determine probable causes of ETs.

Data Collection

Several sources were used to obtain these historical data. The primary source of data was FDEP's public electronic document management system, OCULUS. This system provides public access to permit information, well logs, and inspection records for landfills and municipalities throughout the state. Data that can be accessed through the search catalog includes information regarding air quality, water quality, solid waste disposal, hazardous waste, and more. A detailed list of all Florida landfills was obtained through the Landfill Methane Outreach Program (LMOP) database; this list was then filtered to only include landfills with gas collection systems. Using the filtered list, gas-well monitoring data, leachate treatment methods, and solid-waste reports were compiled for the remaining landfills using the OCULUS database. If OCULUS did not have information for a particular landfill, landfill owners and operators were contacted to provide the missing data.

Case Study Analysis

A detailed landfill analysis was conducted at a local Florida landfill, referred to as Landfill N in this study. This landfill has had ETs since 2007 in an area that is approximately 25 acres; this area is located on the west side of the ~115-acre north cell. A mixture of wastewater treatment facility biosolids and coal ash (N-Viro) was used as alternative daily cover in this portion of the cell and was thought to be the cause of the ETs. To research the potential impacts of the deposited material, two 30-cm exploratory wells were drilled 90 ft deep into this ET zone using a bucket auger. Waste samples were collected during the drilling process at intervals of 1.5 m and tested at the UCF environmental engineering laboratory. Infrared thermometers were also used to measure the temperature of the extracted waste. In addition, temperature was recorded below the landfill liner to determine whether the geomembrane was being exposed to dangerous levels of heat.

According to a study conducted by Jafari et al. (2014), the service life of a geomembrane can be negatively impacted by temperatures between 60-80°C (140-176°F). The same study also stated that high-density polyethylene (HDPE) geomembrane manufacturers do not recommend temperatures greater than 57°C (135°F); HDPE is often used as a component of the landfill liner system. In our study, to test the temperature at the landfill liner, a thermocouple wire was attached to a leachate collection system jet cleaning hose, which was transported by the jet nozzle into a header pipe and placed beneath the ET zone.

Gas, waste, and leachate data analysis was also conducted for this landfill. In addition, a sample of the biosolids/ash mixture was collected to test its permeability and elemental composition. Permeability was tested using the Falling Head Test, which measures the hydraulic conductivity of a soil sample. Elemental composition was measured using X-ray Fluorescence to determine the most abundant elements found within the biosolids/ash mixture.

Gas Analysis

As mentioned above, gas-well temperature and composition data were collected for the 22 Florida landfills via OCULUS and landfill owners/operators. Once collected, a detailed analysis process was conducted. Monitoring data were ordered by date, with duplicate data points removed to avoid skewing gas-well temperatures or gas composition information. In some cases, numerous readings were collected per day; these were dealt with on a case-by-case basis to determine if they were duplicates. Temperature, methane (CH_4), carbon dioxide (CO_2), methane to carbon dioxide ratio (CH_4 to CO_2 ratio), balance gas, oxygen (O_2), and well vacuum readings were all analyzed to find correlations between gas temperatures and gas composition. These readings were averaged on a monthly, quarterly, and yearly basis to determine the change in these values over time.

Special Waste Acceptance

Solid waste reports were also compiled for each landfill to determine whether ash or other special wastes were disposed in each landfill. This information was collected by researching solid waste reports provided in the OCULUS database. These reports listed the tons of Class I and Class III waste, ash residue, and other wastes that were placed in each landfill on a monthly basis. Additional information regarding the composition of "other wastes" was also acquired. This waste could include contaminated soil, special waste, and construction and demolition debris among other things. Further analysis was conducted to determine the correlation between ash disposal and wellhead temperature.

Landfill Design

Investigation of landfill design characteristics was also completed. This included recording the following characteristics for each landfill: landfill geometry, waste-in-place, and leachate treatment methods utilized. Landfill geometry comprises of design specifications such as: total site area, the area in which waste is currently disposed, design landfill depth and current landfill depth. Waste-in-place was tabulated to determine the total landfill design capacity versus the landfill capacity currently used. Leachate treatment methods were identified to determine whether leachate was treated on-site or off-site. The majority of landfill design information was gathered through the OCULUS database; however, in some cases, landfill owners and operators were contacted to provide missing details.

Heat Generation and Movement/ Impact of Temperature on Gas Quality

Heat generation and propagation over time was analyzed for four ETLFs using ArcGIS, a geographic information system, through the creation of maps exhibiting the spatial distribution of temperatures. Models of each landfill were created by georeferencing TIFF files of the landfill maps with basemaps found on ArcGIS; landfill maps were found within the OCULUS database. The basemap is a world view utilizing the WGS 1984 Web Mercator Auxiliary Sphere coordinate system. This step was necessary to ensure that each landfill map was correctly aligned with the world view version.

Each individual gas well was added by matching the well markings located on each landfill map to create a 2-D representation of the corresponding landfill. Well names were added for each of the well locations using the OCULUS landfill maps to ensure that the wells corresponded to the correct location. The annual average temperature for each gas well was then entered and data were interpolated between the wells to create temperature contours. As mentioned in the Literature Review, the Ordinary Kriging interpolation method was chosen based on the recommendation of past landfill gas and groundwater-depth modeling studies. This exercise was repeated over the timeframe of data availability to examine the generation and movement of heat over time and to determine whether heat had propagated from hot sections of the landfills to cooler section of the landfills.

Similarly, gas quality was also analyzed for the four ETLFs using ArcGIS. CH_4 to CO_2 ratio contour maps were created using the same steps listed above. Average annual CH_4 to CO_2 ratios were entered for each individual gas well and then interpolated to determine the impact that ETs may have had on CH_4 to CO_2 ratios within each landfill. Again, Ordinary Kriging was utilized to create the CH_4 to CO_2 contour maps.

CHAPTER FOUR: CASE STUDY LANDFILL

Background Information

A detailed landfill analysis was conducted on a Florida landfill (Landfill N) that has been experiencing ETs for over ten years. ETs have been observed in gas wells on the west side of the ~115-acre north cell in an area that is approximately 25 acres in diameter. This particular landfill disposed of wastewater treatment facility biosolids and coal ash (N-Viro) as an alternative daily cover in this ~25-acre area; it is hypothesized that this is the cause of the ETs.

The investigation included (1) data mining from gas and leachate qualitative and quantitative measurements supplied by landfill operators to identify when the ETs began and how they have progressed, (2) gas quality from impacted and non-impacted wells (serving as controls), (3) impact of depth on landfill temperatures using exploratory wells, (4) analysis of the biosolids/ash material and (5) analysis of leachate quality.

Temperature and gas composition analysis will be discussed in detail in Chapter Five, where gas information from this landfill will be compared with information collected from other Florida landfills.

Depth Analysis

To determine the potential impact that landfill depth has on the potential for ET conditions, two 30-cm exploratory wells were drilled 90 ft into the ET zone. Infrared thermometers were used to measure the temperature of the extracted waste. In addition, temperature was tested below the landfill liner to determine whether the geomembrane was exposed to dangerous levels of heat.

As shown in Figure 3, temperatures were elevated in the waste mass between 40 and 90 ft below the surface for both exploratory wells, with temperatures reaching nearly 200°F in one of the wells. However, it was discovered that the liner system was not exposed to ETs; this is likely because the subsurface serves as an effective heat sink and leachate flow removed excess heat generated within the waste mass.

As evident by the results from Figure 3, there appears to be correlation between depth and temperature. Gas temperatures appeared to follow a “belly curve”, in which temperatures were greatest at approximately 50% depth. This supports data gathered from a study conducted by Yesiller et al. (2005), which focused on four landfills throughout the U.S. and Canada. In this study, minimum temperatures were found along the surface of the landfills; the gas temperatures here were affected by ambient air and changed seasonally. Maximum temperatures were located near the center of the landfill, peaking at around 50% depth rather than at the bottom of the landfill (Yeşiller et al., 2005). A “belly curve” similar to the one found in Figure 3 was also recorded in Yesiller’s study of temperature versus depth for vertical arrays.

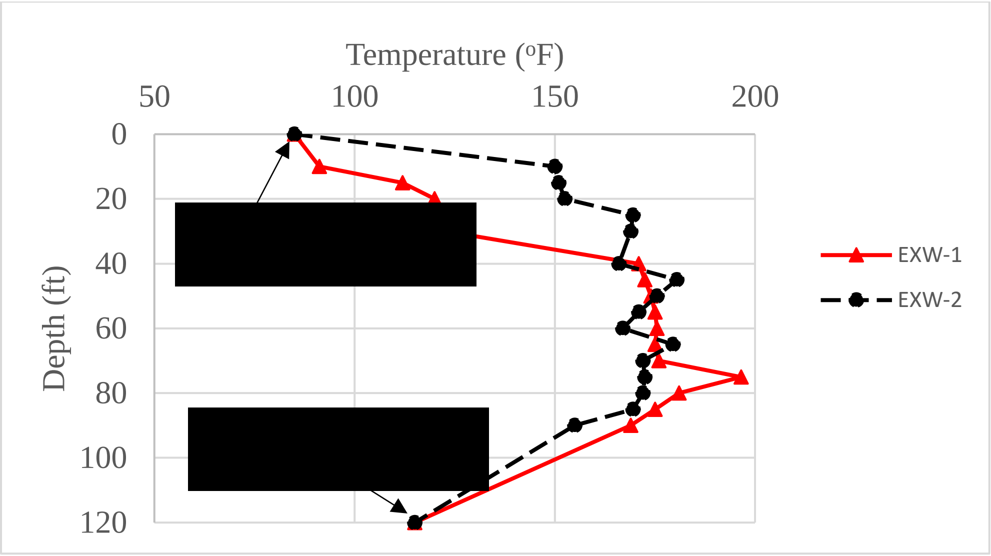


Figure 3: Temperature vs. Depth in Landfill N

N-Viro Analysis

A sample containing a mixture of wastewater treatment facility biosolids and coal ash (N-Viro) was collected from Landfill N and analyzed. As mentioned in the Literature Review, composition of MSW ash differs depending on the source of the ash and the process from which it was generated. In order to evaluate ponding effects of the biosolids, permeability analysis was performed using the Falling Head test. Results indicated an average hydraulic conductivity of 4×10^{-4} cm/sec; this value is similar to that expected for landfilled waste (LANDSS, University of Southampton).

The biosolids/ash sample was also characterized using X-ray Fluorescence to understand the elemental composition. The four most abundant elements found, excluding carbon, were calcium (48% by weight), iron (19%), silicon (10%), and aluminum (7%). The aluminum and silicates presumably originated in the coal ash and are likely involved in exothermic reactions leading to ETs.

Leachate Characterization

Landfill leachate quality and temperature at the landfill liner was also investigated at Landfill N. This was conducted to explore the effects of ETs on leachate quality and whether the geomembrane was in jeopardy due to exposure to heat.

To facilitate the testing of temperature at the landfill liner, a thermocouple was positioned in a header pipe located beneath the ET area by using a leachate collection system jet cleaning hose. The thermocouple was left overnight, and a temperature of 115.8°F was measured the following morning, which is significantly below waste temperatures. Thus, it was concluded that the geomembrane was not in jeopardy, likely because the subsurface is a heat sink and the leachate flow removed excess heat generated within the waste mass.

Leachate quality data were obtained via the OCULUS database. The concentration of organic compounds, particularly ketones including acetone, butanone and aromatic compounds such as ethylbenzene, toluene, and xylene prior to ETs in the north cell (2005-2008) was compared to data collected during the period where ETs were observed (2008-2012). As shown in Figure 4, there was a significant increase in the concentration of all of these organic compounds during the period of ETs in the landfill, supporting the possibility of pyrolysis of organic waste.

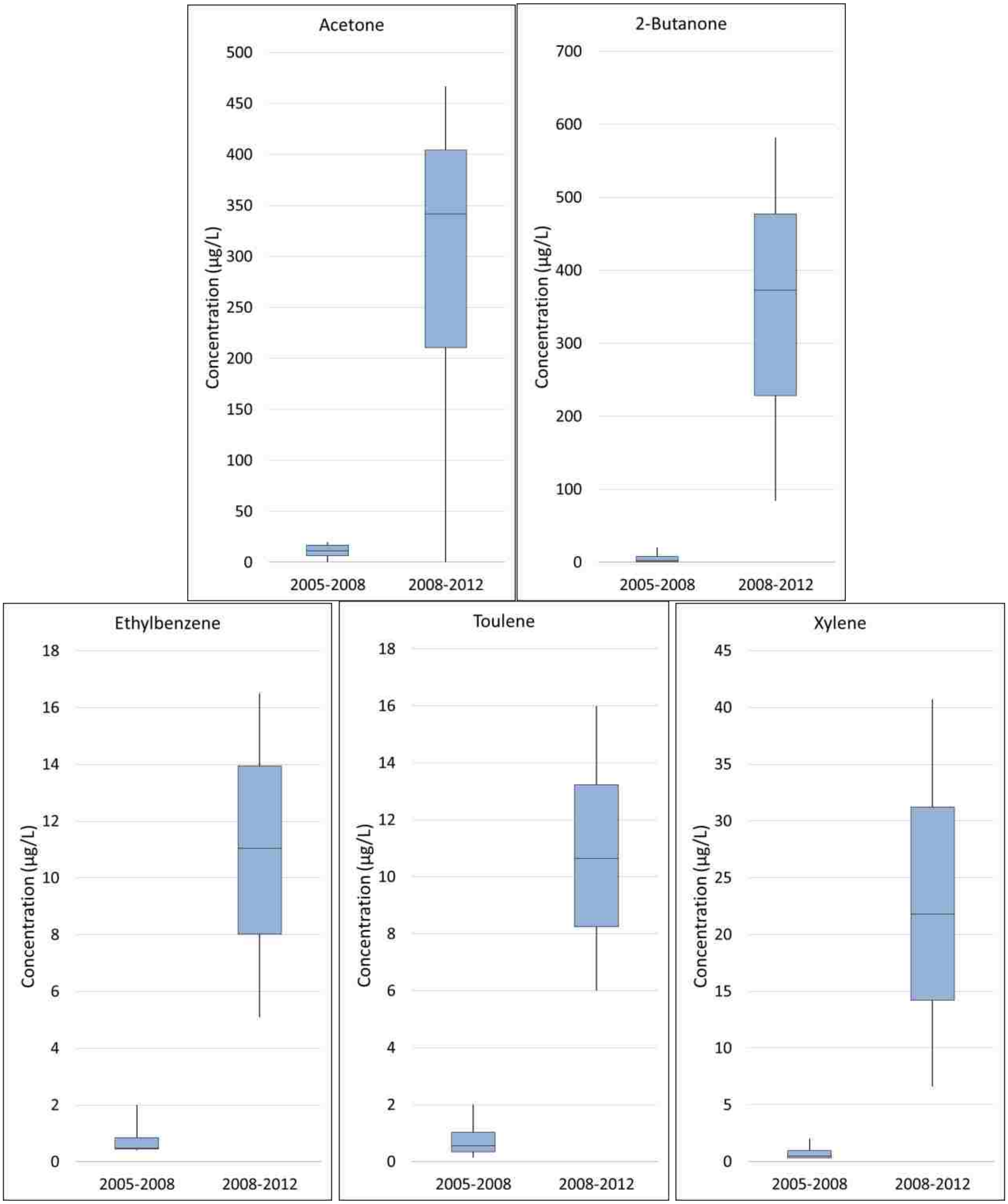


Figure 4: Comparison of ketones (acetone and butanone) and aromatic compounds (ethylbenzene, toluene, xylene) concentrations in the landfill leachate prior (2005-2008) and during (2008-2012) the period of elevated temperatures

CHAPTER FIVE: RESULTS AND DISCUSSION

Historical Gas Data Analysis

A total of 27 Florida landfill cells were studied regarding landfill gas well temperature and waste deposition. Monthly landfill gas well monitoring data was available for 22 of these landfill cells either through the OCULUS database or through landfill operators; the other five landfill cells were evaluated using exceedance data, which provides a semi-annual summary of the landfill gas well system. Of the 27 landfill cells, 74% had temperatures greater than 131°F (55°C). However, as the data for five landfill cells were limited to temperature exceedance information, they could not be evaluated further, as exceedance reports do not provide data regarding gas composition or specific temperature for each gas well. Thus, the following discussion will be focused on the 22 landfill cells with which monthly landfill gas well-head data (including gas temperature, gas flowrates, and gas composition) were provided.

Table 1 provides a summary of available temperature data and the frequency at which gas temperatures exceeded 131°F (55°C) for all 22 analyzed landfill cells. Names of the studied landfills have been removed and replaced with a lettering system "A to U" for anonymity. Note that there are two landfill J's; these are two separate landfill cells located in the same landfill.

Of the 22 landfill cells researched, 10 cells had ETs at over 5% of the wells. When this is expanded to include landfills with over 1% of temperature readings greater than 131°F (55°C), the frequency increased to 13 of 22 landfill cells (59% of landfill cells). The definition of what constitutes a landfill as an ETLF is currently being debated; thus, this percent distinction may be important.

Table 1: Landfill Temperature Compilation

Landfill Letter	No. of Data Points	Length of time studied (days)	Mean Temperature of Gas Wells (°F)	Percent of data points > 131°F	Ash Accepted
A	2434	889	83.8	0.0	No
B	18208	3130	99.5	8.6	No
C	927	2127	92.2	0.3	No
D	3323	1248	102.9	0.0	Yes
E	6101	1079	88.2	0.0	No
F	7197	1437	108.1	17.9	Yes
G	11549	591	118.8	30.9	Yes
H	4440	1796	89.0	0.0	No
I	5130	1275	98.3	6.0	Yes
J1	22775	1807	89.8	2.9	No
J2	23724	1820	97.8	0.9	No
K	4146	1252	95.2	6.2	No
L	6064	2029	93.0	1.7	Yes
M	4832	1629	112.3	14.2	No
N	10524	4028	114.1	27.5	Yes
O	788	1239	111.1	6.1	No
P	278	595	91.2	0.0	No
Q	6440	1069	87.1	0.0	No
R	22911	3935	98.8	11.2	Yes
S	2538	1216	98.1	1.1	No
T	5367	1305	99.4	6.5	Yes
U	2122	1402	89.6	0.0	No

Figure 5 provides a graphical representation of the percent of landfills reporting ET readings. As shown in this figure, 50% of landfills had temperature readings greater than 131°F (55°C) for at least 1.5% of their data readings, highlighting the frequency with which ETs are occurring throughout the state of Florida.

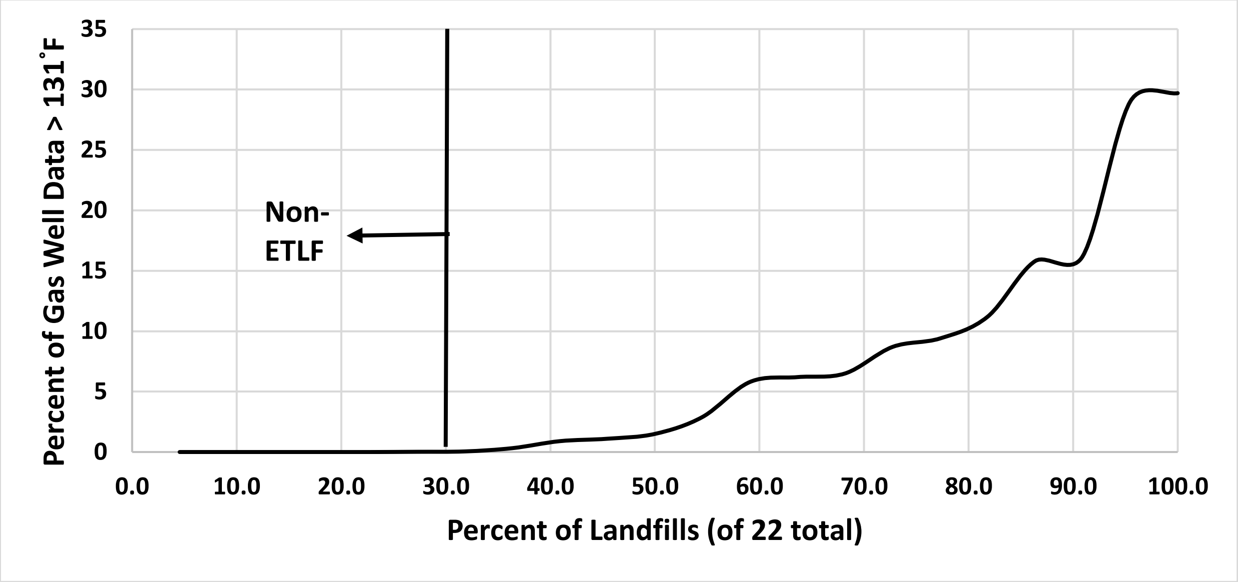


Figure 5: Percent of landfills with elevated temperatures

In addition to temperature data, gas composition data were collected and analyzed to determine the potential impact that ETs had on gas quality. These data included readings for CH_4, CO_2, CH_4 to CO_2 ratio, O_2, and balance gas. It should be noted that not all landfills report their gas composition data, as it is optional to do so.

A low CH_4 to CO_2 ratio is often indicative of problems within a landfill, as either CH_4 content is declining, or CO_2 content is increasing. In a healthy landfill, landfill gas should be composed of primarily CH_4 and CO_2. A recent ETLF study suggested that landfill gas in a non-ET landfill is composed of 50-60% CH_4 and 40-55% CO_2 when using a volume to volume (v/v) ratio. However, as landfills temperatures increase, gas composition shifts to around 60-80% CO_2 v/v and H_2 takes the place of CH_4 (Jafari et al., 2017).

Currently, no specific CH_4 to CO_2 ratio has been identified as the “boundary” or “threshold” for what defines a landfill as an ETLF. Recent ETLF presentations conducted by experts in the solid waste and legislative industries have advised utilizing ratios from anywhere between 0.6-1.0 as ET indicators (Meyer and Staley, 2017). Thus, CH_4 to CO_2 ratio over time was plotted for ET and non-ET gas wells for many of the ETLFs. Examples of two gas wells from Landfill N are shown in Figure 6 and Figure 7. The CH_4 to CO_2 ratio for the non-ET gas well rarely dropped below 1.0, whereas the CH_4 to CO_2 ratio for the ET gas well was frequently below 1.0, indicating that CH_4 quality was impacted.

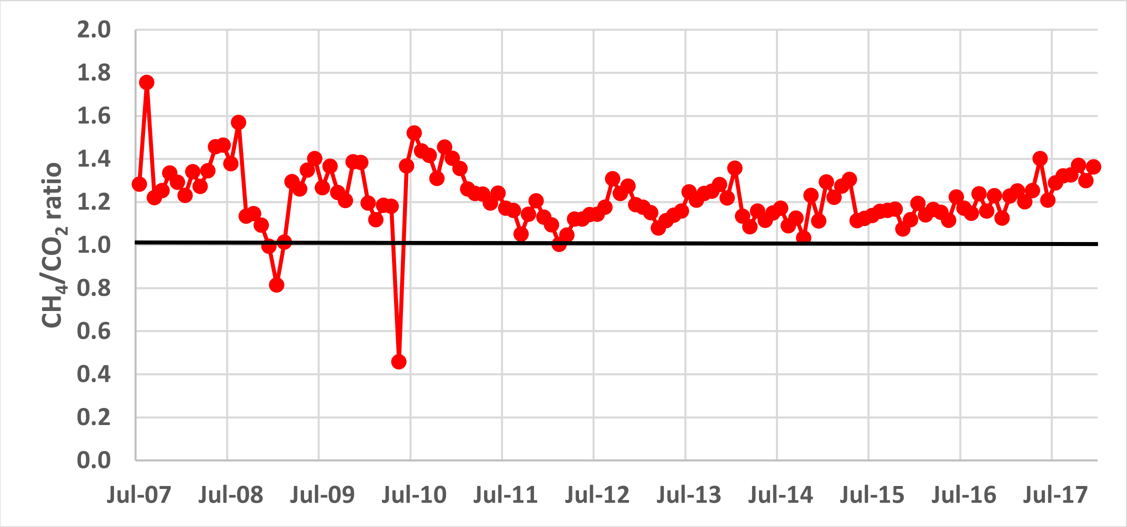


Figure 6: CH_4 to CO_2 ratio for a non-elevated temperature gas well

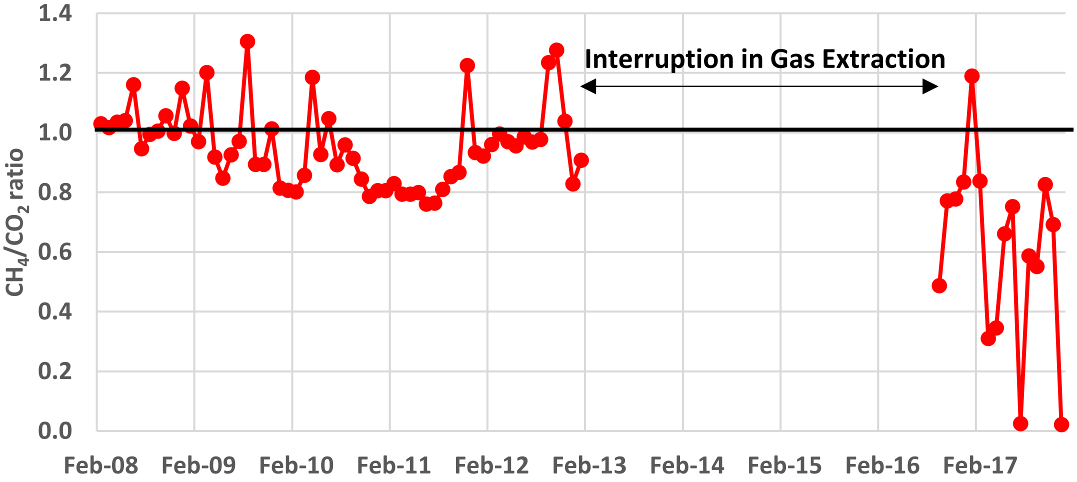


Figure 7: CH_4 to CO_2 ratio for an elevated temperature gas well

In addition, balance gas is often impacted by ETs. Balance gas can be composed of many different gas compounds, although it is most often assumed to be nitrogen (N_2); it could also be composed of H_2 in cases of landfills with methanogenesis inhibition (Barlaz et al., 2016). The ratio of balance gases to CO_2 (referred to as Bal/CO_2 ratio) was tested, as this ratio provides some insight into the potential for air intrusion as a cause of ETs. If air is introduced, the oxygen is likely to be consumed as part of an aerobic reaction, largely producing CO_2 and H_2O (Hao et al., 2017). N_2 in any air introduced will be captured in the measured balance gas. If it is assumed that all of the balance gas is N_2 and all of the oxygen is consumed and produces CO_2, the ratio of balance gas to CO_2 should exceed 7.5.

However, in many cases it cannot be assumed that all of the oxygen is consumed, especially as oxygen data is often recorded at percentages greater than 0% in gas wells (which implies that air intrusion is occurring). Therefore, in the absence of complete consumption, CO_2 and O_2 readings can be added and compared against the balance gas (N_2) within gas combustion (such as CH_4 combustion) in order to conservatively account for potential air intrusion. In this case, the ratio of balance gas (N_2) is compared to the ratio of oxygen in the product gases. An example of CH_4 combustion is found in Equation 13.

$$CH_4 + 2(O_2+3.73N_2) \rightarrow CO_2 + 2H_2O + 7.46N_2 \qquad (13)$$

As shown in Equation 13, the ratio of N_2 to O_2 in the product gases is 7.46/2.0, which equals 3.73. Any reactions that transform oxygen into another chemical species must maintain this ratio. Thus, to account for air intrusion, the ratio of balance gas to CO_2 plus O_2 (Bal/(CO_2+O_2)) should only exceed 3.73 if air intrusion is occurring. Thus, this ratio was tested at each gas well to determine whether this threshold was crossed. Results from two gas wells from Landfill N are shown in Figure 8 and Figure 9.

As shown in Figure 8 and Figure 9, the ratio is well below 3.73 in both wells (ET and non-ET) for the vast majority of the time, suggesting that little if any air is being drawn into the landfill. The increase in balance gas percentage in the ET well is probably due to hydrogen gas accumulation from carbon monoxide hydrolysis and chemical reactions; this carbon monoxide is produced during the pyrolysis of waste.

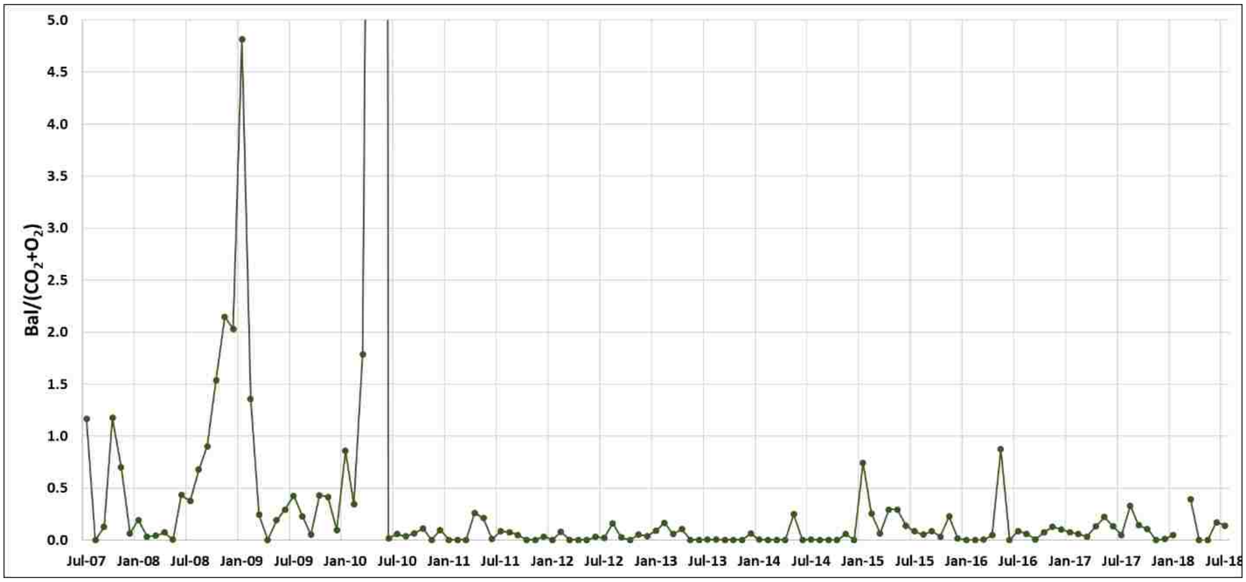


Figure 8: Bal/(CO$_2$+O$_2$) ratio for a non-elevated temperature gas well

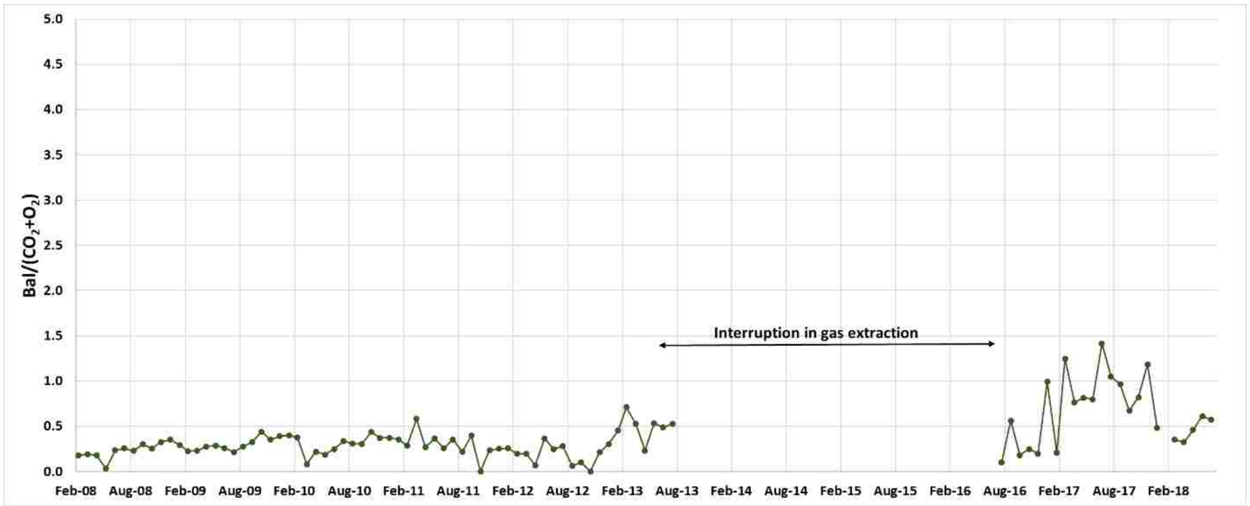


Figure 9: Bal/(CO$_2$+O$_2$) ratio for an elevated temperature gas well

As stated above, the Bal/(CO$_2$+O$_2$) ratio was calculated for all 22 landfills. Results regarding the ET gas wells were compiled in Table 2 to determine whether air intrusion might be causing the ETs found at the ETLFs. A Bal/(CO$_2$+O$_2$) ratio greater than 2.0 was used as a conservative threshold (as stated above, 3.73 is the problematic ratio) that would indicate potential air intrusion; therefore, the percent of data points exceeding this threshold was found and reported in Table 2 for each of the ETLFs.

As seen in Table 2, few ETLFs had readings where the Bal/(CO_2+O_2) ratio was greater than 2.0, as the percent of readings that exceeded this generally stayed within 0-1 percent of total readings. Thus, it suggests that air is not being drawn into these ETLFs and that air intrusion is likely not the cause of their ETs.

Landfill R did report that over 5% of ET data points had a Bal/(CO_2+O_2) greater than 2.0; this is much greater than all other ETLFs. When researched further, it was found that in these scenarios, CH_4 readings were abnormally high in some of the gas wells (above 60% v/v), while CO_2 readings in these wells were very low (below 25-30% v/v). This suggests a very high CH_4 to CO_2 ratio; the average CH_4 to CO_2 ratio for the ET gas wells reporting a Bal/(CO_2+O_2) ratio greater than 2.0 was approximately 1.75. Thus, it is possible that oxygen intrusion was the cause of some of the ETs in this particular landfill. However, it is important to note that this still accounts for only a little over 5% of the ET data points with this landfill. Therefore, the majority of ET readings for this landfill are likely not due to oxygen intrusion.

As shown in Table 2, Landfill M also had nearly 2% of their ET readings with a Bal/(CO_2+O_2) ratio above the conservative threshold. However, unlike with Landfill R, the wells that had a Bal/(CO_2+O_2) ratio greater than 2 also had a low CH_4 to CO_2 ratio (averaging 0.76). For those wells, the CH_4 readings were low (averaging 17% v/v), whereas the CO_2 values averaged 23%; therefore, it is possible that air intrusion has occurred. Regardless, as with Landfill R, the majority of ET readings for the landfill were not likely not due to oxygen intrusion.

Table 2: Balance Gas Composition for Florida ETLFs

Landfill Letter	**Percent. of ET Data Points**	**Length of time studied (days)**	**Mean Temperature of ET Gas Wells (°F)**	**Percent of ET data points of Bal/(CO2+O2) > 2**	**Ash Accepted**
B	8.6	3130	137.4	1.1	No
F	17.9	1437	142.4	1.0	Yes
G	30.9	591	153.7	1.0	Yes
I	6.0	1275	138.7	0.0	Yes
J1	2.9	1807	137.4	0.5	No
J2	0.9	1820	132.9	0.9	No
K	6.2	1252	135.7	0.4	No
L	1.7	2029	138.1	0.0	Yes
M	14.2	1629	136.2	1.8	No
N	27.5	4028	142.2	0.8	Yes
O	6.1	1239	134.8	--	N/A
R	11.2	3935	140.5	5.6	Yes
S	1.1	1216	133.0	--	No
T	6.5	1305	137.1	--	Yes

Characterization of Florida Landfill with Elevated Temperatures

To achieve a better understanding of ETLFs, waste deposition reports and landfill geometry were analyzed for all 22 landfill cells to determine whether ash disposal and landfill geometry influenced the creation of ETs. This analysis included researching landfill characteristics such as waste composition, landfill size, landfill depth, design capacity, current waste-in-place (in tons), and leachate treatment methods.

Effects of Ash Disposal on Gas-Well Temperatures

Ash disposal is hypothesized to be a cause of ETs in landfills. Florida combusts approximately 10% of managed MSW, therefore it is possible that ash is disposed along with unburned MSW. For this reason, information regarding the placement of ash in each of the 22 landfill cells was noted in Table 1. This ash could be disposed of as a component of the landfill cover or within the landfill working face. Eight out of the twenty-two landfill cells (36% of landfill cells) had ash disposed within the time periods researched for this study. Seven of these eight landfill cells (88% of landfill cells that take ash) had ETs in many of their gas wells. When the five landfills reporting temperature exceedances are included, these percentages increase to 37% and 90%, respectively.

Therefore, research was conducted to determine the possible correlation between ash and ETs. This analysis was completed by comparing the percentage of ash disposed versus total waste disposed within each landfill to the number of gas wellhead readings that exceeded 131^{o}F (55^{o}C).

Figure 10 provides a comparison of the percentage of gas wells with temperatures exceeding 131^{o}F (55^{o}C) and the percentage of total waste reported as ash for Landfill L (an ETLF) between 2015-2017. This landfill did not receive large quantities of ash, with most of their disposed waste being unburned MSW; the percent of total waste as ash ranged between 5-15% until ash was no longer accepted after October of 2016. For much of 2015 and the early parts of 2016 a trend was observed. As ash disposal increased, the number of ET readings often increased, and as ash disposal decreased so did the number of ETs. However, once ash was no longer accepted, ET readings dropped to 0% within a few months.

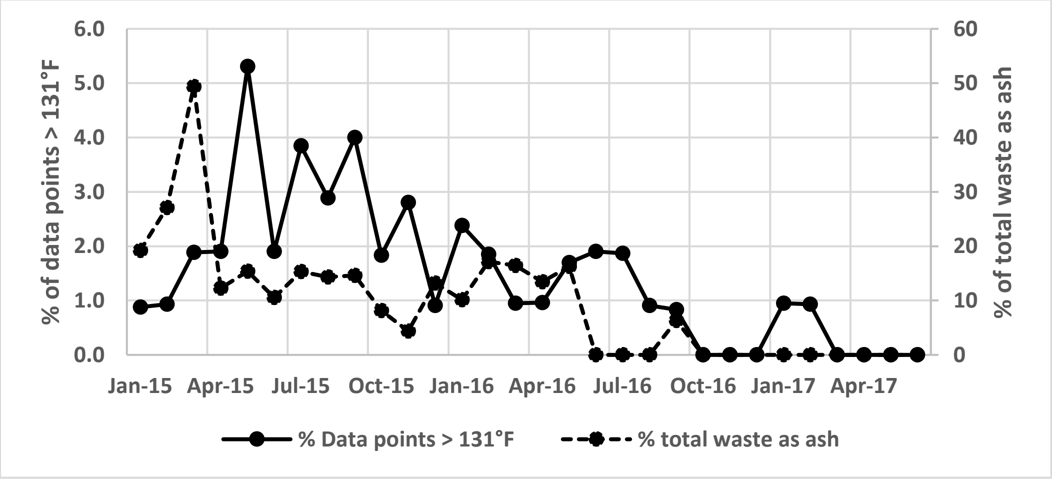


Figure 10: Percentage of ash and elevated temperature gas data points at Landfill L (>131°F)

Figure 11 provides a comparison of the percentage of gas wells with temperatures exceeding 131^{o}F (55^{o}C) and the percentage of total waste reported as ash for another ETLF (Landfill R) from 2002-2017. This landfill is co-located with a MSW waste-to-energy (WTE) incinerator that produces substantial quantities of ash throughout the year; thus, ash is the largest waste component disposed in this landfill. The percent of total waste as ash ranged between 75% and 95% for most months. Values below 75% were due to the construction of an additional incinerator, required maintenance, and disposal of yard waste generated during a hurricane, as described in their annual solid waste reports. The consequences of these events on ET creation are discussed below.

Between 2006-2007, there was a significant increase in the number of ET readings; this is hypothesized to have occurred due to a large increase in yard waste disposal as a result of a hurricane that made landfall in 2006. This explains the sharp decrease in ash disposal, as much of the landfill had to be utilized to accept both yard waste and unburned MSW. As expected, unburned MSW and yard waste contain higher levels of moisture and organic material than ash; this could provide the moisture and "fuel" source necessary to initiate heat generation. The increase in temperature due to the unburned MSW and yard waste are also visible within landfill contour maps between 2007 and 2008; these are shown in Figure 25. Landfill contour maps will be discussed in more detail later in this chapter.

As shown in Figure 11, similar reductions in ash disposal also occurred in 2010 and 2016. In 2010, facility maintenance required the incinerator to be shut off for a significant period of time. Once the incinerator was turned off, only unburned MSW was landfilled. However, fewer ET readings were reported in 2010-2011 than in 2009. Additional gas wells were constructed in 2011 at the north section of the landfill; this is portrayed by the blue square in Figure 25. These gas wells did not have ETs as represented by the green color in the landfill maps, which indicates an average temperature of 90-100°F. Therefore, although the number of high temperature wells remained the same between 2010 and 2011, the total number of gas wells with temperature data was greater, which caused the percent of ET readings to decrease.

In 2016, a second WTE incinerator unit was added; however, this required the original incinerator to be shut off for a couple months. This again led to an increase in unburned MSW disposal and a reduction in ash production and disposal. In addition, new gas wells continued to be added during this time span, indicated by the unmarked area located above the black square at the north section of the landfill map in Figure 25. A slight increase in ET readings occurred between 2016-2017, as seen in Figure 11, showing that the increase in unburned MSW may have provided the "fuel" necessary to promote ETs.

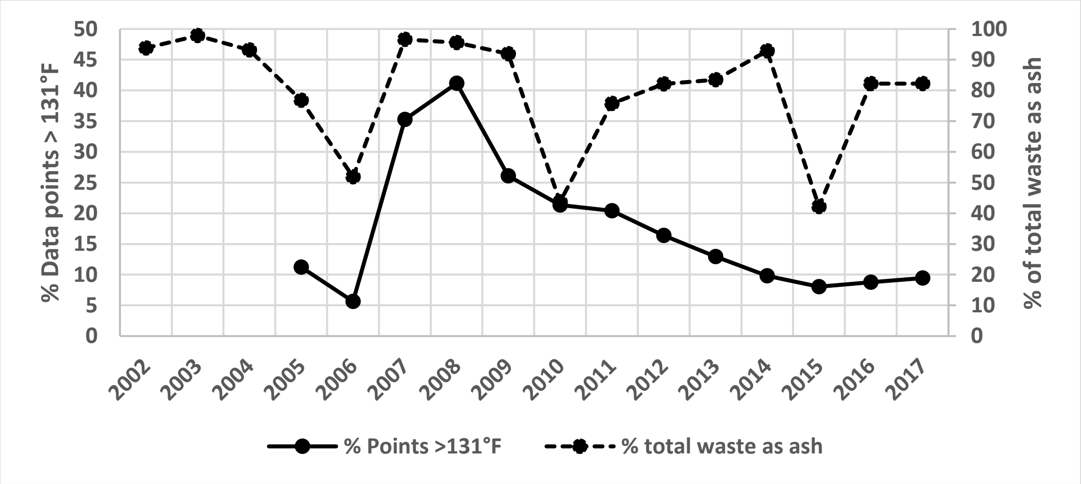


Figure 11: Percentage of ash and elevated temperature gas data points at Landfill R (>131°F)

It is possible that unburned MSW does not create ET conditions to the same extent as yard waste because yard waste is 100 percent organic, whereas MSW is composed of both organic and inorganic materials. In addition, yard waste may contain more moisture than MSW, allowing for the high moisture levels necessary to initiate heat generation. This may illustrate why high levels of ETs were found following the disposal of yard waste in 2006 rather than when MSW was disposed in 2010 and 2016.

Additional gas wells were also constructed in the northern section of this landfill between 2007 and 2017 (as shown in Figure 25); thus, it is possible that the number of high temperature wells remained the same, but the total number of wells increased, causing the percent of ET readings shown in Figure 11 to decline because of the additional data.

To highlight the potential impact of ash on gas well temperatures, data analysis was conducted to determine the effect of ash disposal on the maximum temperature measured in the landfill gas wells. To do this, the amount of ash disposed was divided into three classes: ‘No-ash’, ‘Medium-ash’, and ‘High-ash.’ Landfill cells that did not accept ash fit into the no-ash category; this was the case for 14 of the landfill cells. Landfill cells that accepted 5-50% of the total waste as ash averaged over the period of data availability were characterized in the medium-ash category. The landfill cell that contained greater than 50% of the total waste as ash was placed in the high-ash category. Seven landfill cells were characterized as medium-ash cells, including Landfill R, which had periods of medium-ash and high-ash disposal.

As shown in Figure 12, medium-ash landfill cells had the highest maximum temperatures within the landfill gas wells, with an average maximum temperature of 174°F between the seven landfill cells. The high-ash landfill cell had a maximum gas well temperature of 130°F, while no-ash landfill cells had an average maximum temperature of 136°F. Therefore, it appears that there is a maximum ash content that supports ET creation; landfill cells that receive some ash (but not a majority of waste as ash) have higher ETs than landfills that receive significant quantities of ash.

A student t-test was conducted to determine the statistical significance of these findings; a confidence interval (CI) of 95% was applied for this test and all future t-tests mentioned in this thesis. Results indicated that the differences are statistically significant, suggesting that there is minimal probability that the difference between average maximum temperatures between ash-accepting landfill cells and non-ash-accepting landfill cells occurred by chance.

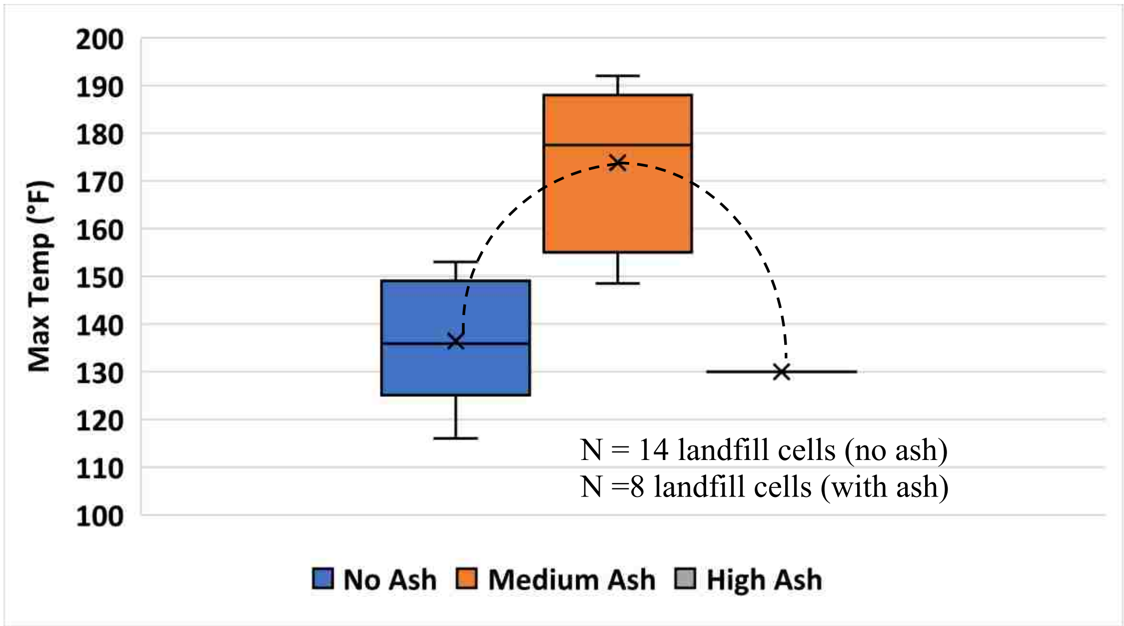


Figure 12: Maximum gas-well temperature vs. percent of ash disposed in landfills

Comparable results were found when testing the percent of ET readings reported for each landfill cell versus the percent of ash disposed in each cell. In this test, the percent of ET readings (temperatures exceeding 131°F) was recorded for as long as ash was disposed within a landfill. Again, as with the previous test, there were seven landfill cells that were included in the medium-ash category, and one landfill cell in the high-ash category.

As exhibited in Figure 13, medium-ash landfill cells had the highest percentage of ET readings, with an average of 11.3% of data points that were considered elevated in temperature. No-ash landfills had an average of 3.3% of data points with ETs, while the high-ash landfill had no ET readings.

Thus, as with Figure 12, it appears that landfill cells that receive some ash (but not a majority of waste as ash) have a higher incidence of ETs within each landfill cell when compared to landfills that receive significant quantities of ash or no ash at all. This indicates that there may be an optimal level of ash that may promote ET conditions.

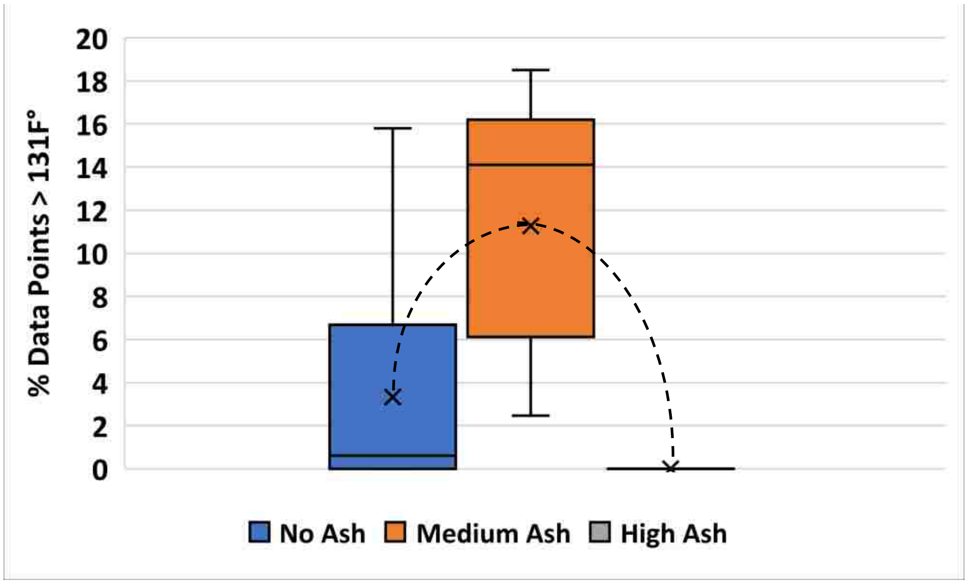


Figure 13: Percent of elevated temperatures vs. percent of ash disposed in landfills

Similar results were found when testing the percent of ETs for each landfill cell versus the maximum percent of ash disposed. In other words, the percent of ET readings were plotted solely during the period in which the maximum tonnage of ash was disposed in each landfill cell. As shown in Figure 14, the percent of data points with ETs was much greater for the medium-ash landfill cells when compared to the no-ash and high-ash cells. Medium-ash landfill cells had on-average 13.7% of data points with ETs whereas no-ash and the high-ash landfill had 3.3% and 0% of data points with ETs, respectively. Results again support the idea that there may be an optimal level of ash (likely within the medium-ash category) that may promote ET conditions.

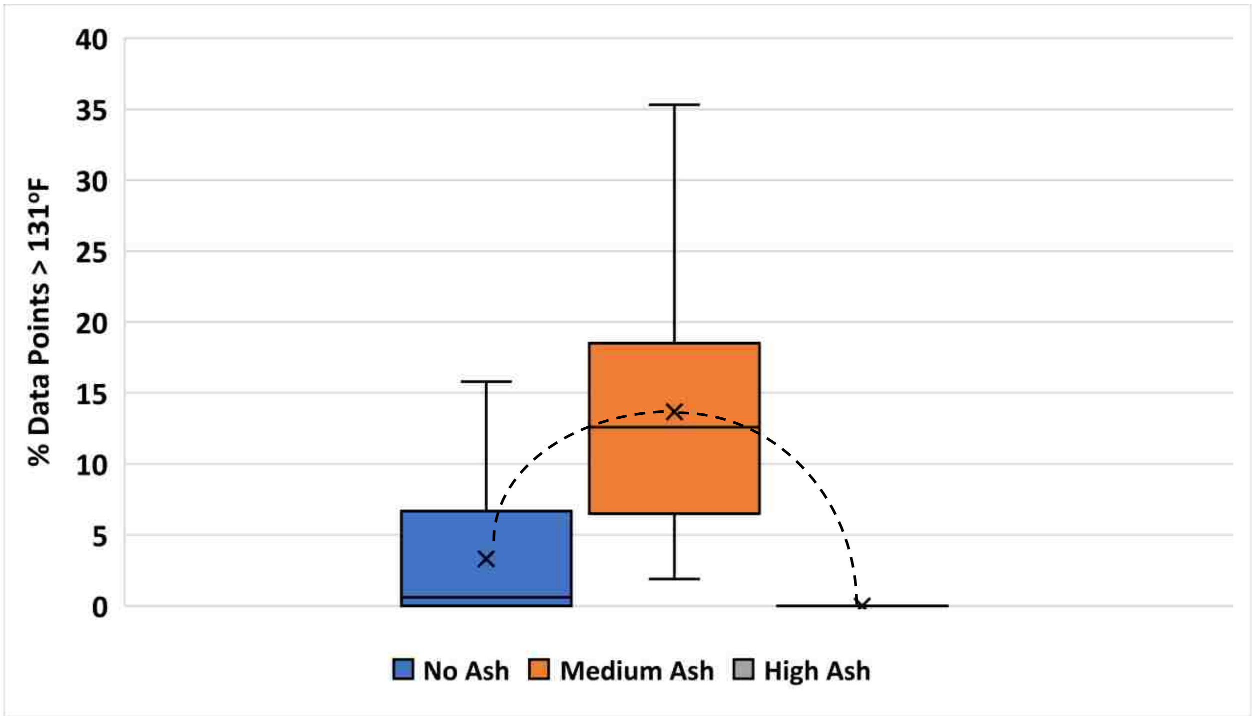


Figure 14: Percent of elevated temperatures vs. maximum percent of ash disposed in landfills

Average Landfill Geometry

Total site area, current landfilled area (presently accepting waste disposal), design landfill depth, and current landfill depth were compared between each landfill to determine whether any of these landfill design characteristics impact the potential for landfill cells to develop ETs. Detailed landfill geometry characteristics for each Florida landfill can be found in Table A-1, which is located in Appendix A.

Table 3 shows the averages of these components for ETLFs and non-ETLFs. As exhibited from this table, ETLF cells in this study tended to be larger than non-ETLF cells both in site area and landfill depth. As shown in Figure 15, ETLF cells tend to be deeper, averaging in depth around 152 feet. In contrast, non-ETLF cells averaged 130 feet in depth. This additional depth could have the potential to produce conditions beneficial to the creation of ETs. However, when performing a student t-test (p=0.05), it was found that the difference in average depth between the

ETLF and non-ETLF cells is not statistically significant, probably because of the large variation in data.

Table 3: Average landfill geometry (by landfill type)

	Site Area (acres)	Current Landfilled Area	Design Landfill Depth (feet)	Current Landfill Depth (feet)	Well Depth (feet)
Non-ETLF	195	82	130	112	73
ETLF	846	141	152	148	96

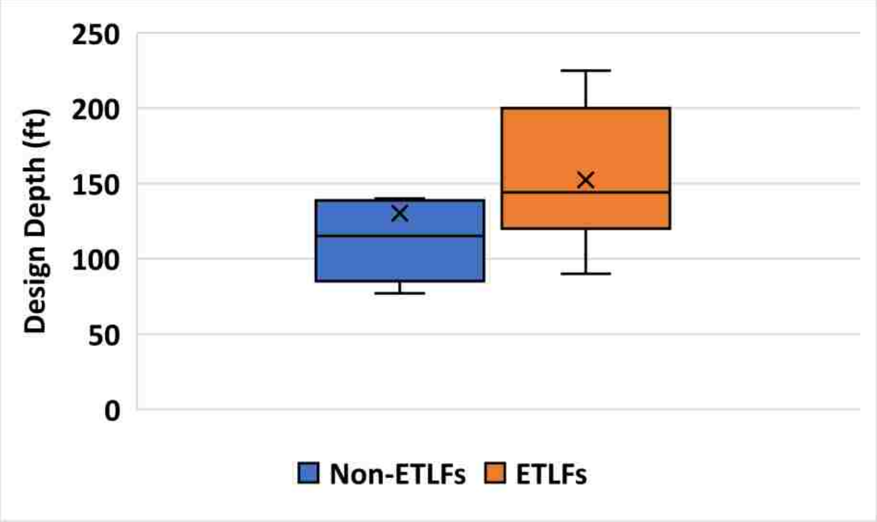


Figure 15: Design Depth (by landfill type)

Design and current landfill depths are of interest because depth may an indirect indicator of the impact of pressure within a landfill; therefore, additional landfill depth may result in heightened pressure within the landfill. This could greatly influence landfill gas temperatures, as gas pressure is directly correlated with gas temperature through the Ideal Gas Law. In theory, as gas pressure increases, gas temperature should also increase. However, this assumes that volume stays constant within a landfill, which is unlikely.

In addition, landfill depths are of concern due to the potential for deeper landfills to allow for leachate ponding. Ponding occurs when water collects within a section of the landfill; as stated in the Literature Review, chemical reactions containing aluminum and iron deposition require water to be present. Thus, ponded water may promote ETs due to the chemical reactions between metals and pooled water. Stationary water also causes heat to dissipate more slowly, trapping it over time.

Leachate Treatment Method

Unfortunately, we were unable to evaluate leachate characterization results for the 22 landfills, as landfill owners are no longer required to send leachate quality data to the FDEP. Due to this, leachate quality data are very limited in OCULUS. However, leachate treatment methods were compiled for 22 landfills to examine the possibility of a relationship between on-site treatment/disposal and ETs.

Leachate recirculation may increase the possibility of leachate ponding within a landfill. Figure 16 presents treatment data divided into three categories: ‘Recirculation’, ‘Other’, and ‘None’. ‘Recirculation’ includes landfills that are permitted to recirculate leachate; however, recirculation may not be utilized continuously. In some cases, landfill owners only recirculated leachate during periods of excess leachate production or as a method to control dust on the working face. ‘None’ indicates that on-site leachate treatment methods were not utilized for these landfills and that all leachate treatment was conducted off-site through a publicly owned treatment works (POTW). The designation of ‘Other’ includes landfills that apply other on-site treatment or disposal methods besides recirculation; one example is biological treatment of leachate using sequencing batch reactors (SBRs). Detailed leachate treatment methods for each landfill are tabulated in Table A-2, which is in Appendix A.

As exhibited in Figure 16, recirculation is more commonly applied in the non-ETLF cells, with 50% of non-ETLF cells permitted to utilize leachate recirculation. In contrast, ETLF cells often utilize other on-site treatment methods in order to treat their leachate, with only 21% of ETLFs permitted to recirculate leachate through their cells.

There is the potential that some of these ETLF cells are experiencing ETs due to leachate ponding; however, additional testing and communication with operators is required to determine whether this is occurring in these ETLFs. As of now, this is just a statistical observation between ETLF and non-ETLF cells.

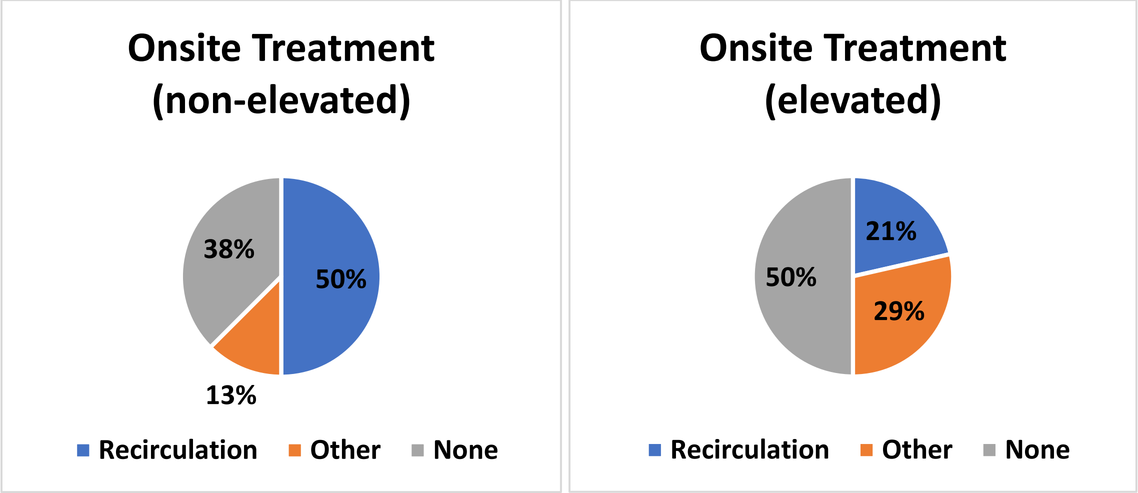


Figure 16: On-site leachate management for (a) non-ETLF cells and (b) ELTF cells

Average Landfill Capacity

Average waste-in-place and landfill capacity was recorded for each landfill cell. Detailed information for each landfill cell is in Table A-3, which is in Appendix A. Much of these data were obtained from the LMOP database, as many landfills did not upload landfill capacity information. Unfortunately, the LMOP is voluntarily updated, meaning that some of the waste-in-place data may be slightly outdated by a year or two. However, it is still a useful resource in understanding the design capacity and waste-in-place for each type of landfill.

Average capacity for ETLF cells and non-ETLF cells is displayed in Table 4. ETLFs on-average have a much larger design capacity as well as average current waste-in-place when compared to non-ETLFs. However, the percent of landfill capacity used is on-average larger for non-ETLFs. Two separate student t-tests were performed to compare the average landfill design capacity and average current waste-in-place for the ETLF cells and non-ETLF cells. In both cases, the results were statistically significant. This indicates that there is minimal probability that the difference between average landfill design capacity and average current waste-in-place between ETLF cells and non-ETLF cells occurred by chance.

Table 4: Average Landfill Capacity (by landfill type)

	Landfill Design Capacity (tons)	**Waste in Place (tons) - 2016**	**% of Landfill Capacity Used**
Non-ETLF	8,125,236	4,665,581	65
ETLF	42,937,097	20,047,247	54

Individual Landfill Analysis

In order to further understand what characterizes a landfill as an ETLF, additional data comparisons were conducted on an individual-landfill basis. This included calculating the percent of time that ET gas wells had temperature readings greater than 131°F. Gas wells were considered "ET gas wells" if they had at least one temperature reading greater than 131°F. Thus, each of these wells was evaluated regarding the amount of time that they were "elevated" in temperature. Landfills that have ET readings over long time periods in many wells are more likely to be considered ETLFs, whereas landfills that have ET readings over long time periods for a couple of wells could be non-ETLFs with an outlier well or two.

As seen in Figure 17, half of the ET wells at four out of the 14 (29%) ETLF cells had ETs at least 30% of the time. In addition, it was found that 10% of the wells at 10 out of the 14 (71%) ETLF cells had ETs at least 50% of the time. This indicates that a significant percentage of temperature readings greater than 131°F occur frequently in many gas wells rather than in a few outlier wells over extended periods of time.

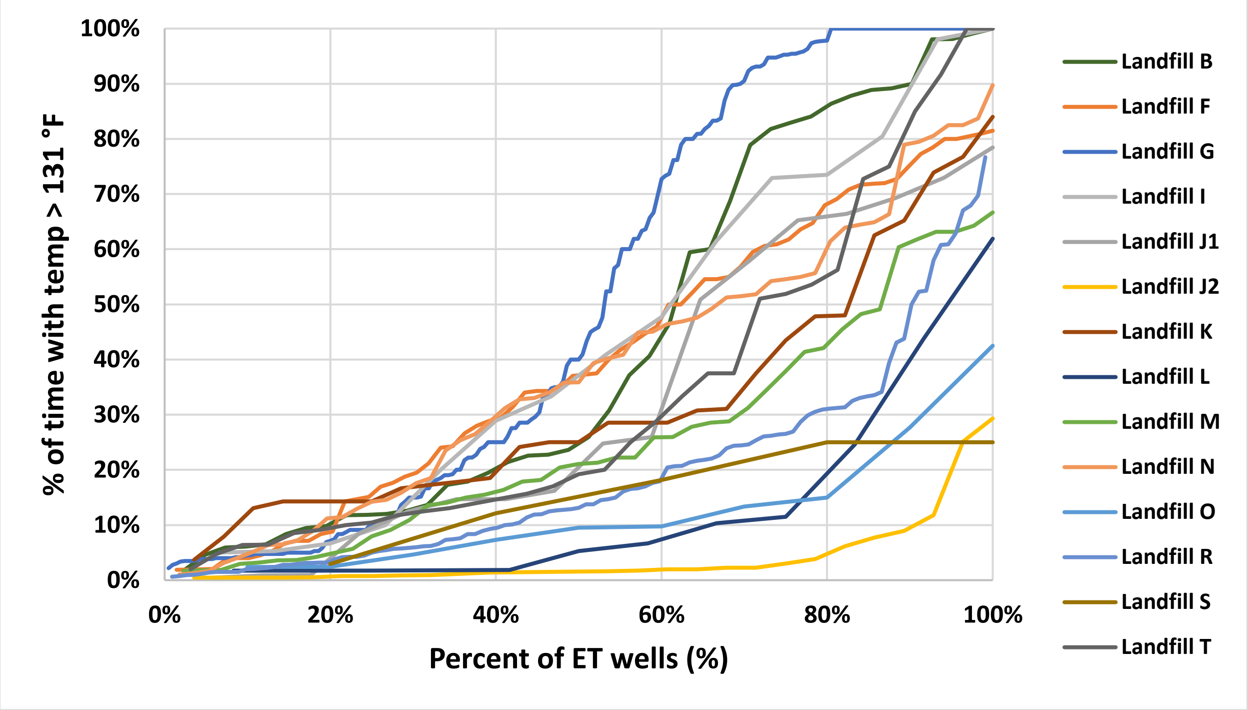


Figure 17: Percent of time ET Wells had temperatures greater than 131°F

Similarly, the percent of time that ET gas wells had a CH_4 to CO_2 ratio below 1 was also compiled for the ETLFs. As stated earlier, CH_4 to CO_2 ratios below 1 may be an indicator of ETs, as high temperatures have the potential to negatively impact methanogens, resulting in reduced CH_4 quality and thus a low CH_4 to CO_2 ratio. Two of the landfill owners (Landfills O and T) do not report CH_4 or CO_2 information; thus, two of the landfills from Figure 17 are missing in Figure 18. For this reason, only 12 ETLF cells were used for CH_4 to CO_2 ratio analysis.

As seen in Figure 18, half of the ET wells at three of the 12 ETLF cells (25%) had CH_4 to CO_2 ratios below 1 for at least 10% of the time. At the same landfills (Landfills F, G, and N), 10% of the ET gas wells had a CH_4 to CO_2 below 1 at least 40% of the time. These three landfills also had gas wells with ETs for long periods of time. Thus, this indicates correlation between ETs and low CH_4 to CO_2 ratios.

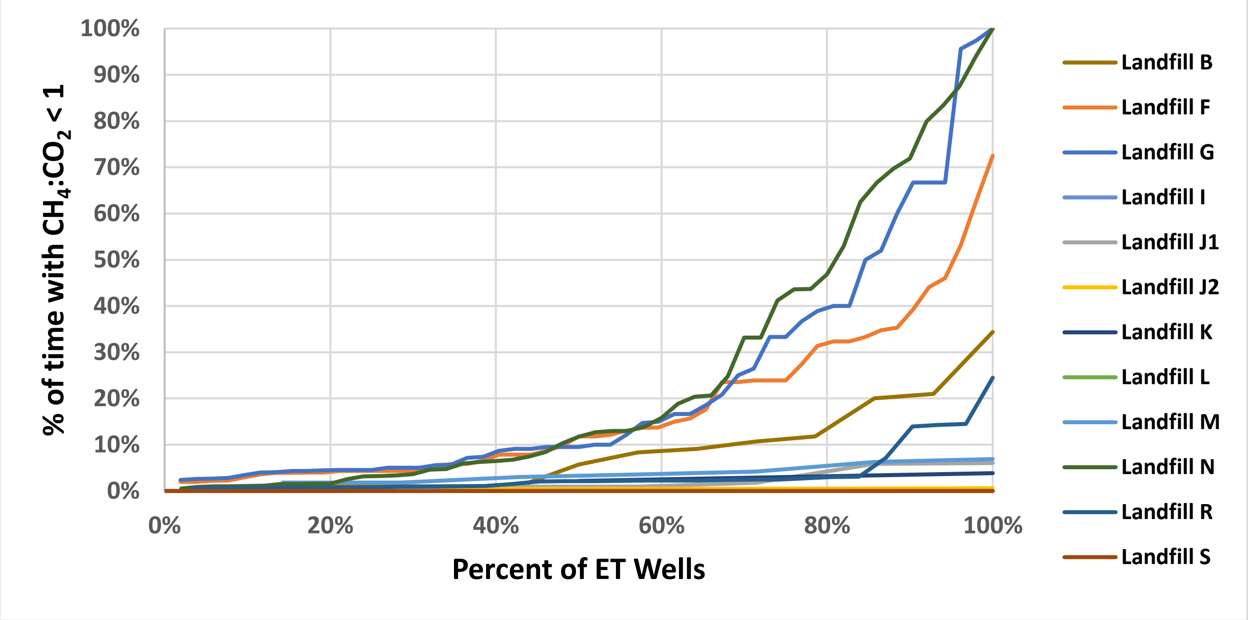


Figure 18: Percent of time ET Wells had CH_4 to CO_2 ratio < 1

Recently, many landfill experts have been utilizing 145°F and a CH_4 to CO_2 ratio below 0.6-0.9 (depending on the source) as thresholds representing ET scenarios rather than 131°F and a CH_4 to CO_2 ratio below 1, as was used in the previous examples (Meyer and Staley, 2017). These experts argue that temperatures below 145°F do not significantly impact CH_4 quality within a landfill. For this reason, Figures 17 and 18 were re-created with different thresholds to test how frequently ET wells report temperatures greater than 145°F and the impact that the higher temperatures may have on CH_4 to CO_2 ratio. Results are shown in Figure 19 and Figure 20.

Using similar divisions as those shown in Figure 17, it was found that half of the ET wells at two out of the 14 (14%) ETLF cells had ETs for only approximately 3% of the time. This is a large decrease from the same test conducted in Figure 17. Similarly, it was found that only one of the 14 (7%) ETLF cells had 10% of their ET wells with ETs greater than 145°F for at least 50% of the time. This is significantly less than the results found when testing the percentage of temperature readings greater than 131°F. Therefore, this analysis indicates that considerably fewer gas wells had temperature readings greater than 145°F when compared to those that had temperature readings greater than 131°F.

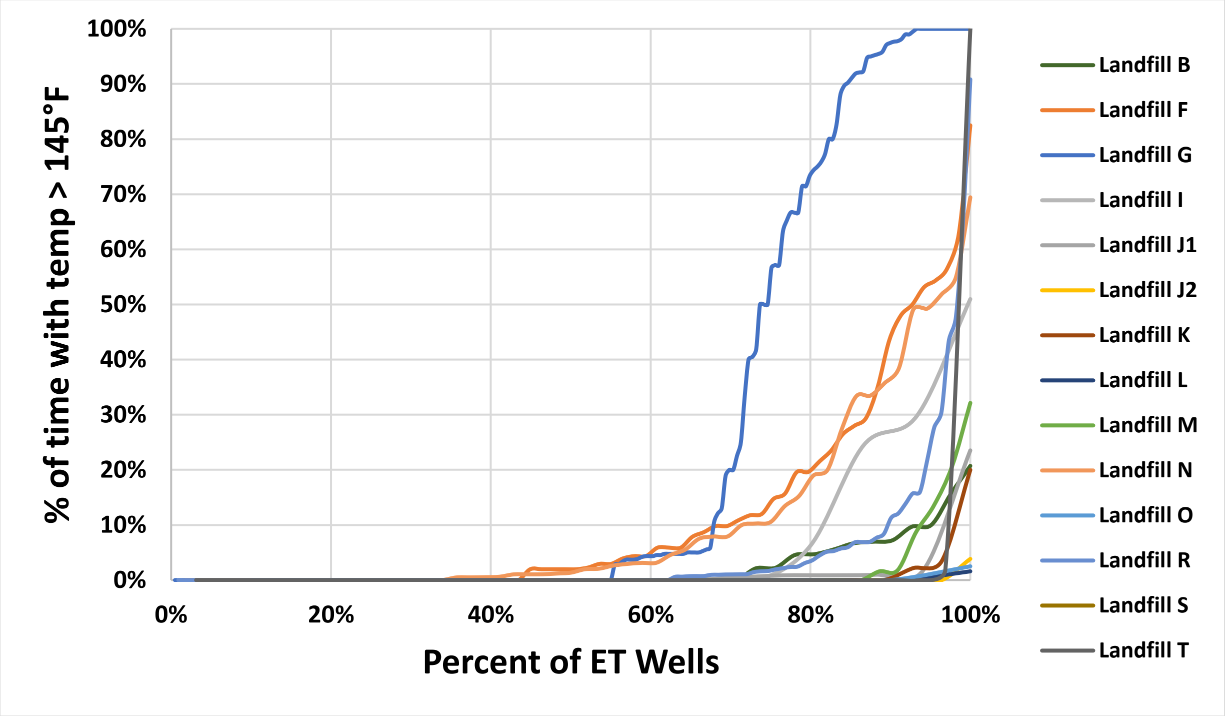


Figure 19: Percent of time ET Wells had temperatures greater than 145°F

When analyzing the percent of time ET wells had a CH_4 to CO_2 ratio below 0.8, similar findings were discovered. As seen in Figure 20, ETLFs had far fewer CH_4 to CO_2 ratio readings below 0.8. Ten percent of ET wells at one landfill (Landfill N) had a CH_4 to CO_2 ratio below 0.8

at least 40% of the time. This is much less than the results found when testing the percentage of CH_4 to CO_2 ratios below 1.

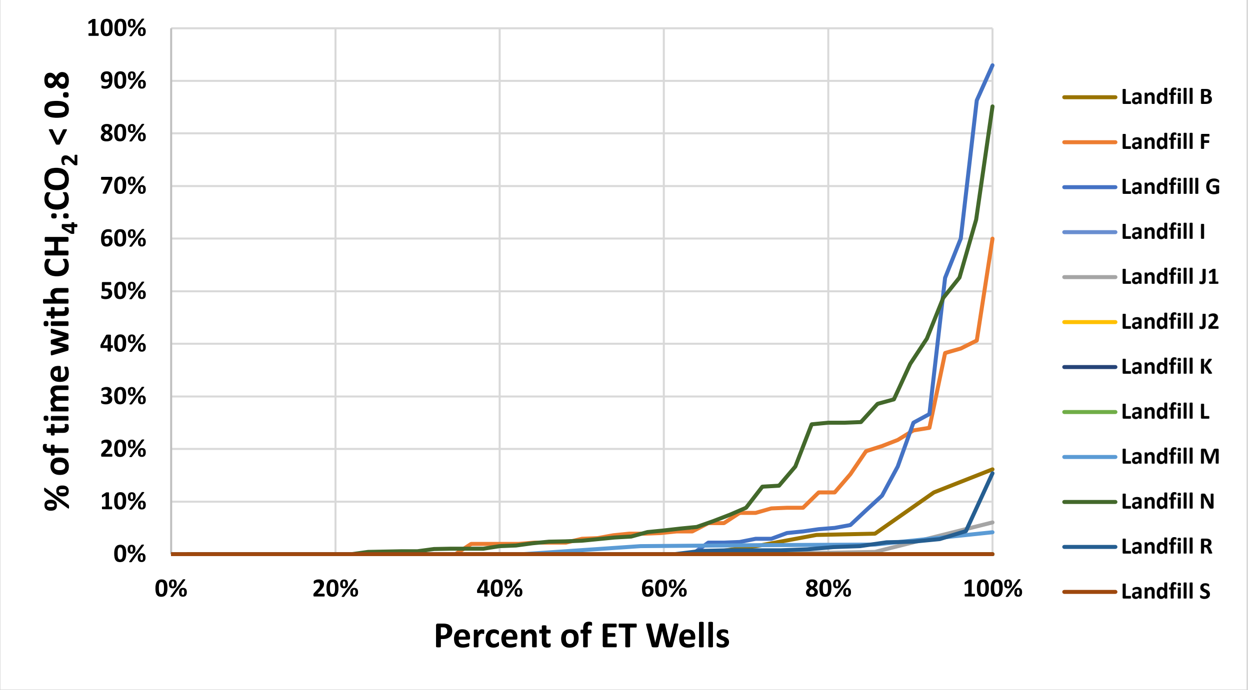


Figure 20: Percent of time ET Wells had CH_4 to CO_2 ratio < 0.8 at temp greater than 145°F

Cumulative Landfill Analysis

Another way to analyze the correlation between CH_4 to CO_2 ratios and ETs is by conducting a cumulative landfill analysis. A cumulative landfill analysis aggregates the temperature and CH_4 to CO_2 data collected from all 22 landfill cells and examines the correlation between the two variables. Results are found in Figure 21. Values of the CH_4 to CO_2 ratio were averaged over five-degree temperature intervals. The initial point is at 131°F, which represents non-ET gas well data up to a temperature of 131°F (the boundary between non-ETs and ETs) and then increases at five-degree temperature intervals up to a temperature of 176°F, which includes all gas wells with temperatures greater than 171°F.

As shown in Figure 21, average CH_4 to CO_2 ratios were the greatest for non-ET gas wells, with an average of 1.4. The average CH_4 to CO_2 ratio remained around 1.3 until temperatures increased above 155°F. Beyond 161°F, the average CH_4 to CO_2 dropped significantly until it was below 1.0 above 166°F. The lowest average CH_4 to CO_2 reading of 0.73 occurred at the last point of the graph, which encompassed all points greater than 171°F. Therefore, it appears that temperature has minimal impact on CH_4 quality below 155°F.

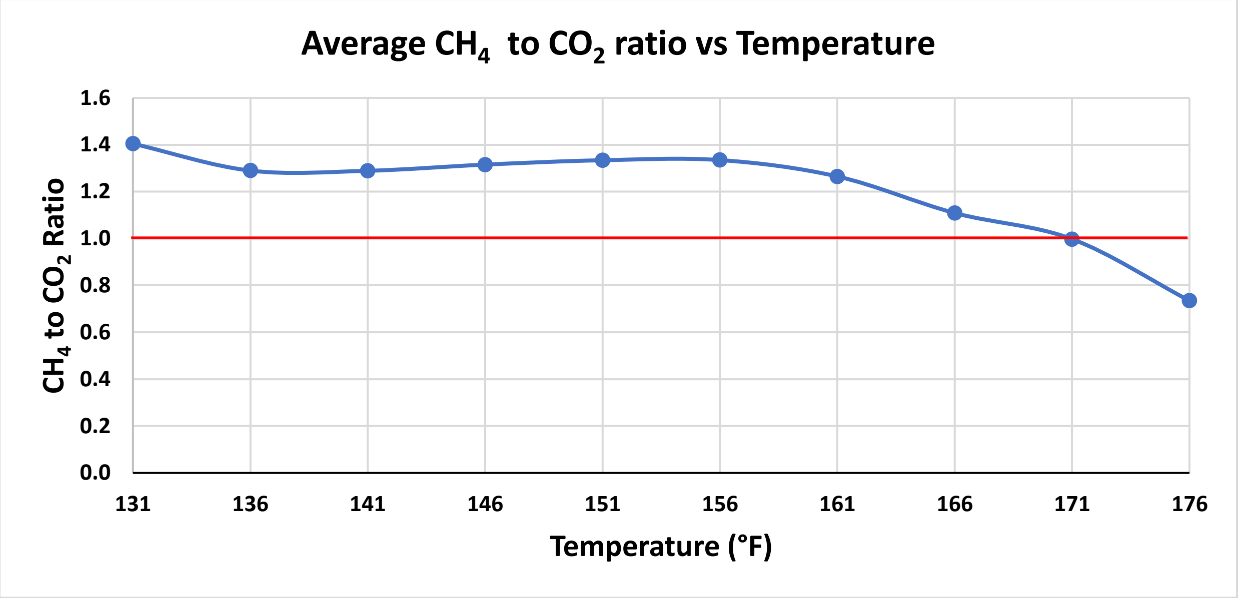


Figure 21: Average CH_4 to CO_2 ratio vs Temperature

The relationship between temperature and CH_4 to CO_2 ratio was further analyzed by computing the percentage of ET data points with CH_4 to CO_2 ratios less than 1, 0.8, 0.6, and 0.2, using the same five-degree temperature intervals from Figure 21. Thus, analysis was conducted for each of these CH_4 to CO_2 ratios; results for each ratio are exhibited in Figure 22.

From Figure 22, it is apparent that temperatures greater than 150°F impact the CH_4 to CO_2 ratio, as noted by the steep jump in the percentage of ET data points with CH_4 to CO_2 ratios below 1 and 0.8. However, ETs did not appear to lead to CH_4 to CO_2 ratios below 0.6 until temperatures exceeded 171°F. It is also interesting to note that non-ET data points had a larger percentage of low CH_4 to CO_2 ratios than did ET data points that encompassed temperatures between 131°F and 145°F. Thus, by these results, it is possible to assume that ETs below 150°F may not substantially impact methanogens.

However, Jafari et al. (2016) discovered that gas wellhead temperatures underpredicted waste temperatures measured using downhole thermocouples by 20-40°F. Therefore, waste temperature may actually be nearer to 170-175°F, which is above the temperature upper limit for thermophilic methanogens (167°F) reported by Nozhevnikova et al. (1999) and Zinder et al. (1984). Gas collection pipes are typically slotted over most of the depth of the landfill, therefore the data collected at the well head represents an average value both along the depth and throughout the radius of influence which may account for the high gas quality despite the high temperatures.

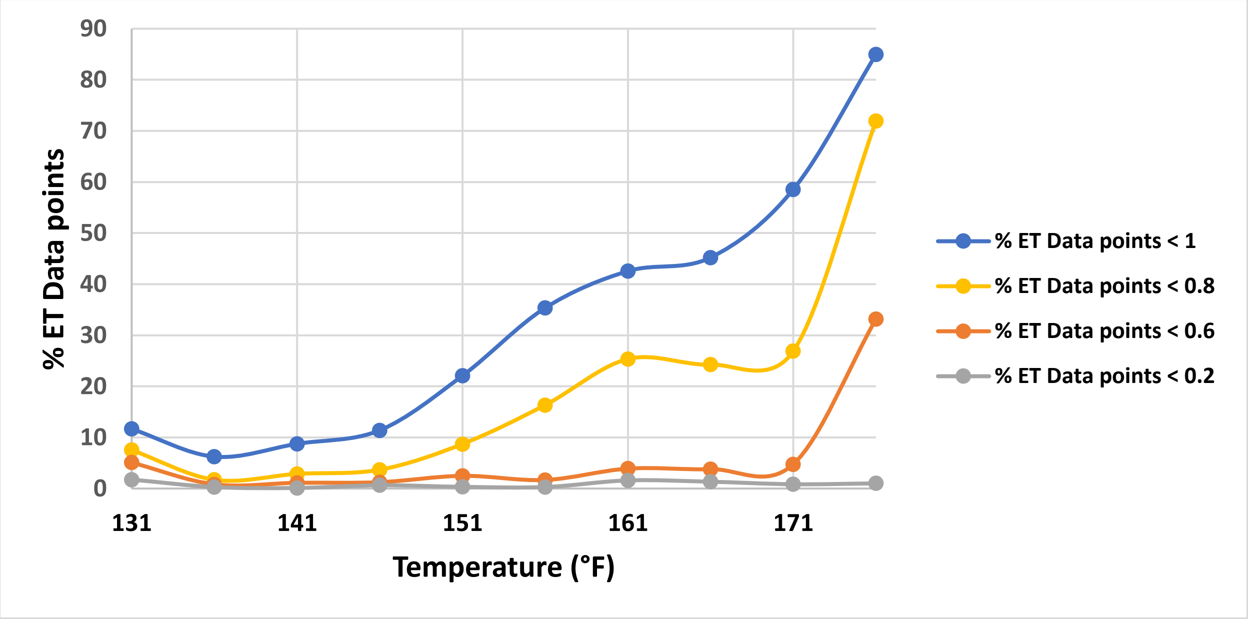


Figure 22: Percent of ET Data Points vs Temperature at various CH_4 to CO_2 ratios
(Data Points for non-ET landfills; CH_4 to CO_2 ratio <1=12%, <0.8=8%, <0.6=5%, 0.2=2%)

Heat Generation and Movement

The relationship between heat generation and the movement of heat within landfills was analyzed by using ESRI's ArcGIS software. As stated in the Methodology, this was conducted to determine the potential for heat propagation. If special wastes such as ash were known to be placed in a landfill cell, the landfill maps created in ArcGIS could potentially display the ability for heat to propagate from gas wells located at the initial disposal location to gas wells located farther away from the disposal location. Unfortunately, exact disposal locations of ash or other special wastes were only known for one landfill (Landfill N); for other landfills, these locations could only be assumed based on the heat generation and propagation exhibited in the contour maps that were created using ArcGIS.

Four ETLFs were studied and mapped using ArcGIS. Each landfill is initially discussed on an individual basis; results are compared between the landfills in a summary section at the end of this sub-chapter. Maps focus on periods in which ETs were reported; thus, temperature contour maps were created primarily for periods of ETs or fluctuating temperatures (which occurred frequently in ETLFs). However, in certain cases, maps were also created for non-ET periods. To account for the potential gaps in data, temperature contour maps that encompass the entirety of data availability for each of the four ETLFs can be found in Appendix B.

Landfill N

As mentioned in Chapter Four, Landfill N has experienced ETs in gas wells on the west side of the ~115-acre north cell in an area that is approximately 25 acres. This landfill disposed of wastewater treatment facility biosolids and coal ash (N-Viro) as an alternative daily cover in this area. The temperature contour maps are shown below in Figure 23.

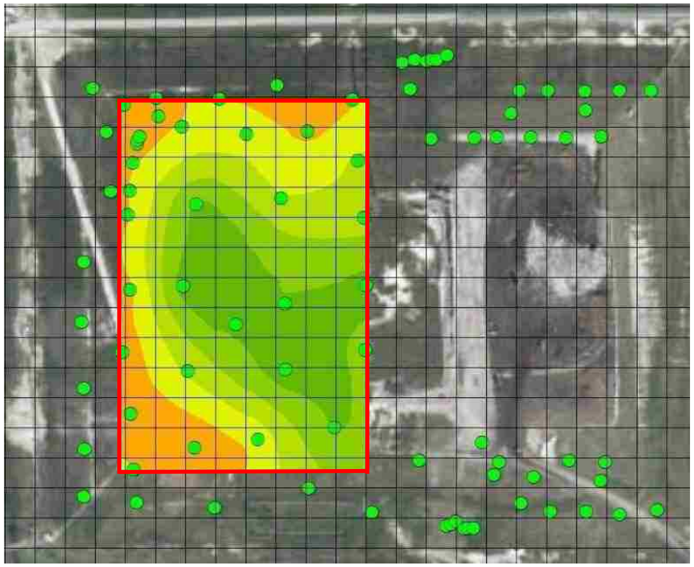
Temperatures are represented by different colored contours and a legend is attached to each landfill map. Landfill expansions occurred multiple times during the 11-year timespan, resulting in the addition of many gas wells. Different colored squares (red, blue, and black) were included within the temperature contour maps to illustrate the various landfill expansions and document when they occurred; this information is also found within the legend of each landfill map.

Gas well temperature data were provided for this landfill between 2007-2018. However, temperature contours for 2013-2016 were not included because landfill operators shut off the gas wells during much of these four years in an effort to lower gas temperatures. Thus, the temperature readings for these years were not representative of what would have occurred had the gas wells been left open. Gas wells were left open during the latter half of 2016; however, as the maps portray average temperatures for the entire year, including 2016 could potentially skew the validity of the annual average temperature maps.

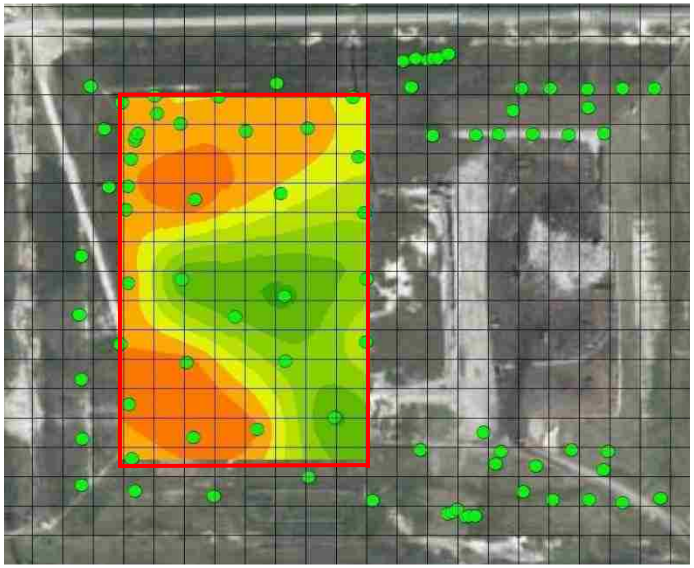
A significant result discovered from Figure 23 is the movement of heat and increased heat generation observed in the northern and western sections of the landfill between 2007 and 2011. This heat generation can likely be attributed to the placement of the N-Viro ash/biosolids mixture, as it was placed within the “hot spot” area that is clearly defined in the 2011 temperature contour. Exact dates of disposal are unknown; however, it is believed to have occurred between 2005 and 2010. If this is true, it could provide evidence that heat movement, or heat propagation is a possibility within landfills.

Landfill maps for 2013-2016 were not included in this analysis, as landfill operators decided to shut off the ET gas wells in an effort to “contain” the temperatures to their respective well locations. However, when the wells were turned back on in 2017, the opposite effect happened, as shown in the 2017 and 2018 landfill maps. It appears that the ‘trapped’ gas located below the ET wells travelled to the eastern sections of the landfill cell, transporting heat through condensation in cooler sections. In addition, the section in which the ash/biosolids mixture was placed had higher temperatures than ever before, as heat had been trapped in the central portion of the landfill.

Therefore, it is unknown exactly how long it may have taken for the ETs shown in years 2010-2012 to dissipate following completion of the reactions and removal of the heat generated by these reactions. Regardless, it is safe to conclude that turning off the gas wells caused the landfill heat to propagate through gas transportation and condensation, as the gas was driven elsewhere to active gas wells in which it could be released.



2007



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Red square = 2007-2008 wells
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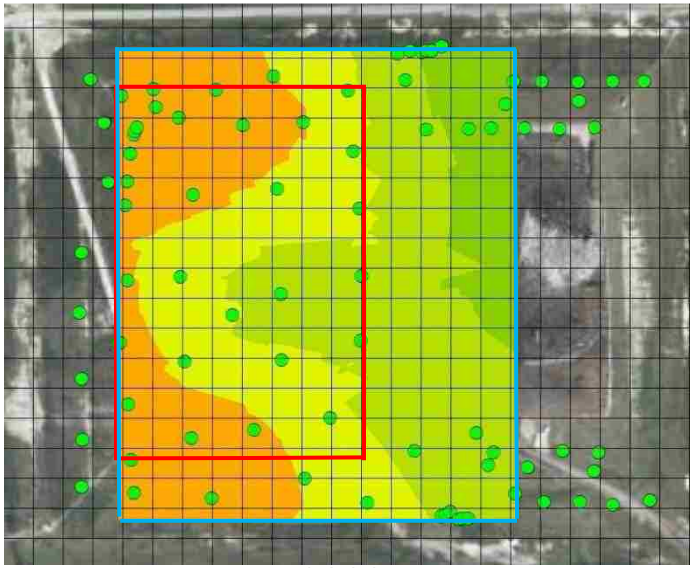
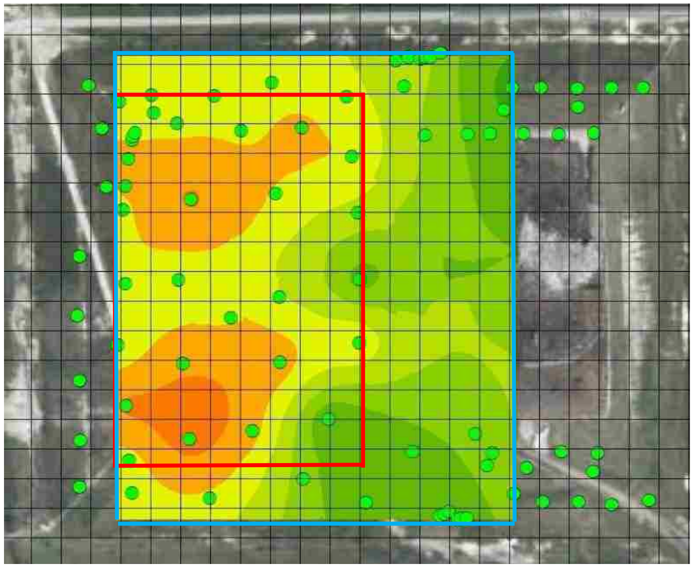


2009



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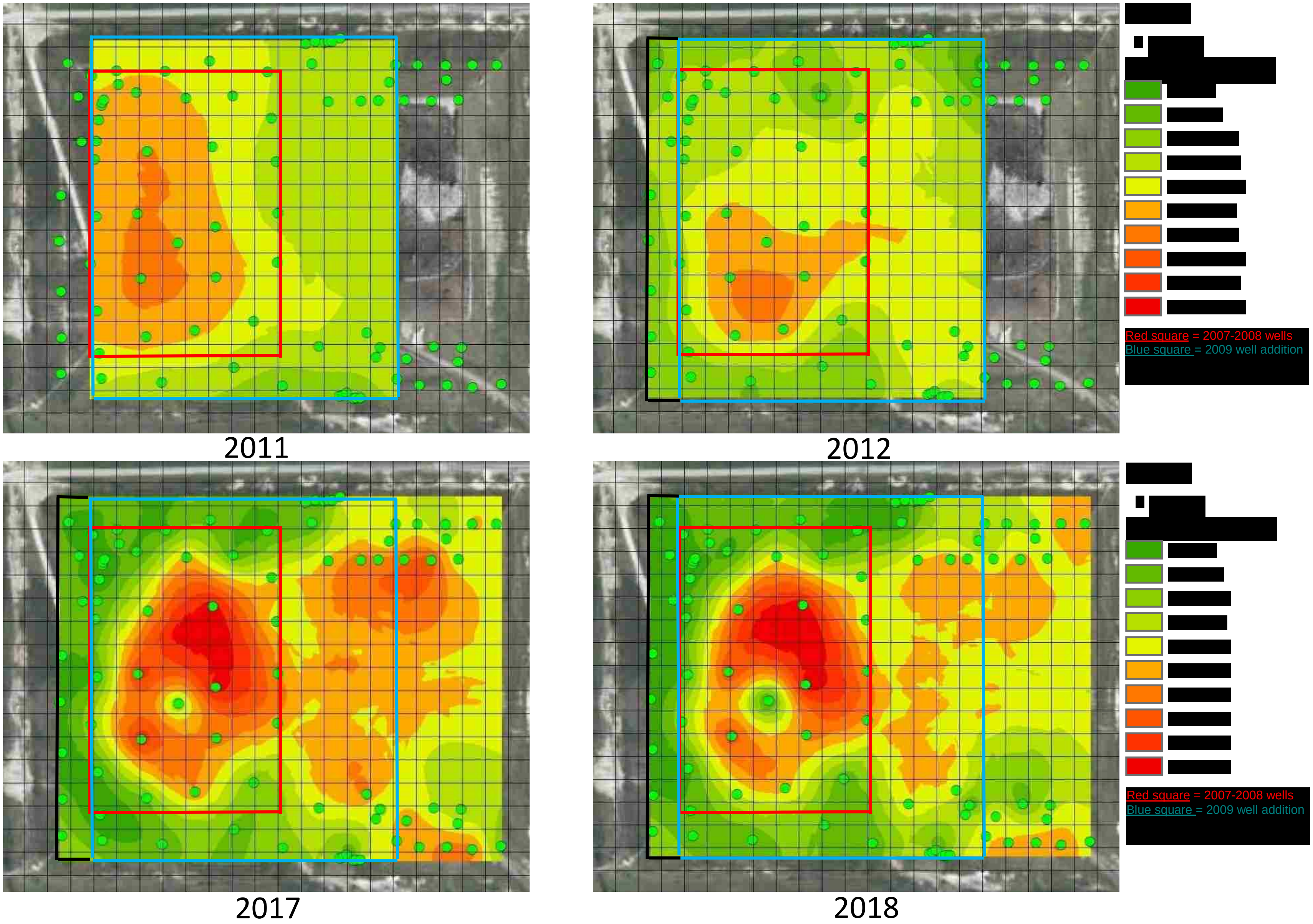
Red square = 2007-2008 wells
Blue square = 2009 well addition



2011

2012

2017

2018

Figure 23: Temperature Contour Maps for Landfill N

Landfill B

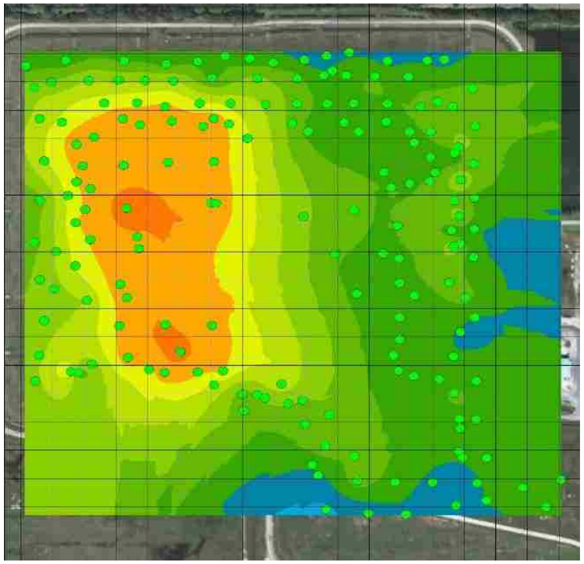
Landfill B is an ET landfill with a current landfilled area of 190 acres and a maximum landfill depth of 160 feet. ETs have been reported in the northwest section of the landfill in an area that was about 37 acres during peak ET conditions in 2010. The ETs are represented by the orange colors seen in Figure 24.

Unlike Landfill N, this particular landfill does not accept ash for disposal, nor does it apply ash as a component of its daily cover. Thus, the cause of the ETs for this landfill is unknown. As exhibited by the contour maps shown in Figure 24, little heat movement occurred within this landfill, as ETs were contained in the northwest section of the landfill between 2010 and 2016. Instead, this landfill displays a pattern of cooling and heating between 2012 and 2016, with the ET zone ultimately shrinking over time. Landfill maps for 2017 and 2018 were not shown as there were no ETs to report in those years. However, these maps are available in Figure B-2 in Appendix B.

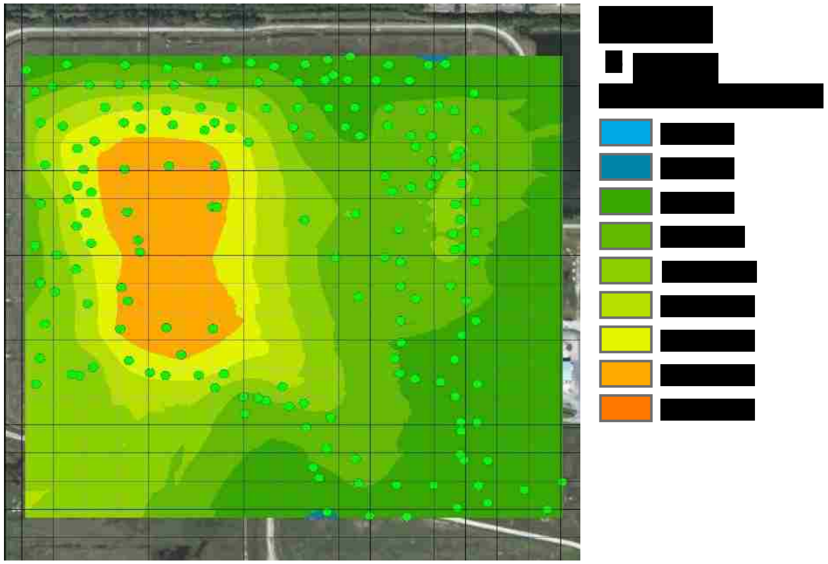
It is unlikely that the ETs found between 2010 and 2016 are from air intrusion, as Landfill B had very few gas wells with high Bal/(CO_2+O_2) ratios. As mentioned earlier, a Bal/(CO_2+O_2) ratio greater than 2.0 was used as a conservative threshold (3.73 is the problematic ratio) that would indicate potential air intrusion. As shown in Table 2, Landfill B had 1.1% of ET data points with a Bal/(CO_2+O_2) ratio greater than 2.0. Therefore, this suggests that air intrusion is likely not the cause of the ETs.

Therefore, it appears that whatever initiated the ETs may have been exhausted after the eight-year time period. This supports findings gathered from a study conducted by Yeşiller et al. (2005), which concluded that it took a significant amount of time for waste to decrease in temperature within the studied landfills. However, it is possible that the landfill may have had

ETs prior to 2010; unfortunately, we were unable to retrieve gas wellhead data for earlier years. Thus, it may have taken longer than eight years for the landfill to cool.



2010



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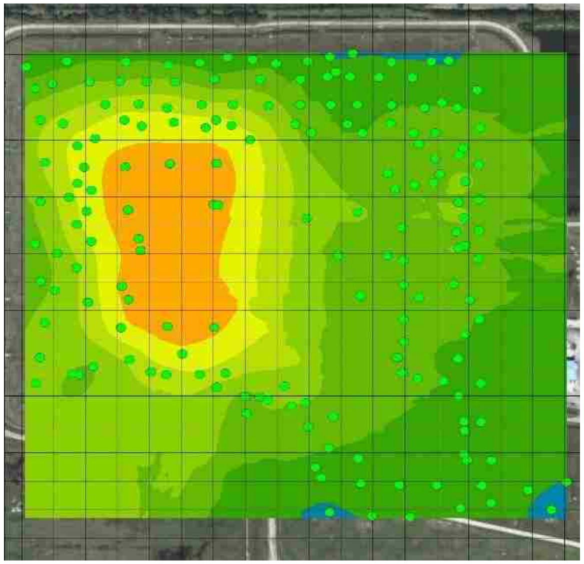
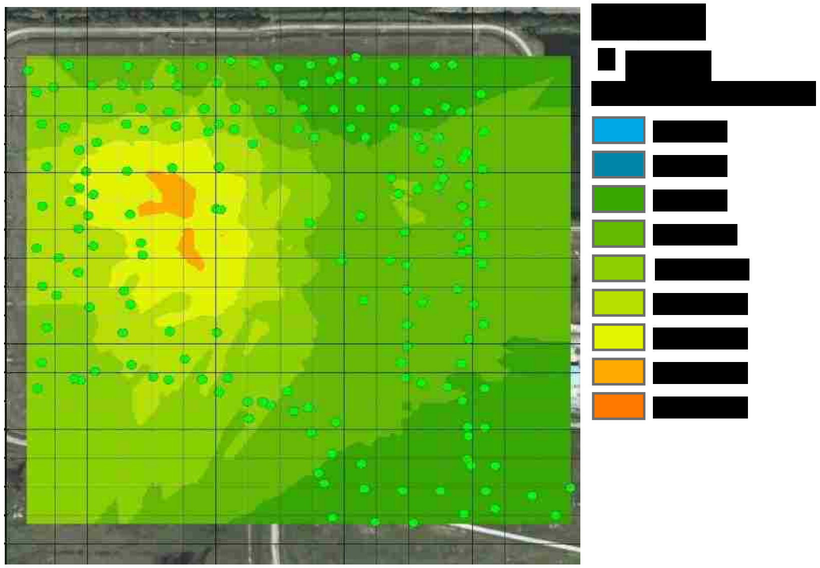


2012



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2013

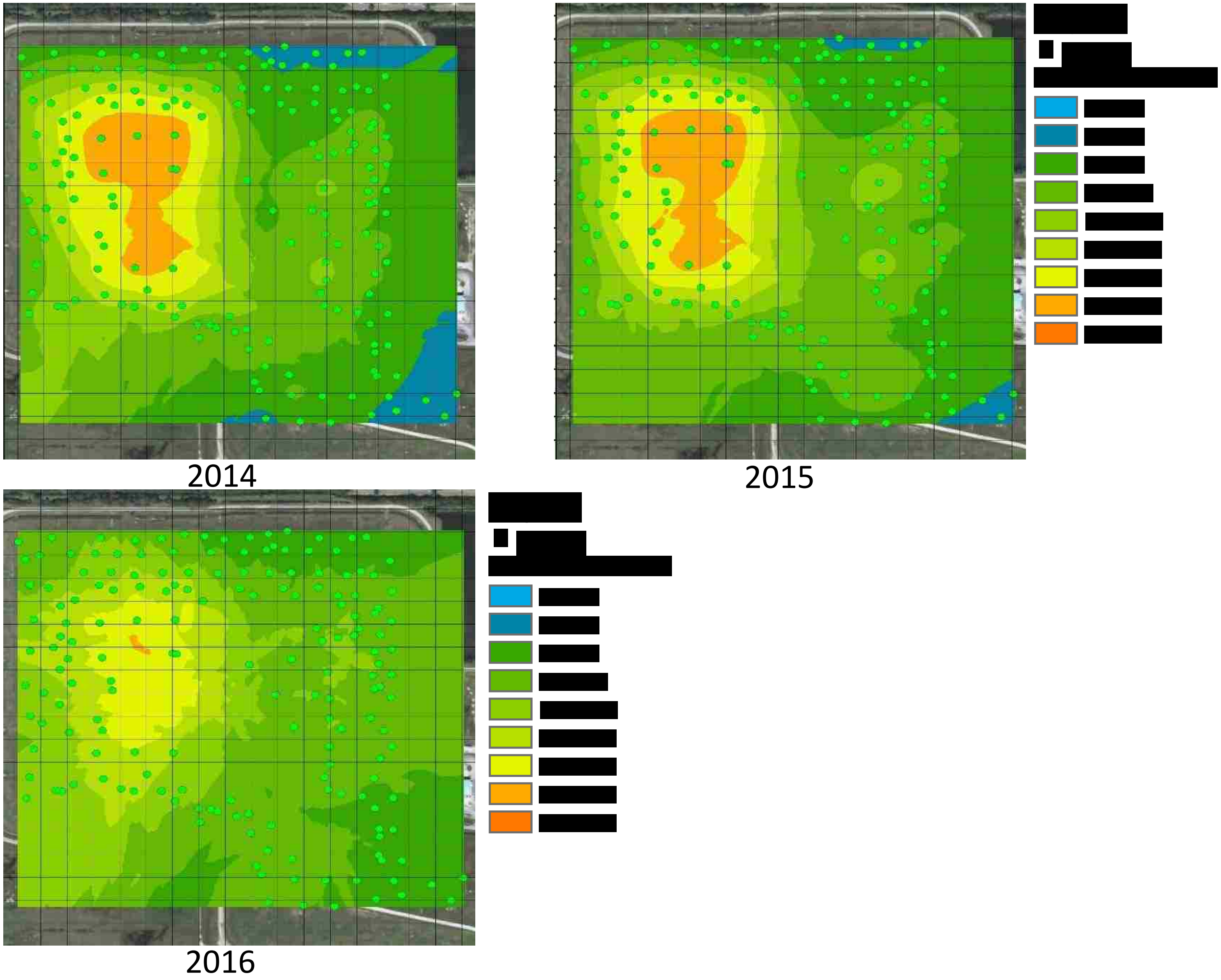


Figure 24: Temperature Contour Maps for Landfill B

Landfill R

Landfill R is an ET landfill with a current landfilled area of 158 acres and a maximum landfill depth of 144 feet. ETs have been reported in the central and southern sections of the landfill that covered approximately 25 acres at peak ET conditions (occurring in 2008). As with Figures 23 and 24, the ETs are represented by the orange colors shown in Figure 25.

This particular landfill accepts and disposes of ash within the landfill, as it is co-located with two incinerator units, both of which run year-round. In fact, on average, 80 percent of the waste disposed in this landfill (in tons) is ash residue.

As with Landfill N, new gas wells were constructed throughout the studied time period due to multiple landfill expansions. Thus, different colored squares (red, blue, and black) were included within the temperature contour maps to illustrate the various landfill expansions and document when they occurred; this information is also found within the legend of each landfill map. As indicated by the legend in Figure 25, new gas wells were constructed in 2011 and 2013, 2015, and 2017. The red square indicates the years 2007-2010, in which minimal gas wells were added. As seen in 2011, a few gas wells were added as the landfill expanded slightly northward. This is represented by the blue square added to the landfill maps in 2011-2012. However, a significant number of gas wells were also added in 2013, 2015, and 2017, as landfill expansions moved far northward; 2013 additions are portrayed by the black square.

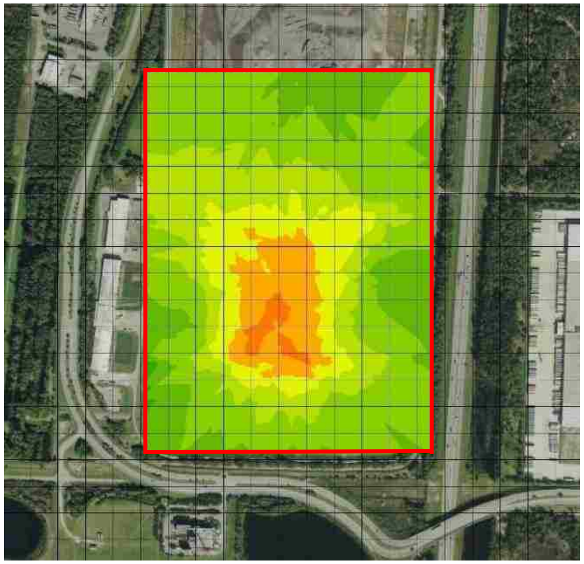
As shown in Figure 25, a pattern of heating and cooling occurred within this landfill between the years 2008-2011; the exact cause of this is not fully understood. However, several events occurred during this time span that may have contributed to the onset of ETs. In 2006, only 52% of the yearly waste disposed was ash, as a hurricane made landfill in late August/early September, causing yard waste and unburned MSW to be placed in the landfill. As was mentioned earlier in the chapter, fuel sources such as moisture and organic materials are necessary to heat-producing reactions. Therefore, it would make sense that ETs would develop in 2007-2008, as the additional moisture and organic matter may have reacted with calcium/lime content present in the ash. It is not clear as to what caused the temperatures to decrease again in 2009. In 2010, facility maintenance was occurring on the lone WTE incinerator unit (the second incinerator unit was not added until 2016). Due to the incinerator being down, only 44% of the yearly waste disposed was ash. It is hypothesized that the additional moisture and organic matter from the unburned MSW attributed to the increase in ETs in 2010.

No ETs were indicated by the temperature contour maps beyond 2012 (as seen in Figure B-3 in Appendix B); however, there were still instances of ETs within this landfill between 2012-2017, as shown in Figure 11. As additional wells were constructed in the northern section of the landfill in 2011, 2013, and 2015, it is possible that the number of high temperature wells remained the same, but the total number of wells increased, causing the interpolations to misrepresent what may be happening in the landfill. Interpolations utilize data from multiple points and construct a conservative value from it; thus, it is possible that the interpolations underestimated the incidence of ETs by “smoothing” out the data, as was mentioned in the Literature Review.

Furthermore, as seen in the contour maps between 2015-2018, there is a definite increase in temperature in the northern section of the landfill, as temperatures reached 120-130°F in 2017-2018. This area is where current waste is disposed, as additional landfill sections continue to be opened in the northern section of the landfill. Thus, incinerator maintenance in 2016 may have caused the increase in temperature due to additional unburned MSW being disposed in the northern section of the landfill. Although ETs are not present in the landfill contour maps between 2017 and 2018, there is a definitive increase in temperature in this section of the landfill, possibly with a few ET gas wells included. This is supported by Figure 11, which showed that the percent of ET data points increased slightly in 2017.

Therefore, it appears that the driver of the ETs in the southern section of the landfill may have been exhausted after a 10-year period. It is possible that Landfill R may have had ETs prior to 2007, as there was a brief reduction of ash content in 2005 (when compared to 2002-2004). Unfortunately, we do not have enough gas data to create interpolation maps for 2005-2006, as the contour maps would be incorrectly skewed due to the lack of gas well data. Thus, this is just a hypothesis as to what might have occurred in the past.

Furthermore, little heat movement occurred within this landfill, as ETs were contained in the central and southern sections of the landfill in 2007-2008 and 2010. In addition, non-ETs between 120-130°F were contained within the central-northern section of the landfill between 2017-2018. However, heating and cooling did occur in this landfill, fluctuating between 2007 and 2011 and increasing in temperature between 2015-2018.



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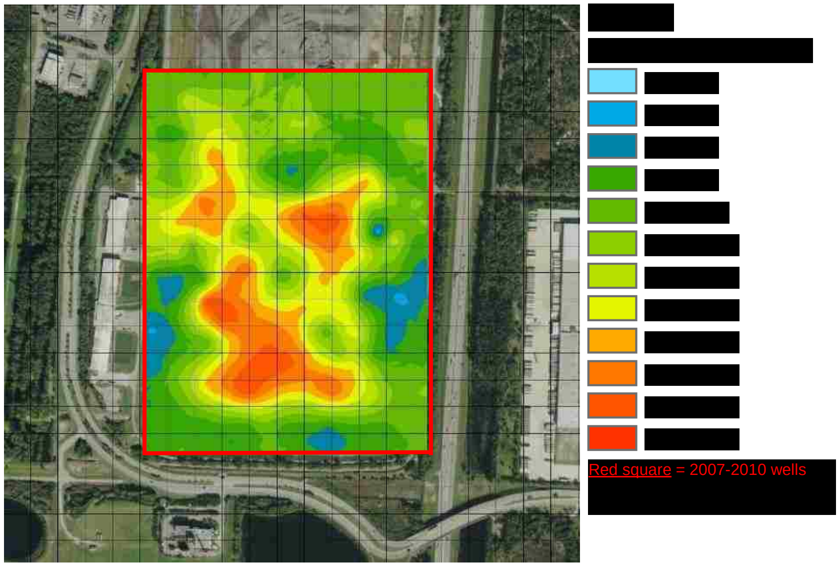

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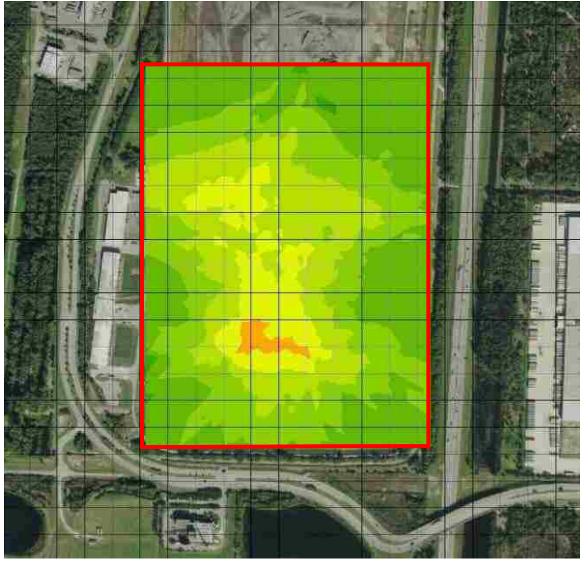

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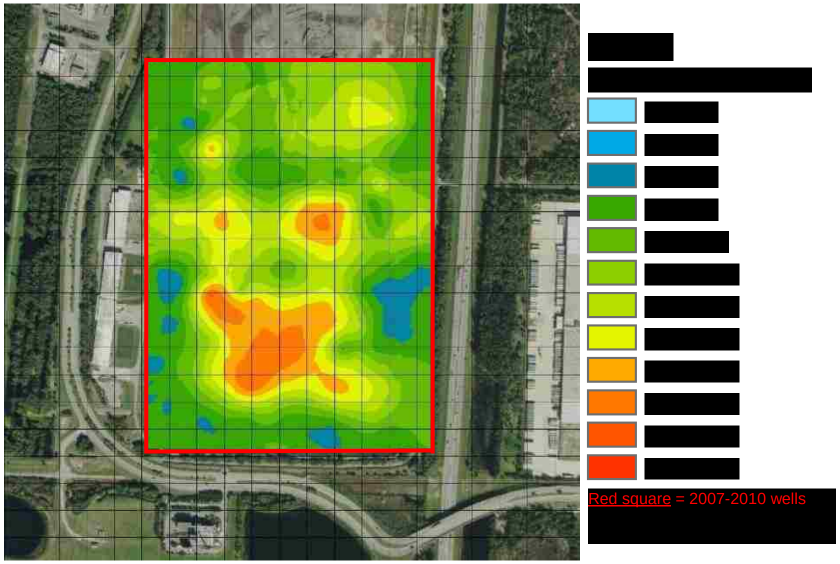

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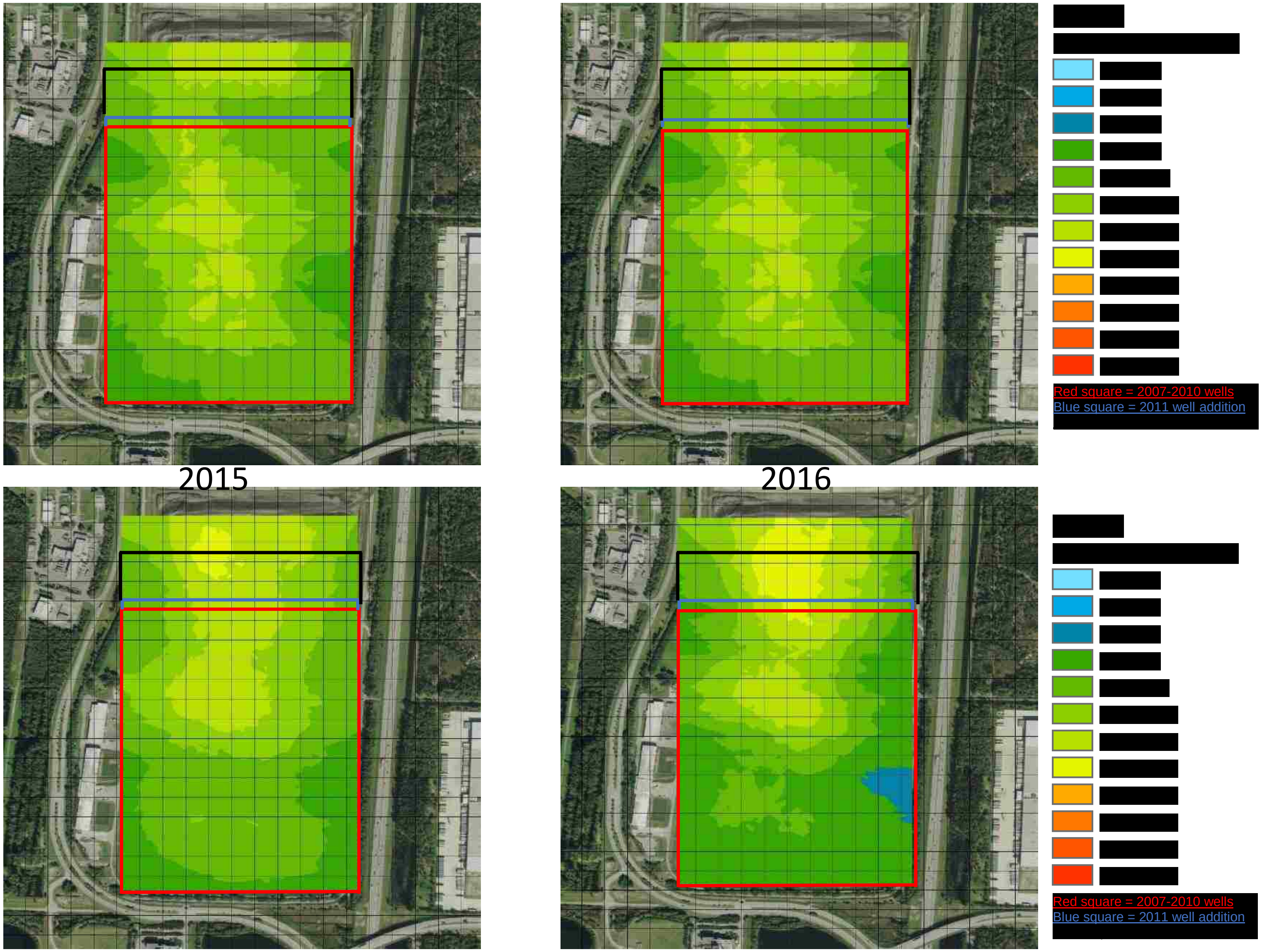


2015

2016

2017

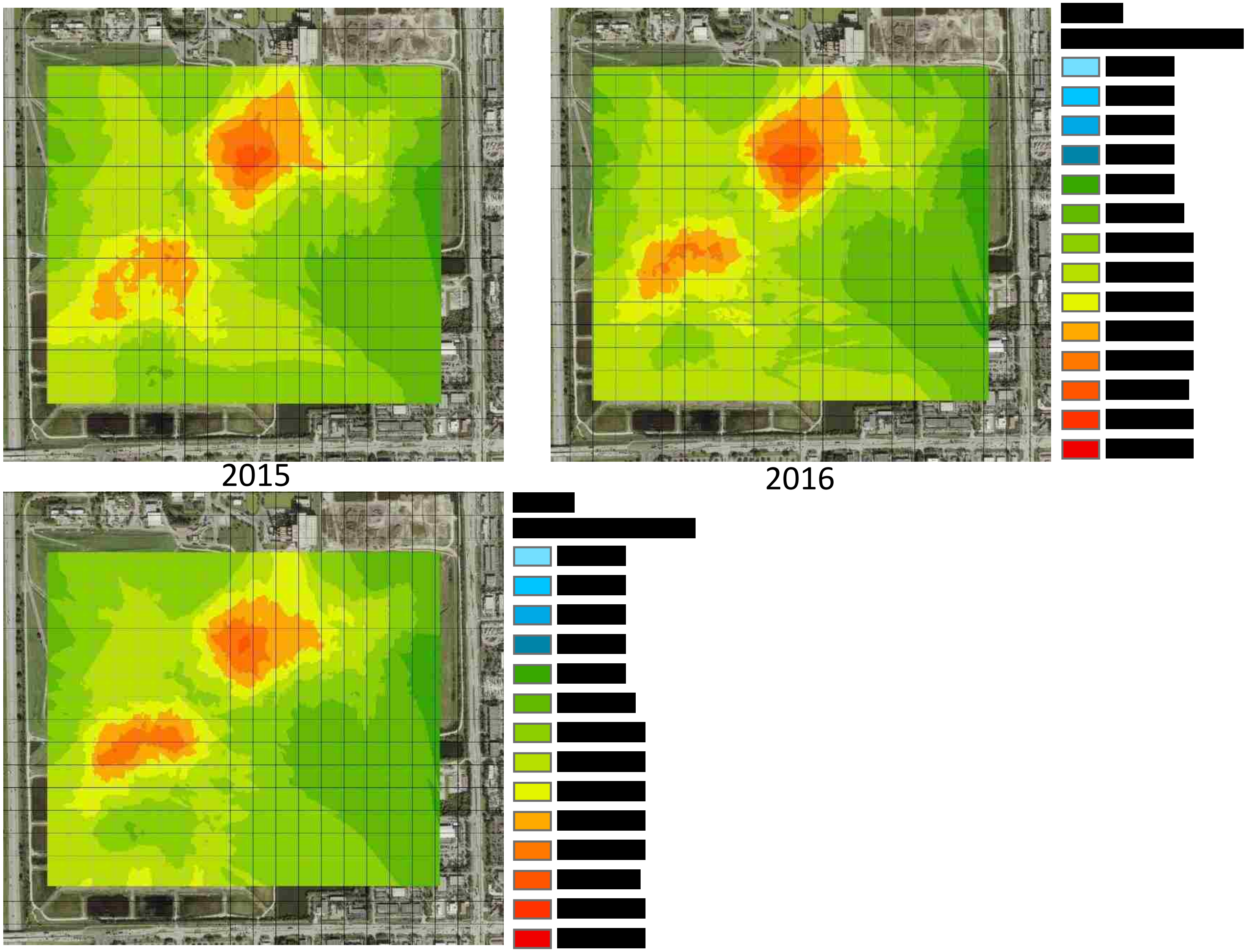
2018

Figure 25: Temperature Contour Maps for Landfill R

Landfill G

Landfill G is an ET landfill with a current landfilled area of 252 acres and a maximum landfill depth of 200 feet. ETs have been reported in the northern and western sections of the landfill that covers approximately 52 acres at peak ET conditions (occurring in 2016). Both zones containing ETs are in somewhat confined locations, showing little heat movement. As with previous Figures 23-25, the ETs are represented by the orange colors shown in Figure 26.

Ash is accepted and disposed within the landfill; it may be hypothesized that the regions in which ETs are located are the primary areas in which ash may have been disposed; exact locations are unknown, however. Unlike the previous three landfills, there is no pattern of heating and cooling in Landfill G; instead, temperatures remain elevated in the northern and western sections during the entirety of the researched time period. Unfortunately, it was not possible to obtain gas wellhead data for this landfill before 2015; thus, it is possible (and very likely) that this landfill had ETs prior to 2015. From data available, it can be observed that slight heating occurred in the northern ET zone between 2015 and 2016, and minimal cooling was exhibited in the same ET zone between 2016 and 2017.



2015

2016

2017

Figure 26: Temperature Contour Maps for Landfill G

Summary

Based on the temperature contour maps created for the four ETLFs, it is apparent that in most landfills, minimal heat propagation is occurring. Instead, these landfills experienced fluctuations of heating and cooling, with half of them cooling to non-ETLF scenarios within the researched time period. This supports the idea that ETs created by a particular waste may decrease in temperature over a time period if not influenced by another driver (Yeşiller et al., 2005). Thus, it is possible that with enough time, Landfill G may soon cool, as gas wells were not turned off at this landfill.

Landfill N is the only landfill that experienced heat propagation. However, it is possible (and likely) that had workers not turned off the gas wells, temperatures would have naturally reduced when the initiating material substance was exhausted (in this case the ash/biosolids mixture), similar to what occurred in Landfills B and R.

Impact of Temperature on Gas Quality

This thesis has clearly emphasized the impact that ETs have on CH_4 quality within landfills. As shown in Figure 21, it was discovered that as temperatures increased, CH_4 to CO_2 ratios decreased.

As with the temperature contour maps created above, CH_4 to CO_2 ratio maps were created for four ETLFs using ArcGIS. CH_4 to CO_2 maps primary displayed results during periods of ETs to determine if there was correlation between low CH_4 to CO_2 ratios and high temperatures. However, in certain cases, maps were also created for non-ET periods, as two of the ETLFs had very high CH_4 to CO_2 ratios, some reaching above 2.0 for long periods of time.

Unlike in the previous section, temperature and CH_4 to CO_2 ratio landfill contour maps will be placed side-by-side for each respective year in order to display potential correlations between the data. For example, temperature contour maps for 2007 will be placed adjacent to CH_4 to CO_2 ratio maps for 2007. To account for the potential gaps in data, CH_4 to CO_2 maps for each of the four ETLFs can be found in Appendix B. These maps exhibit CH_4 to CO_2 contours throughout the entirety of the testing period, even during times in which the ETLFs no longer had ETs.

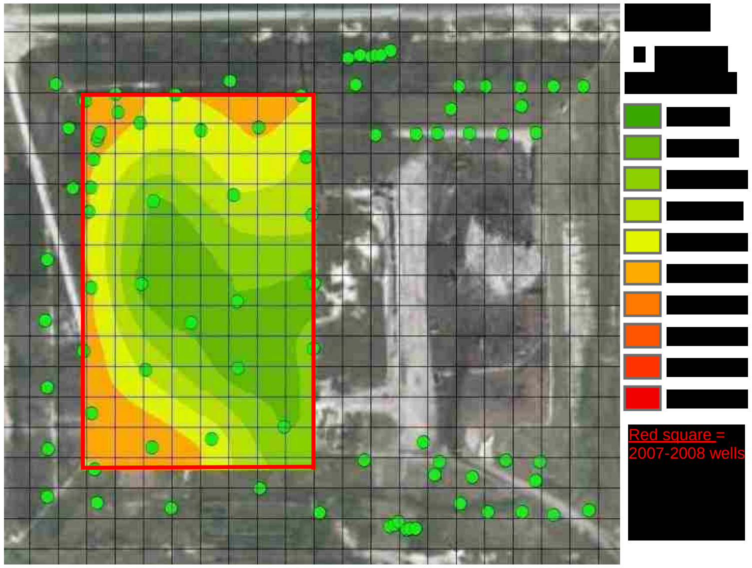
Landfill N

As in the previous section, gas composition data (CH_4 and CO_2 readings) were provided for Landfill N between 2007-2018; however, as gas wells were shut off between 2013-2016, CH_4 to CO_2 maps were not included for this time period. CH_4 to CO_2 maps for this landfill are found in Figure 27.

As stated earlier in this chapter, low CH_4 to CO_2 ratios often indicate that CH_4 quality has been inhibited, likely due to high temperatures. Unlike with gas temperatures shown in Figure 23, low CH_4 to CO_2 ratios were primarily confined to a small section in the western portion of the landfill, measuring approximately 3.5 acres at its largest in 2008. CH_4 to CO_2 ratios below 1.0 were not found in ET zones between 2010-2012. This is odd, as ETs were prevalent within the western section of the landfill during this time period. However, ETs reported between 2007-2012 were between 131-150°F (at its peak). This supports the idea that CH_4 quality may not be greatly inhibited at ETs less than 150°F, as mentioned earlier in the 'Cumulative Landfill Analysis' section.

CH_4 to CO_2 ratios below 1.0 were reported between 2017-2018 in the central-western section of the landfill. However, as previously documented, gas temperatures in this portion of the landfill were much greater during these two years (reaching above 170°F) due to the gas wells being turned off between 2013-2016. Therefore, these findings coincide with the idea that CH_4 quality may only be greatly inhibited at gas temperatures greater than 150°F.

On average, CH_4 to CO_2 ratios for Landfill N ranged between 0.70-1.60 depending on the region of the landfill. High CH_4 to CO_2 ratios were not characteristic of the ET wells, although many ET wells had CH_4 to CO_2 ratios between 1.0-1.15; this even occurred between 2017-2018, when the inactive gas wells were re-introduced to the gas system.



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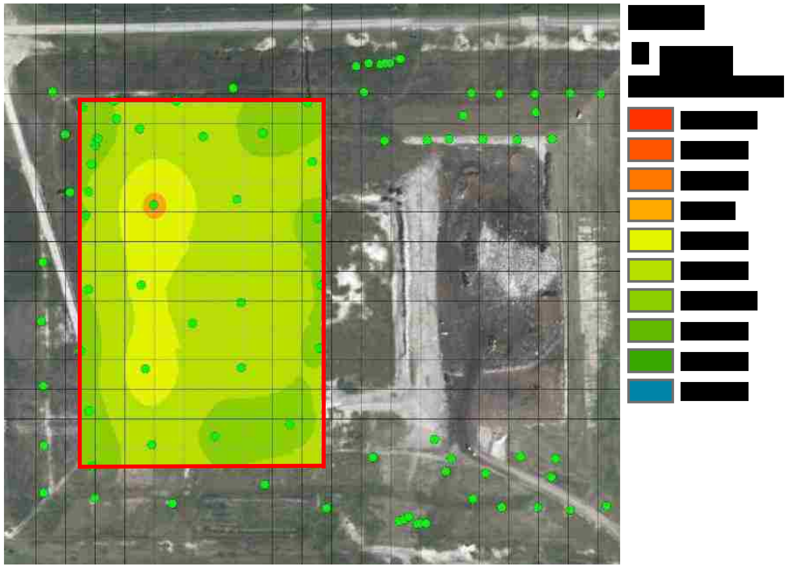

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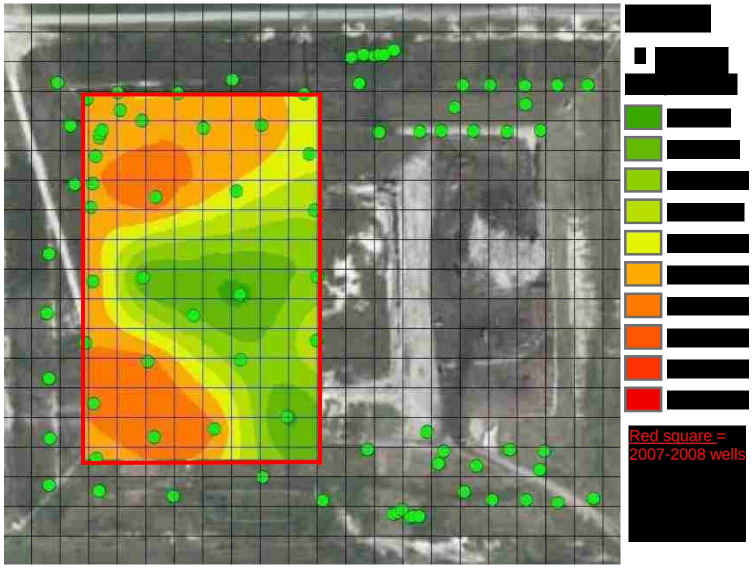

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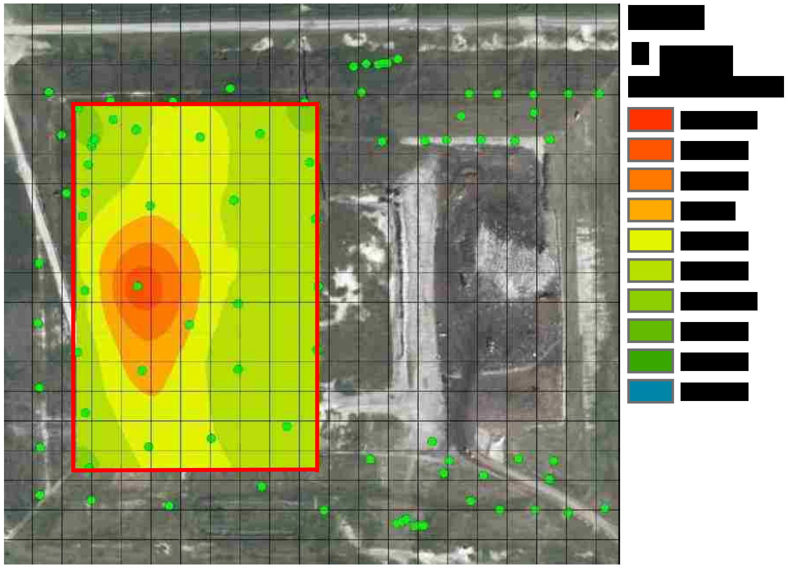

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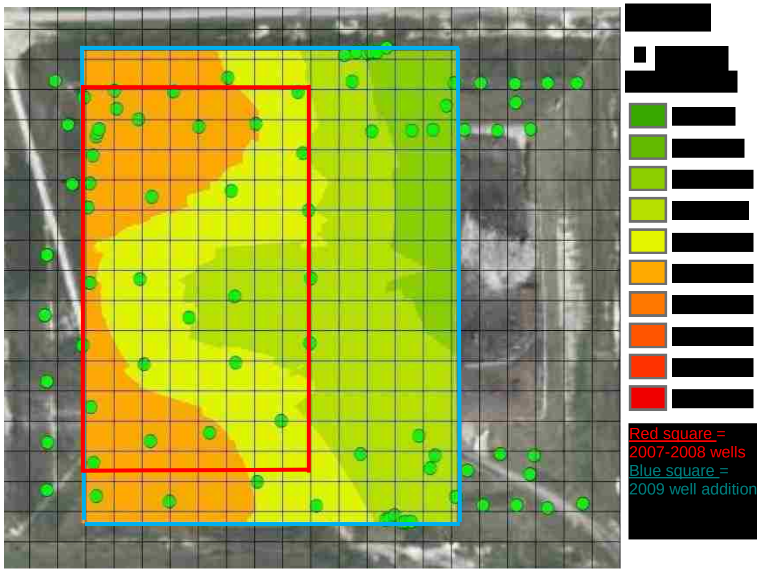

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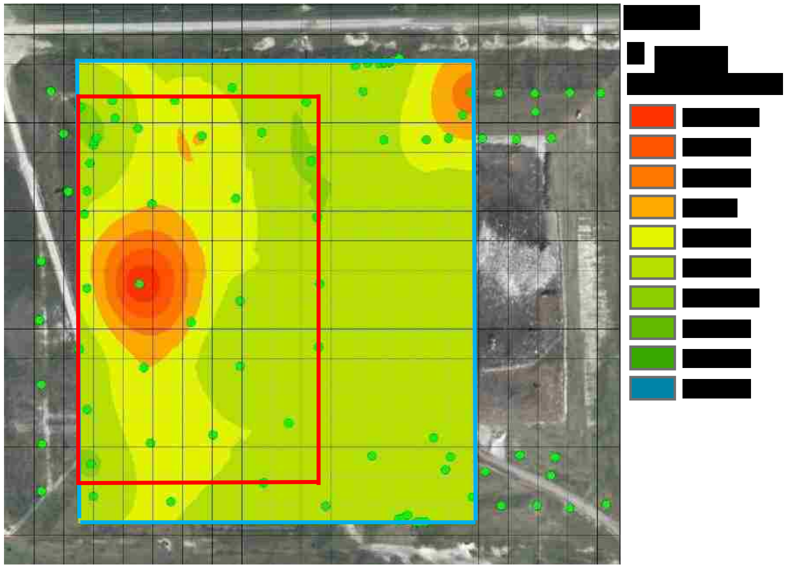

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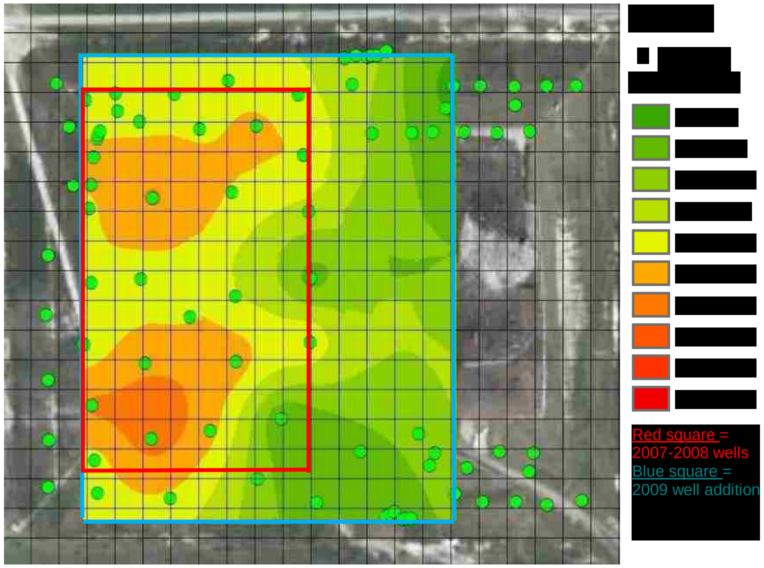

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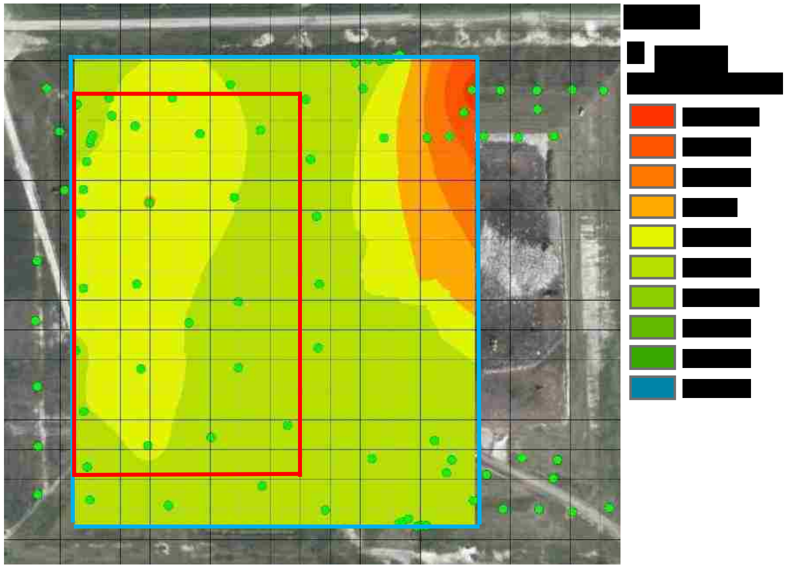

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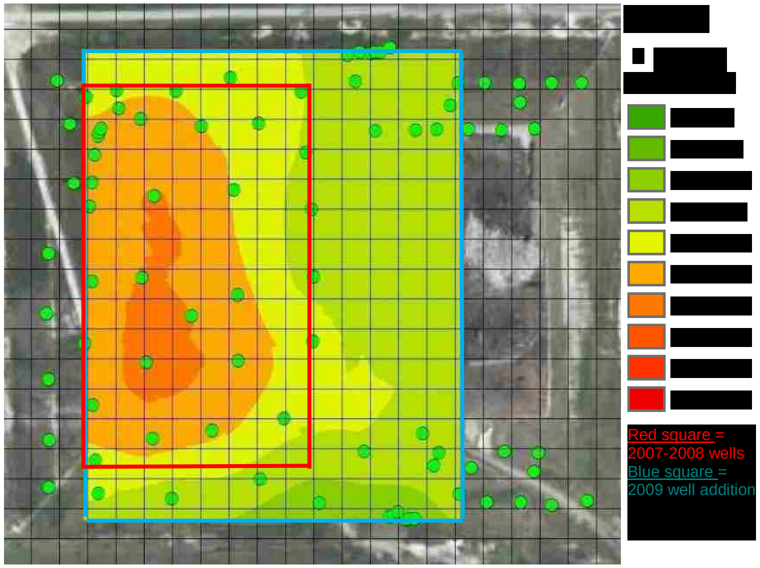

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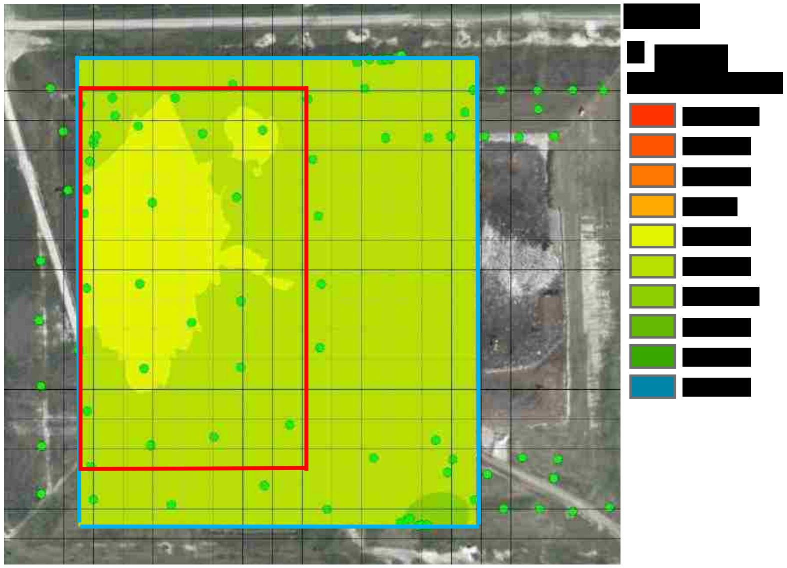

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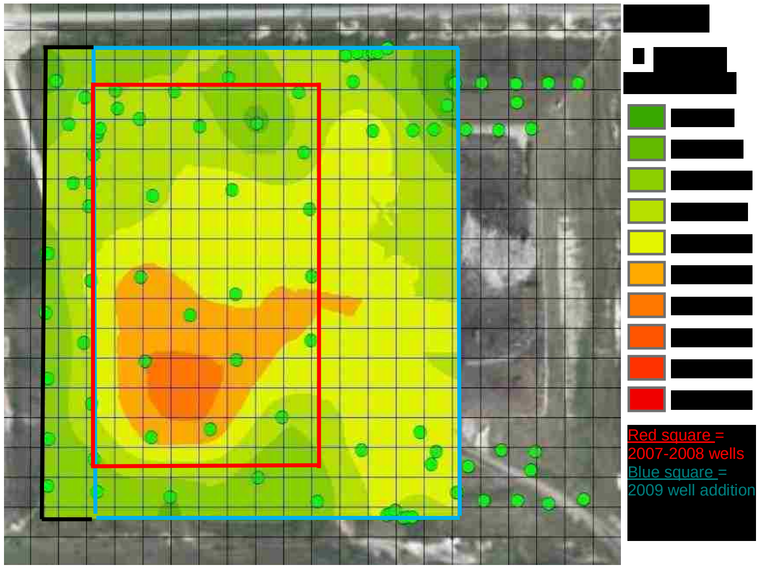

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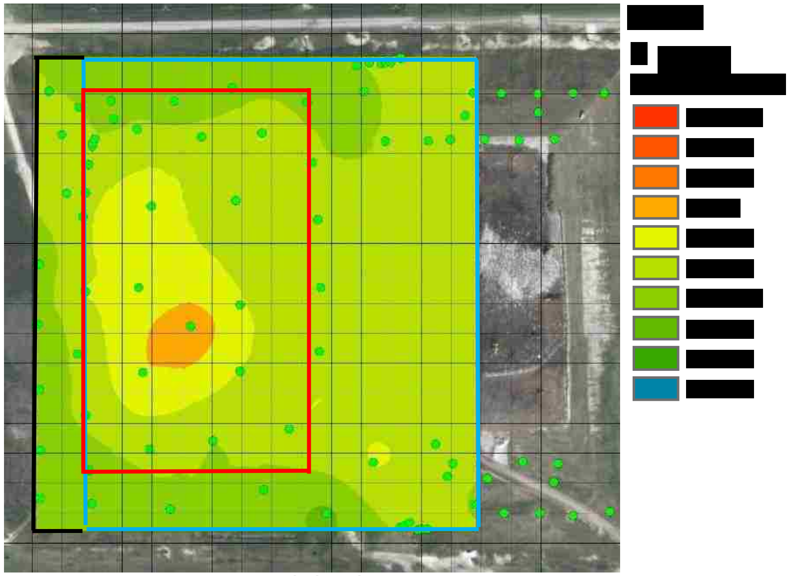

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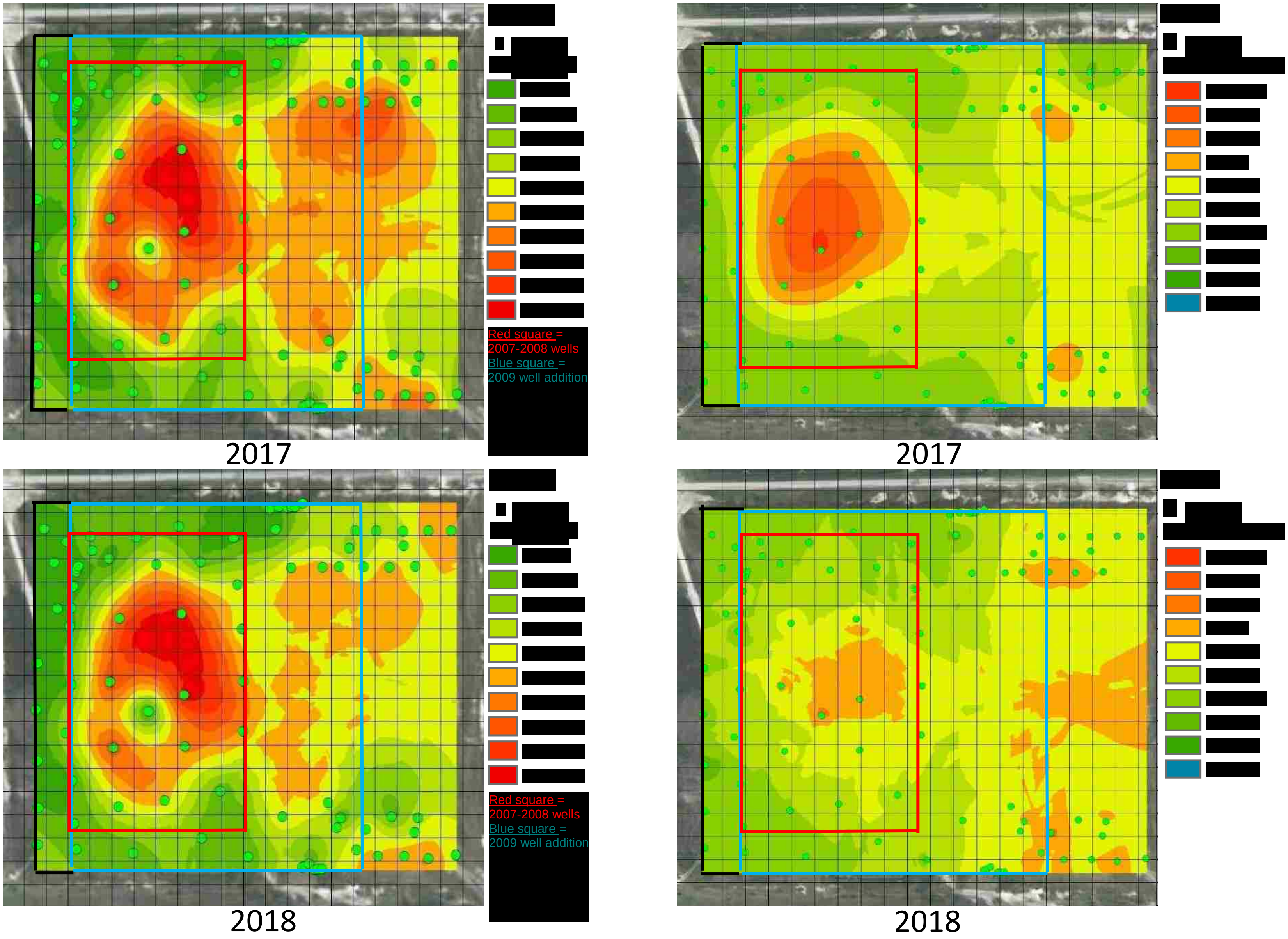


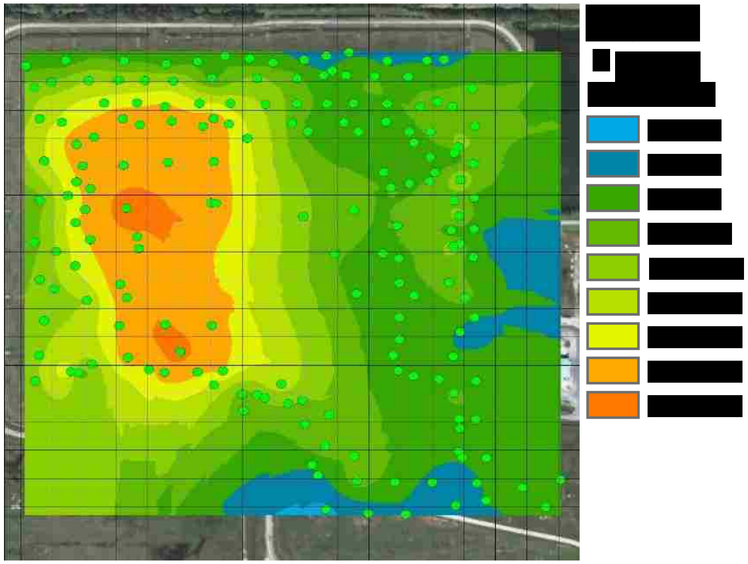
Figure 27: CH_4 to CO_2 Maps for Landfill N

Landfill B

Gas wells at Landfill B did not exhibit low CH_4 to CO_2 ratios; instead, CH_4 to CO_2 data points were above 1 for most gas wells. As seen in Figure 28, ETs were experienced in the northwestern section of the landfill between 2010-2015; however, very few CH_4 to CO_2 ratios below 1 were reported in this section of the landfill. Rather, gas wells in the ET zone had average CH_4 to CO_2 ratios between 1.0-1.15. It appears that even with spot occurrences of low CH_4 readings (as certain wells did have short time periods where CH_4 to CO_2 ratios were less than 1), interpolating the data "smoothed" out the outlier readings within the landfill maps.

CH_4 to CO_2 maps for 2016-2018 are not shown in Figure 28 as ETs were not reported in these years; these maps can be found in Figure B-2, which is located in Appendix B. In fact, CH_4 to CO_2 ratios above 2.0 were experienced in the northeastern section of the landfill, especially during 2016-2018. One landfill professional suggested that ETs may increase the precipitation of carbonates, resulting in reduced CO_2 production and thus a higher CH_4 to CO_2 ratio (Dr. Morton Barlaz, Mar. 2019, Personal Communication). This would only occur in high pH environments, and as the pH of the waste mass is unknown, this can only be suggested as a theory to what might be occurring. The high CH_4 to CO_2 ratio section of the landfill did not experience ETs during the studied period; thus, it cannot be assumed that this is undoubtedly the reason for high CH_4 to CO_2 ratios. This is just a suggestion of what may be occurring.

However, results from Landfill B reinforce the idea that CH_4 quality may only be inhibited at gas temperatures greater than 150°F, as gas temperatures within Landfill B did not exceed 150°F, and thus, CH_4 to CO_2 ratios below 1 were not experienced.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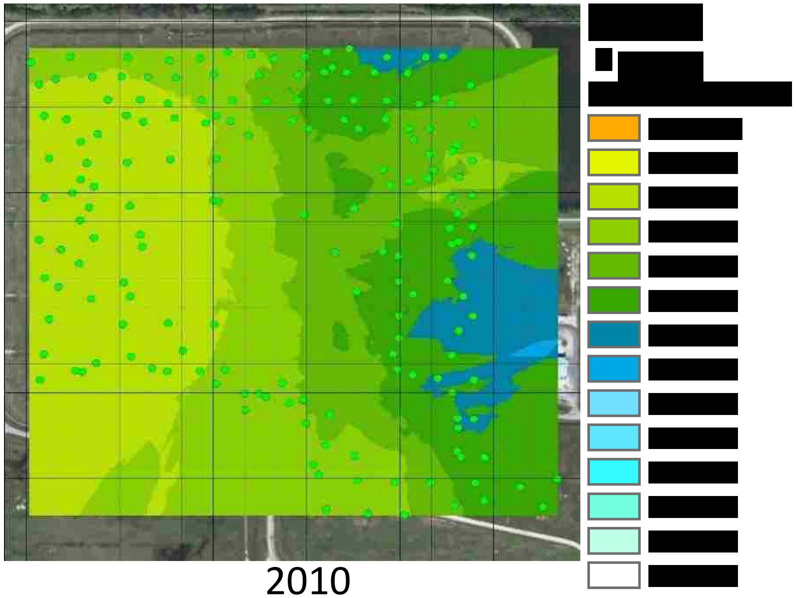
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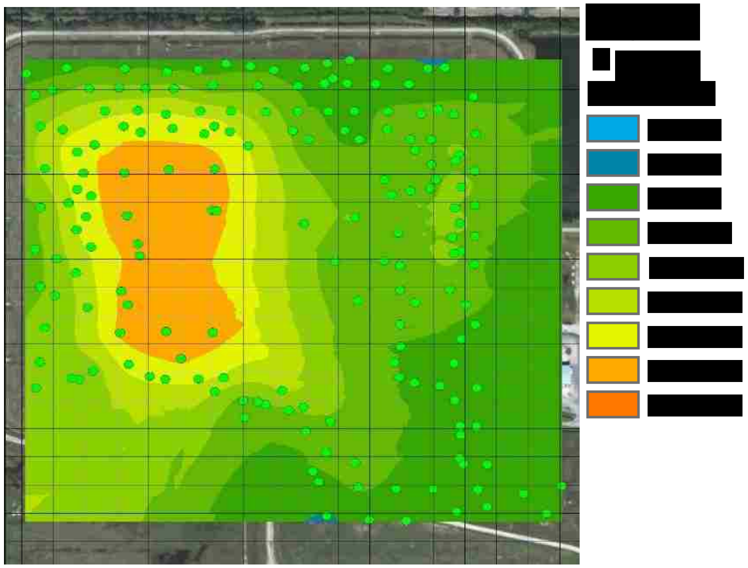
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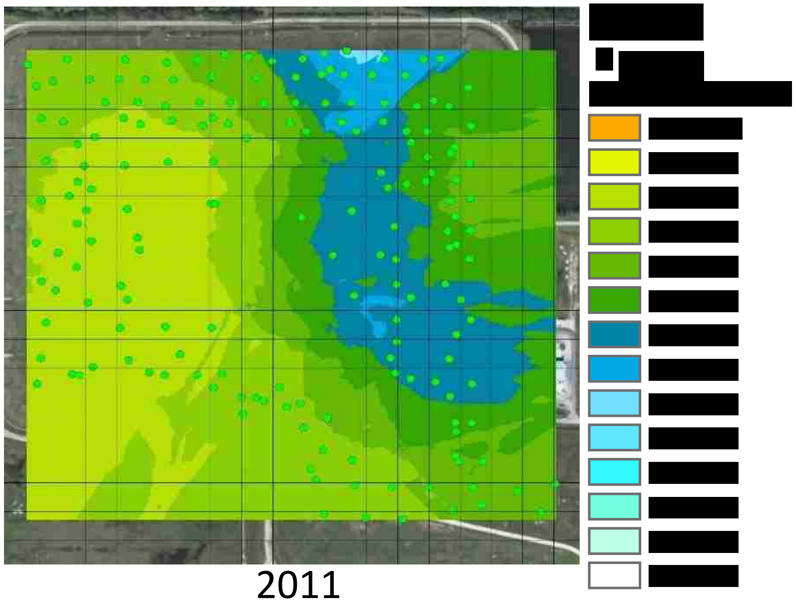
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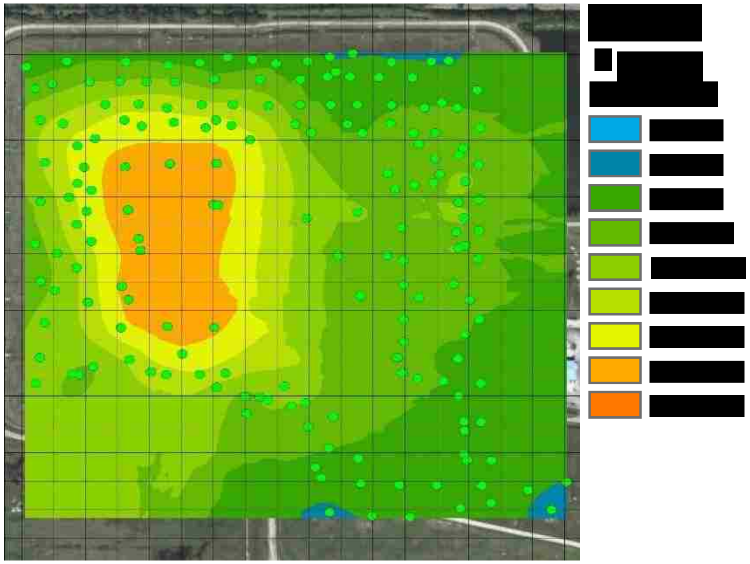

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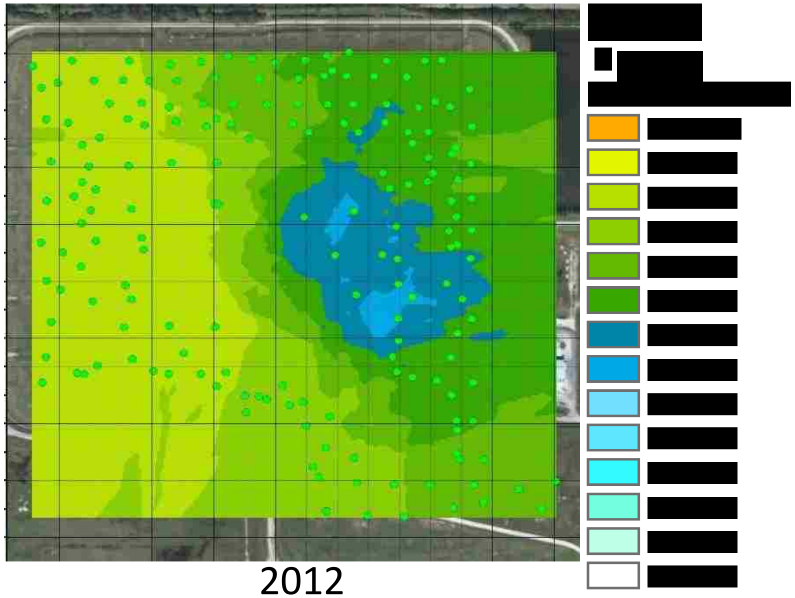

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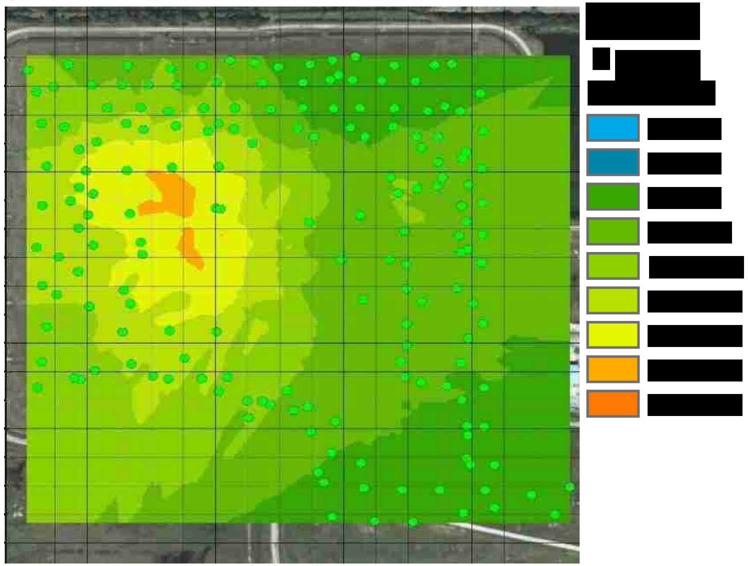

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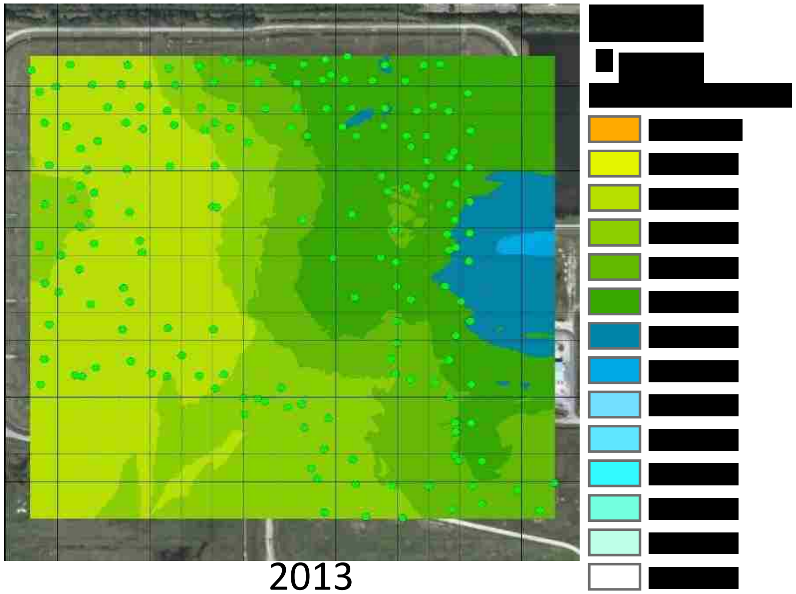

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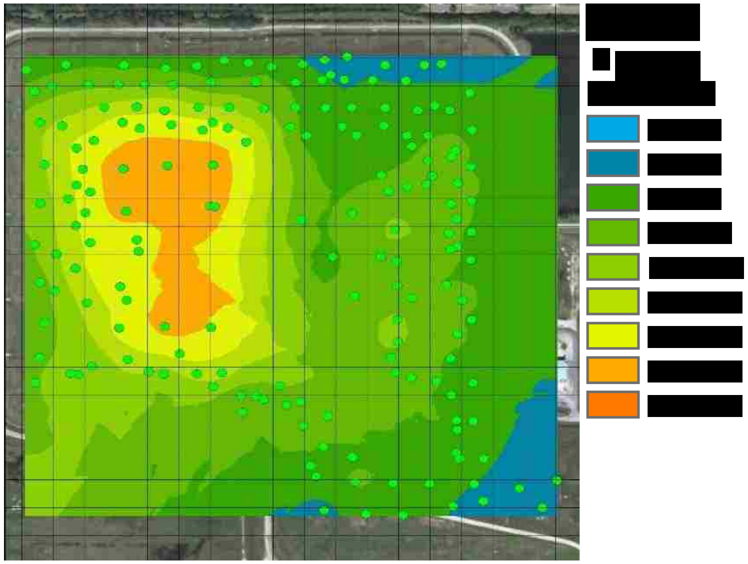

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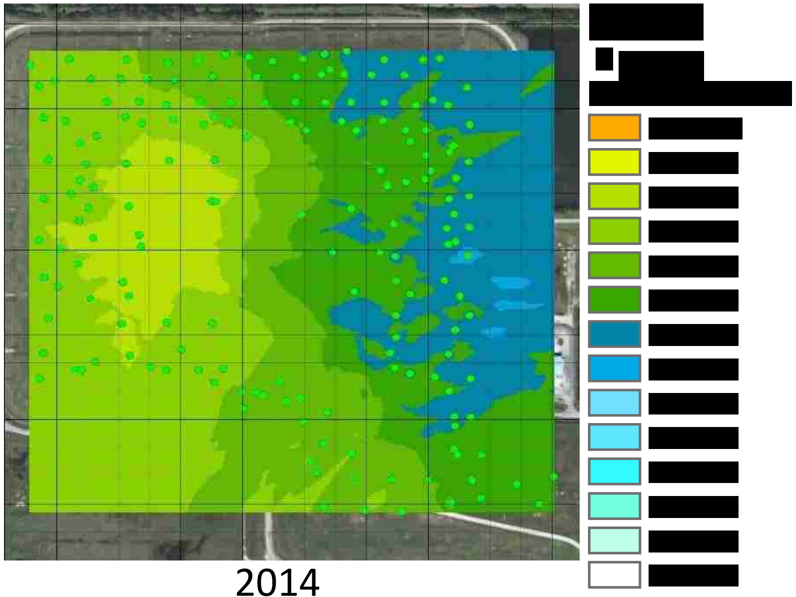

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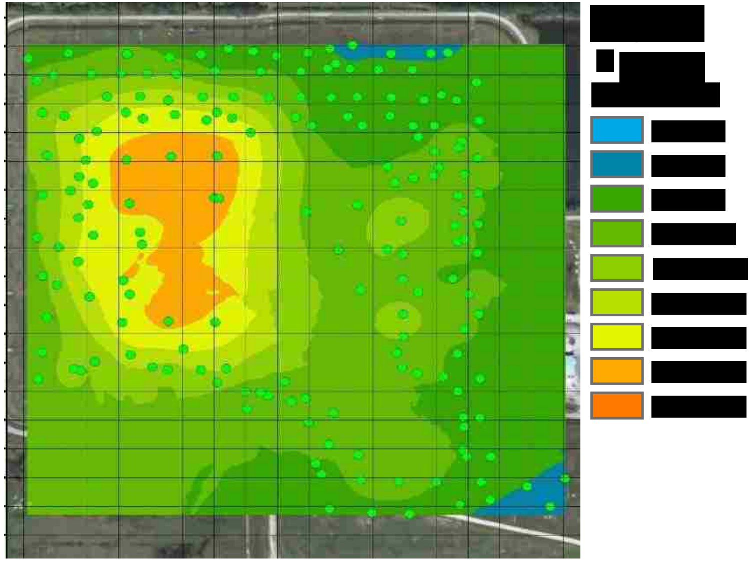

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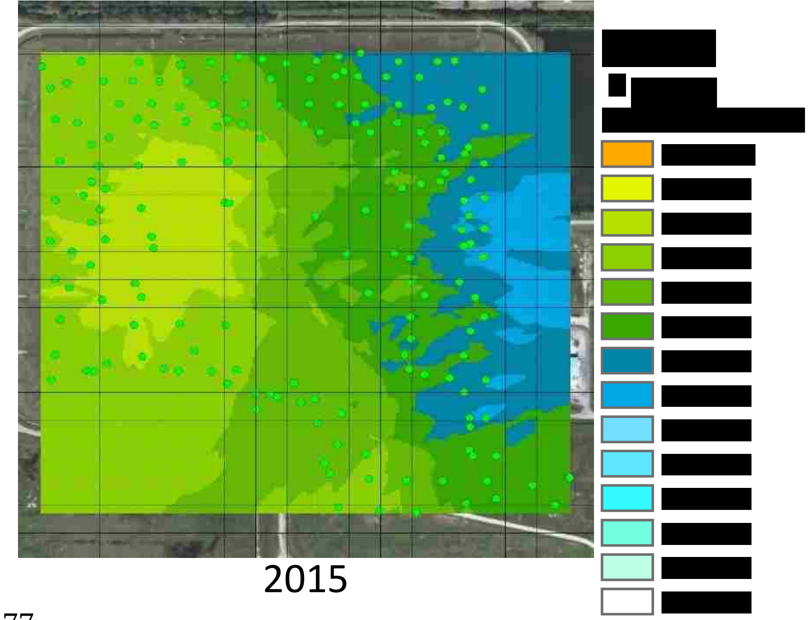

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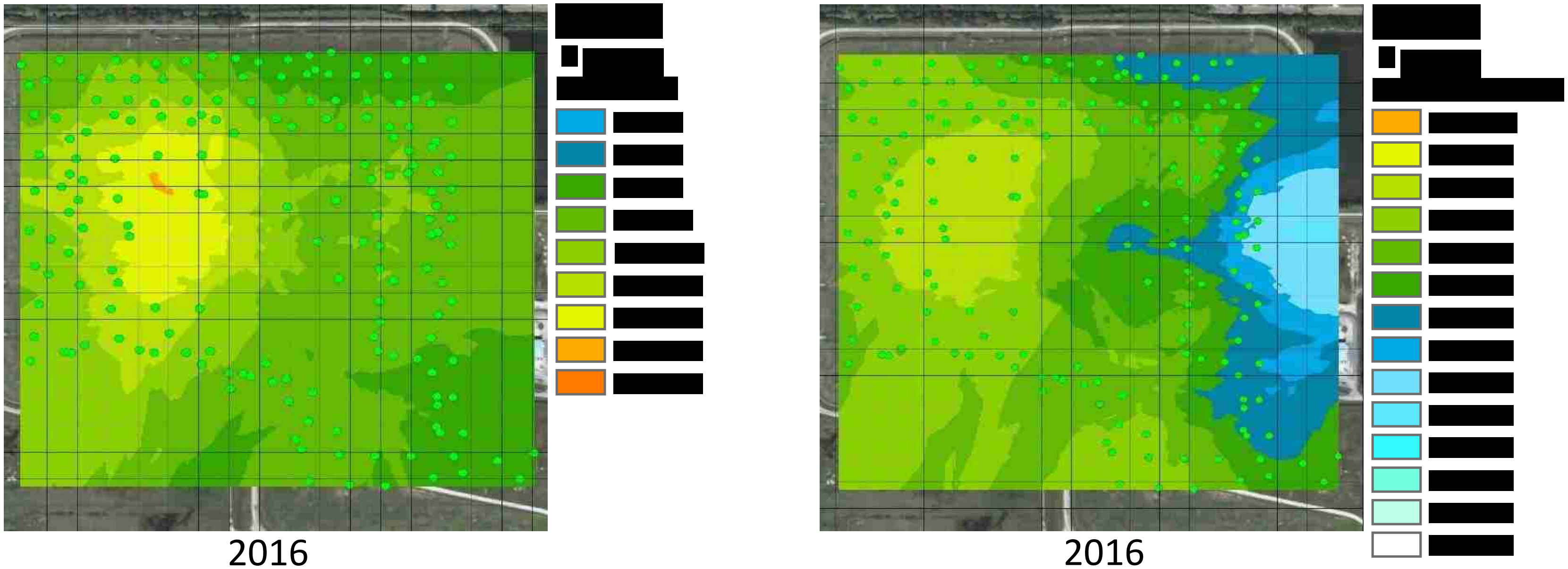

2016

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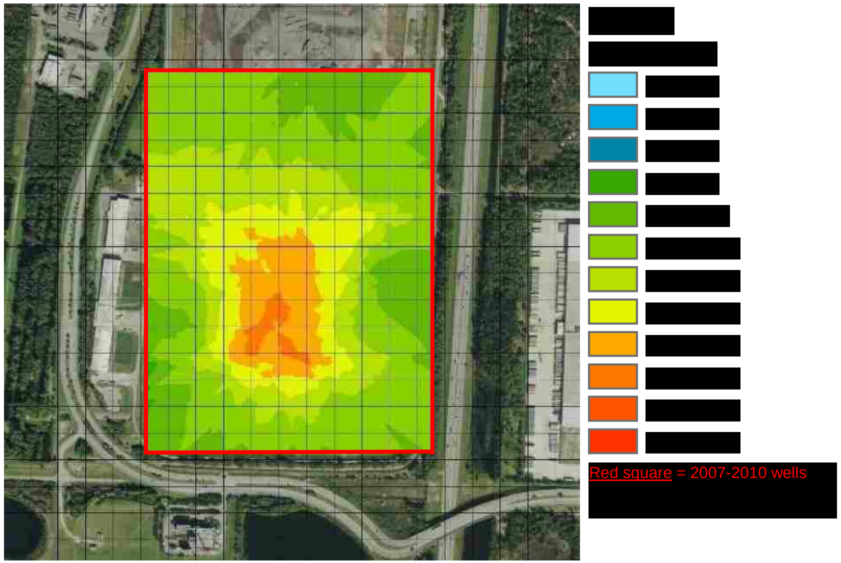
Figure 28: CH_4 to CO_2 Maps for Landfill B

Landfill R

As shown in Figure 29, CH_4 to CO_2 maps for Landfill R exhibited similar characteristics to those created for Landfill B. ETs were experienced between 2007-2010 in the southern section of the landfill; low CH_4 to CO_2 ratios below 1.0 were not observed in this section. Instead, high CH_4 to CO_2 ratios above 2.0 were reported in the southern section of the landfill between 2007-2011. As mentioned earlier, it was suggested that ETs may increase the precipitation of carbonates, resulting in reduced CO_2 production and thus a higher CH_4 to CO_2 ratio (Dr. Morton Barlaz, Mar. 2019, Personal Communication). However, ETs were only experienced in small sections within the high CH_4 to CO_2 ratio zone; therefore, it's not conclusive evidence that high CH_4 to CO_2 ratios are a result of the ETs.

Results from Figure 29 reinforce the idea CH_4 quality may only be inhibited at gas temperatures greater than 150°F, as gas temperatures within Landfill G did not exceed 150°F. Even in 2007 and 2010, where temperatures reached approximately 150°F, gas wells did not report CH_4 to CO_2 ratios below 1. It is possible that this is due to the interpolations "smoothing" out the dataset; however, this landfill has a significant number of ET gas wells throughout the landfill, meaning that readings are not likely being averaged or pulled from far distances.



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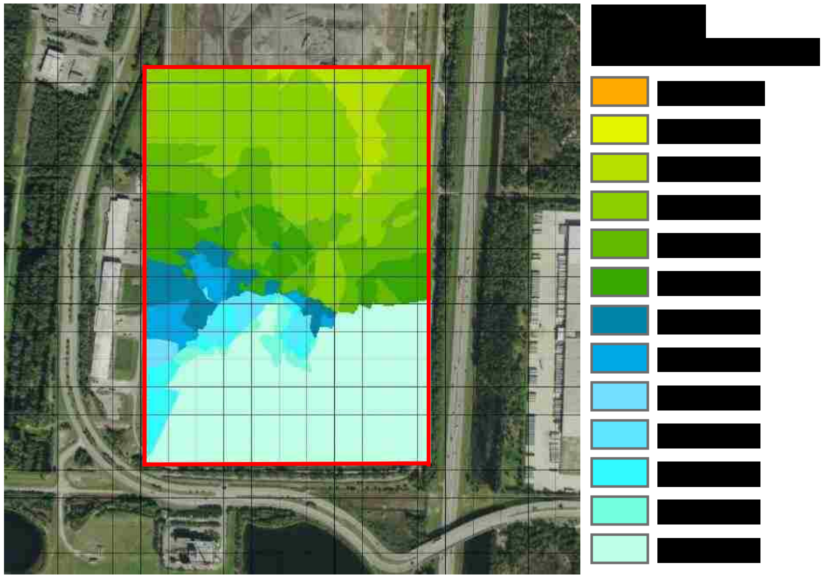

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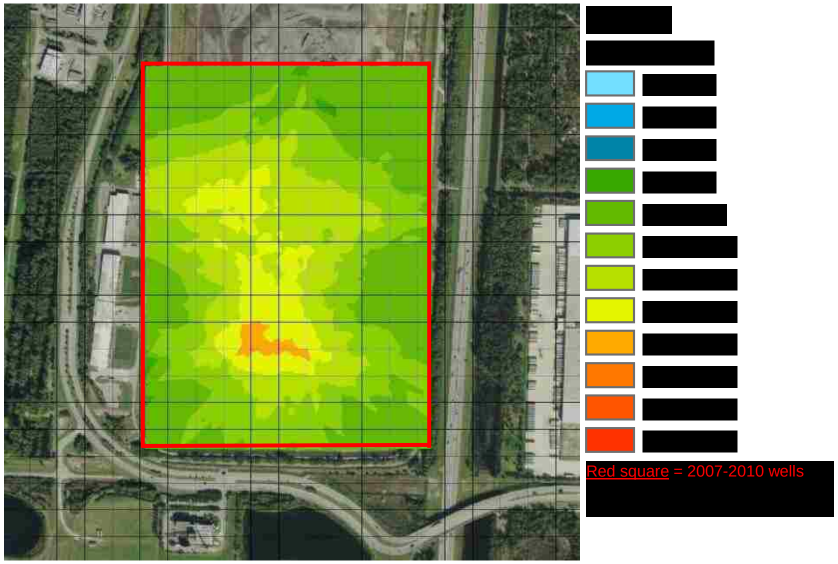

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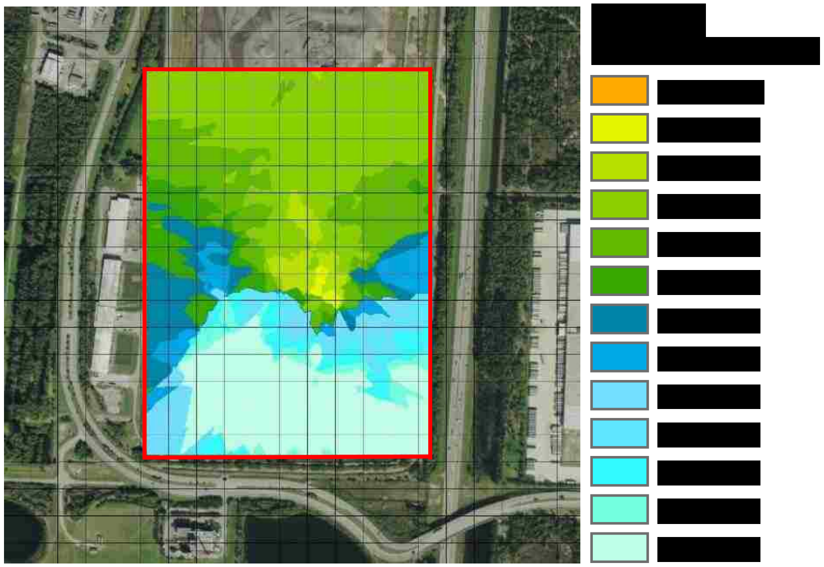

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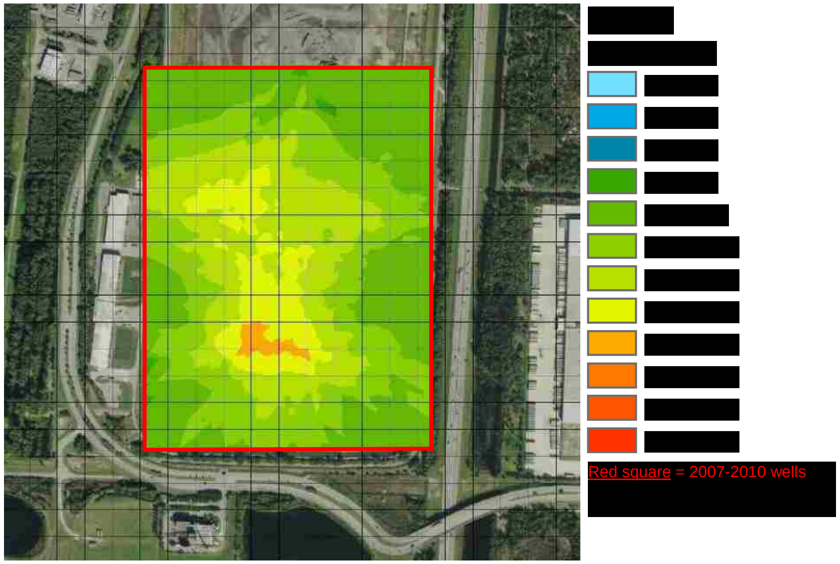
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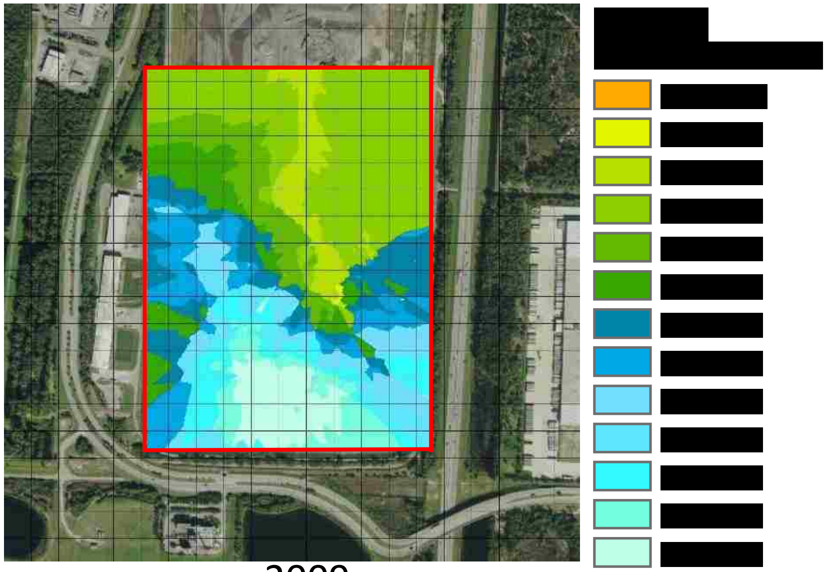
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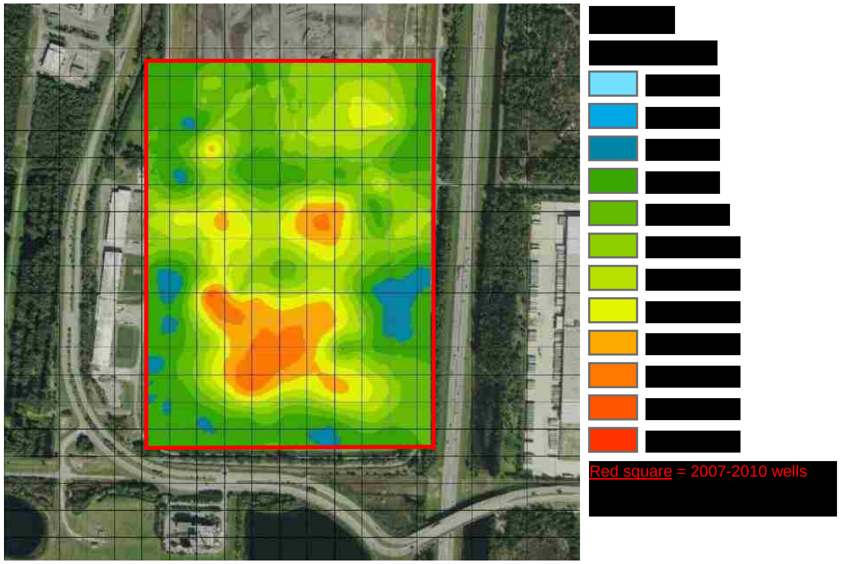
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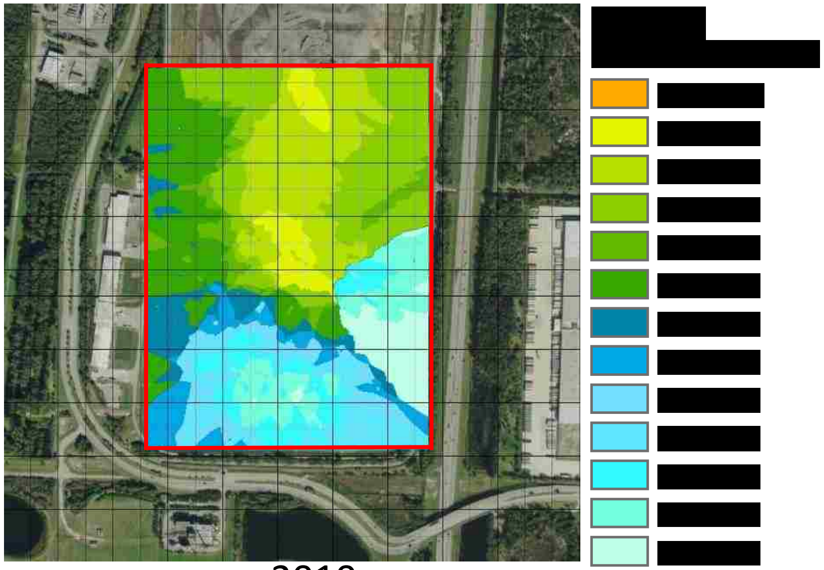
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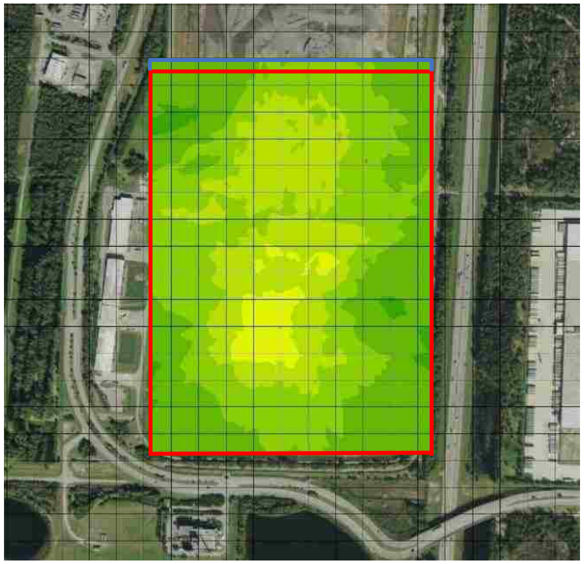

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Red square = 2007-2010 wells
Blue square = 2011 well addition
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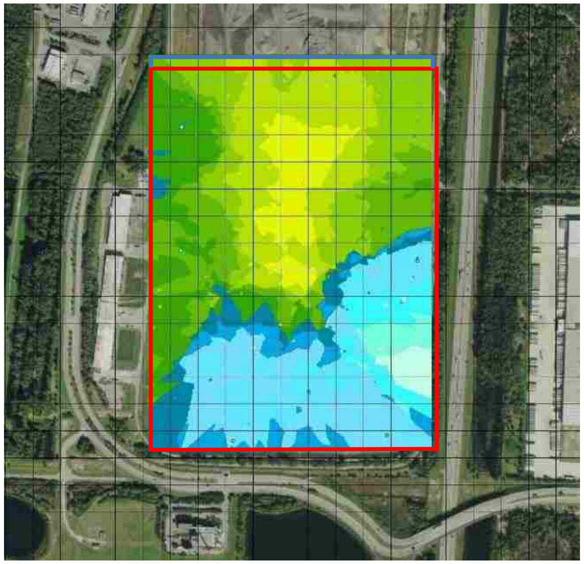

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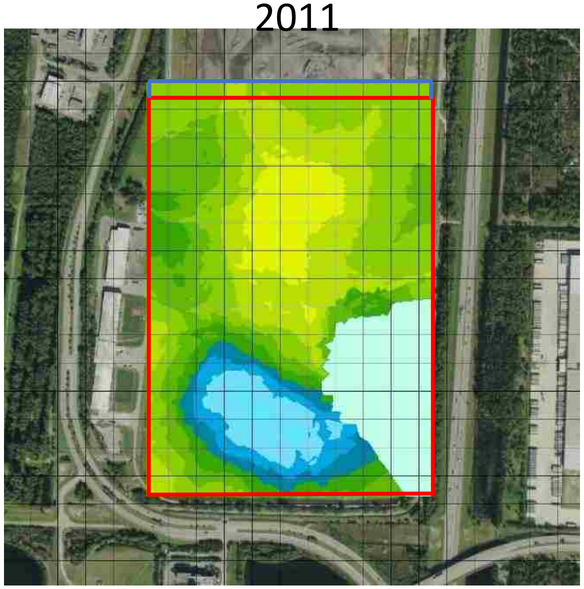

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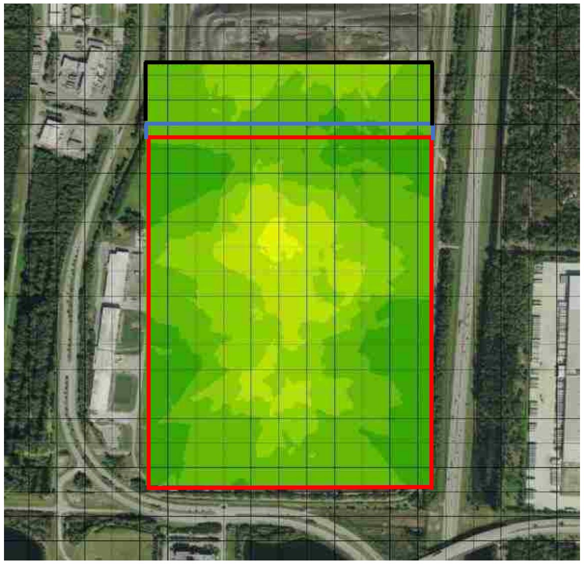

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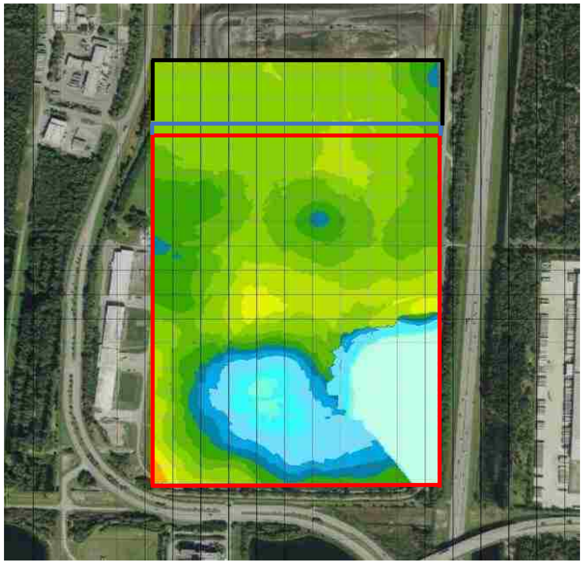

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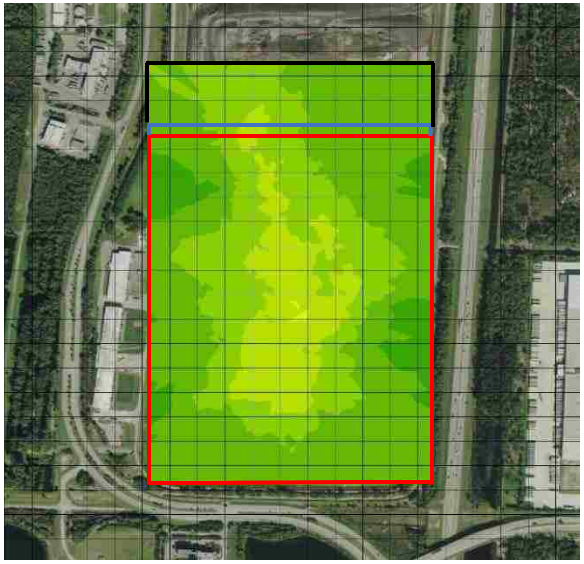

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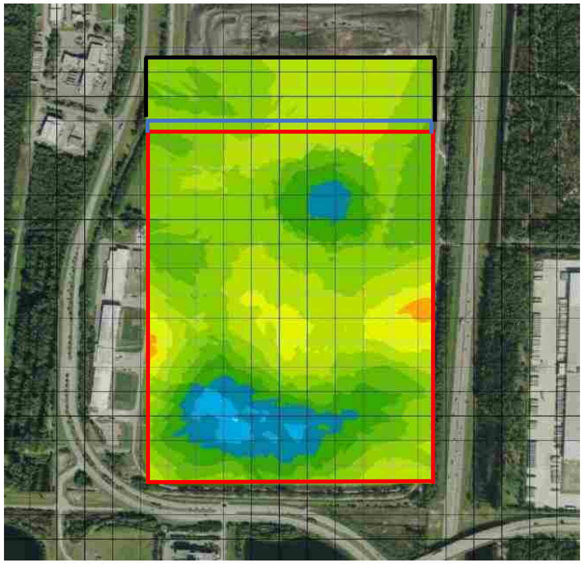
Red square = 2007-2010 wells
Blue square = 2011 well addition

2014



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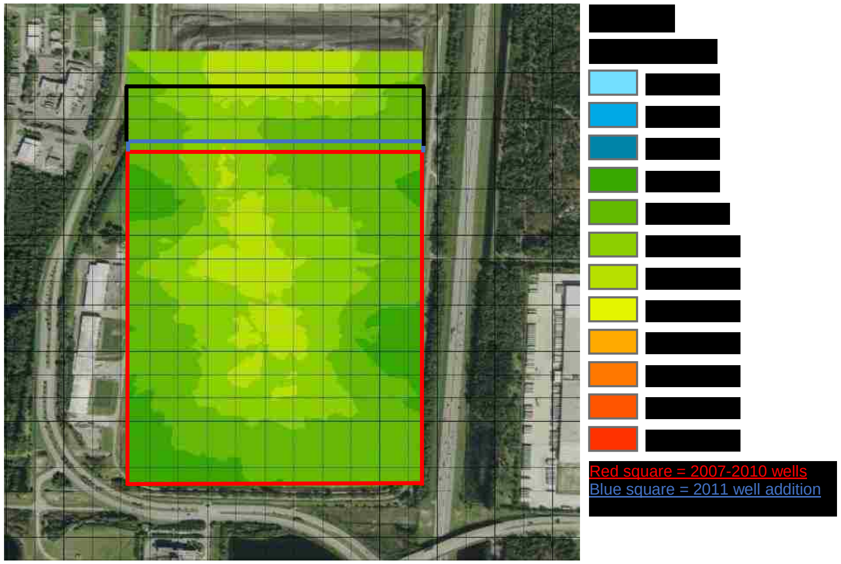
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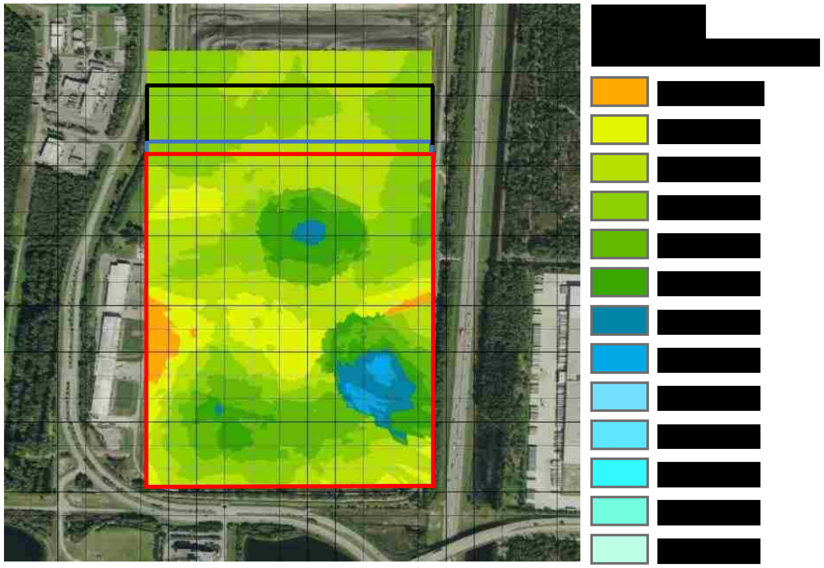
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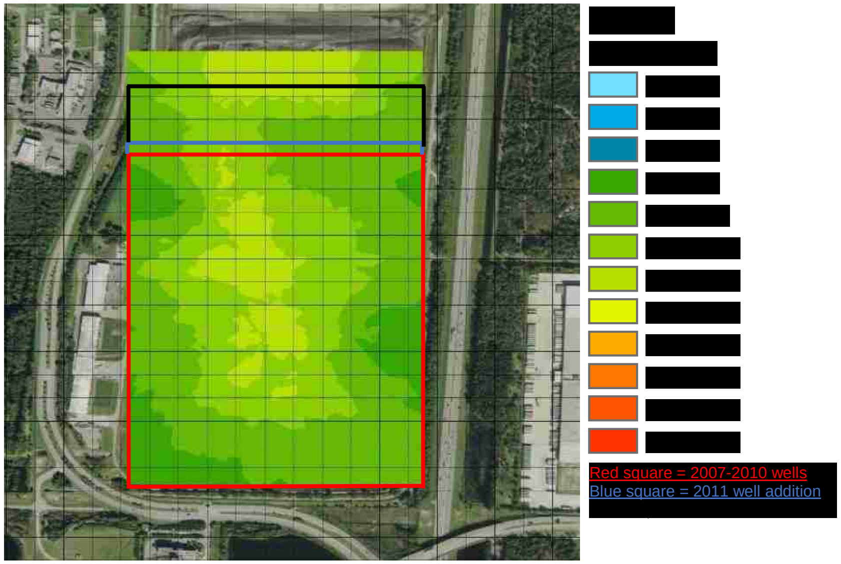
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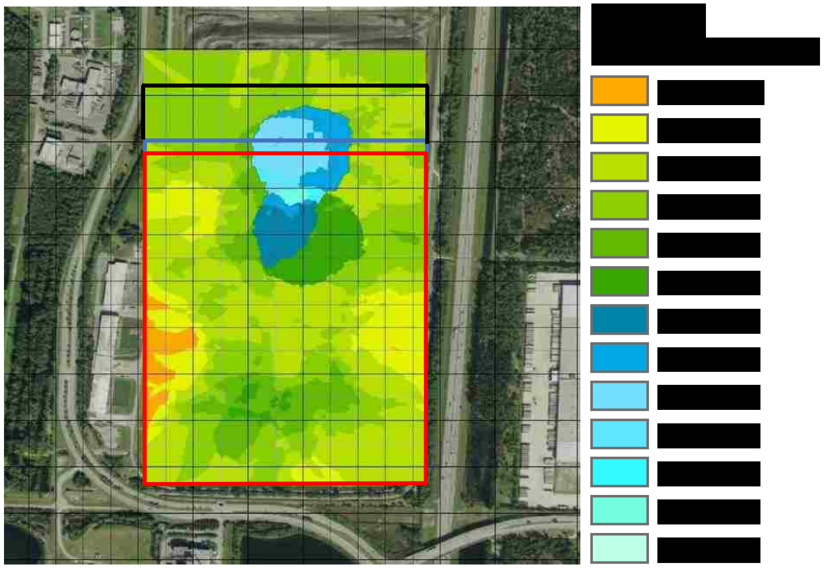
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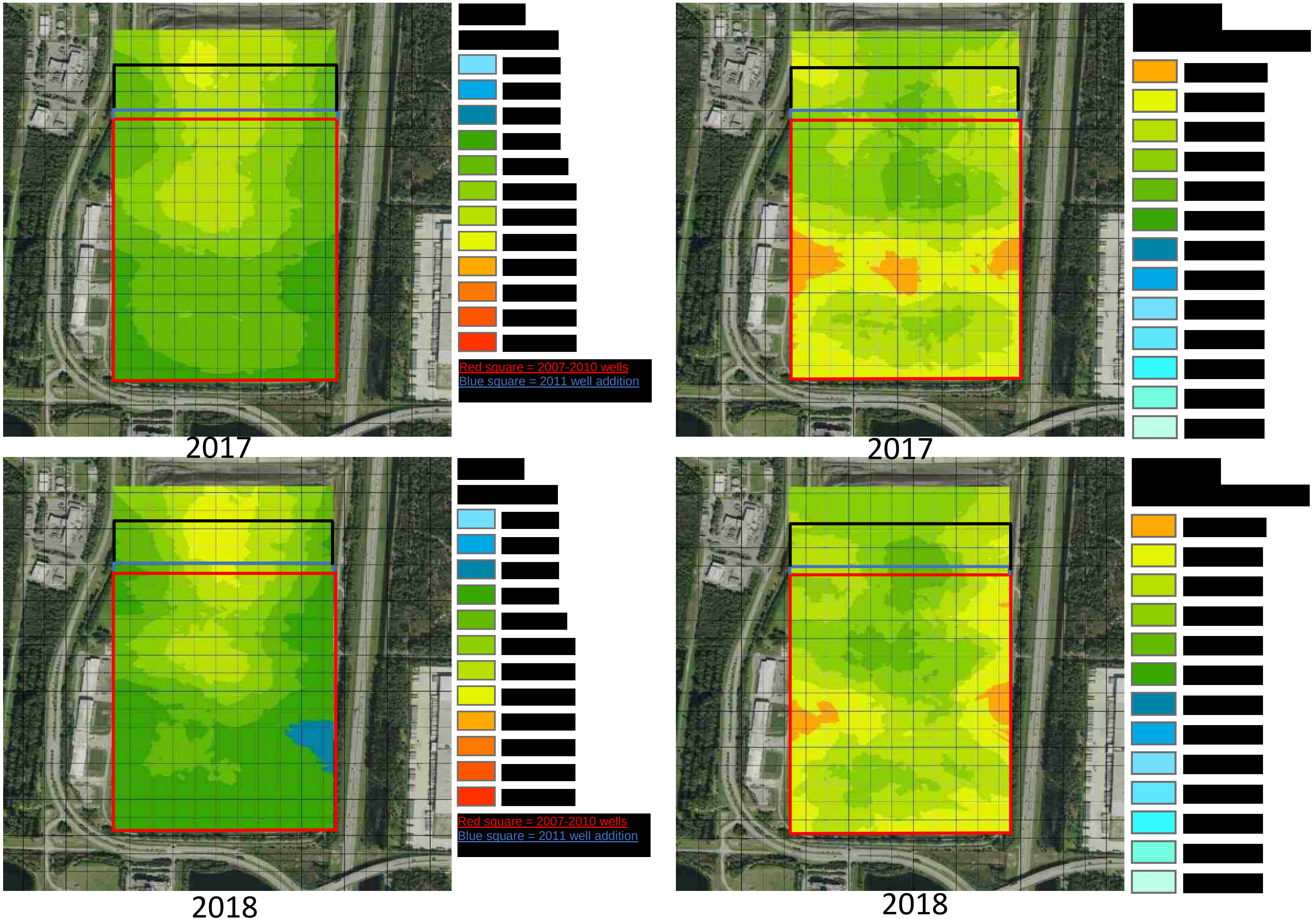


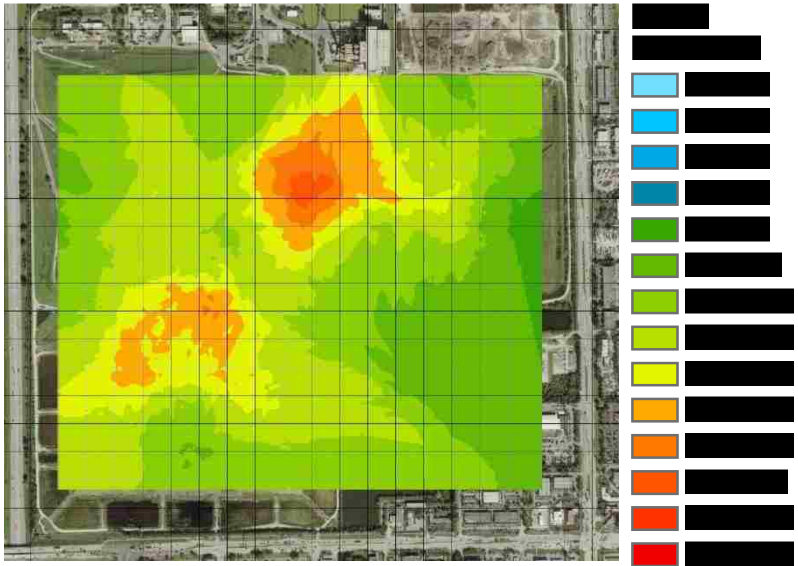
Figure 29: CH_4 to CO_2 Maps for Landfill R

Landfill G

As exhibited in Figure 30, the majority of gas wells in Landfill G had CH_4 to CO_2 ratios above 1.0, usually ranging between 1.0 and 1.3. Few instances of CH_4 to CO_2 ratios below 1 were observed, even in the northern and western sections of the landfill which had ETs. In addition, the low CH_4 to CO_2 ratios were found in areas without ETs. Thus, it is possible that there was another cause beyond high temperatures that resulted in gas wells in the northwest section of the landfill having low CH_4 to CO_2 ratios.

Interestingly, although gas temperatures as high as 170°F were recorded between 2015-2017, only a few instances of low CH_4 to CO_2 ratios were found in the center of the ET zones between 2015-2016. The land area that contained gas temperatures above 150°F was approximately 6 acres at its maximum in 2016. Thus, as high temperatures were well contained, low CH_4 to CO_2 ratios were only found within a limited zone of the landfill.

It is likely that interpolating the data may have "smoothed" out low CH_4 to CO_2 readings within this landfill, as there are gas wells in Landfill G that had CH_4 to CO_2 ratios below 1; this is exhibited in Figure 18. However, Figure 18 also showed that most of these readings occurred in a few gas wells. Thus, it is possible that interpolations may remove these outlier readings as results are influenced by other surrounding data points.



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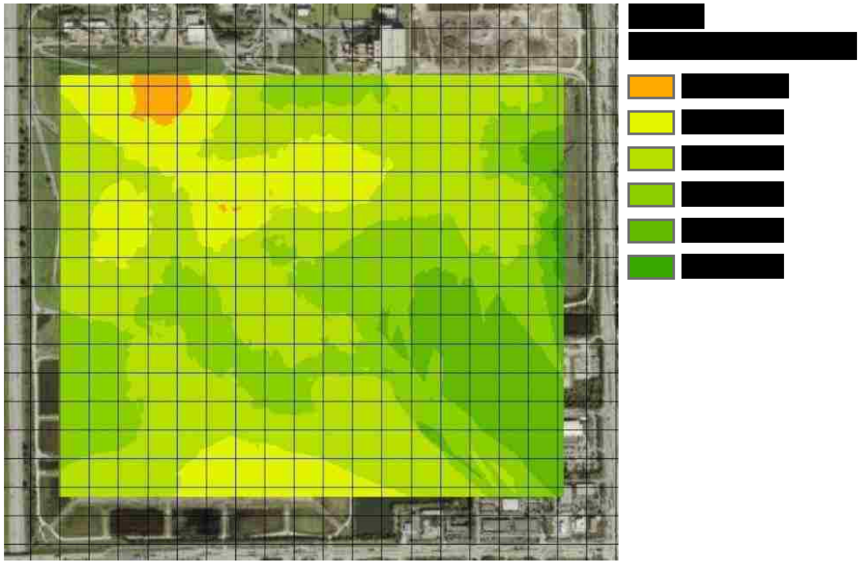

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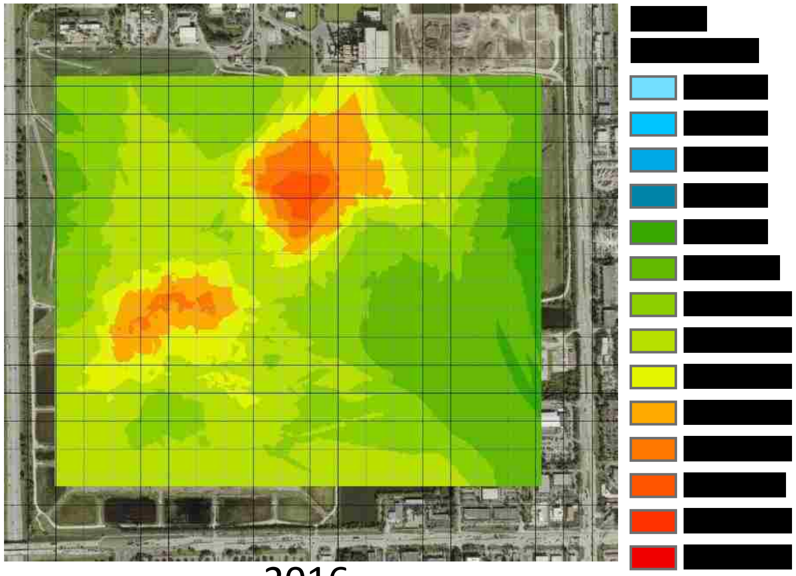

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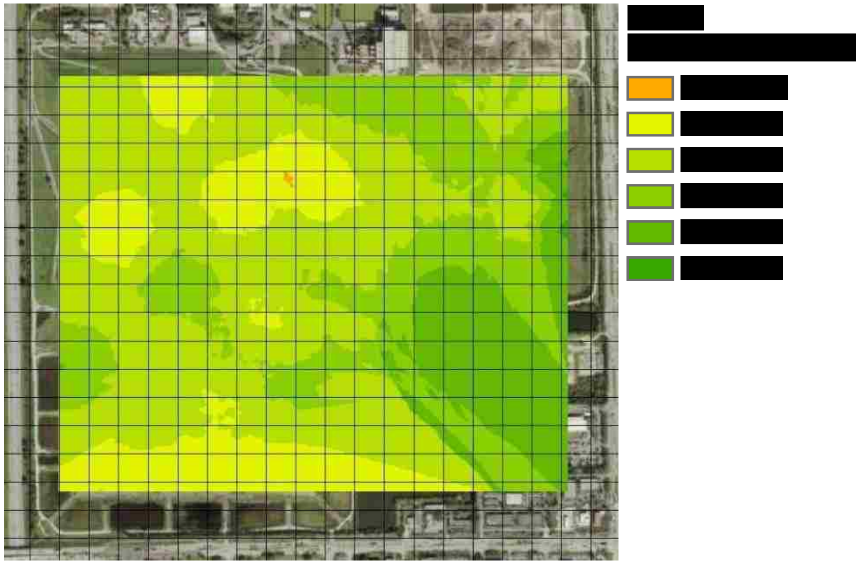

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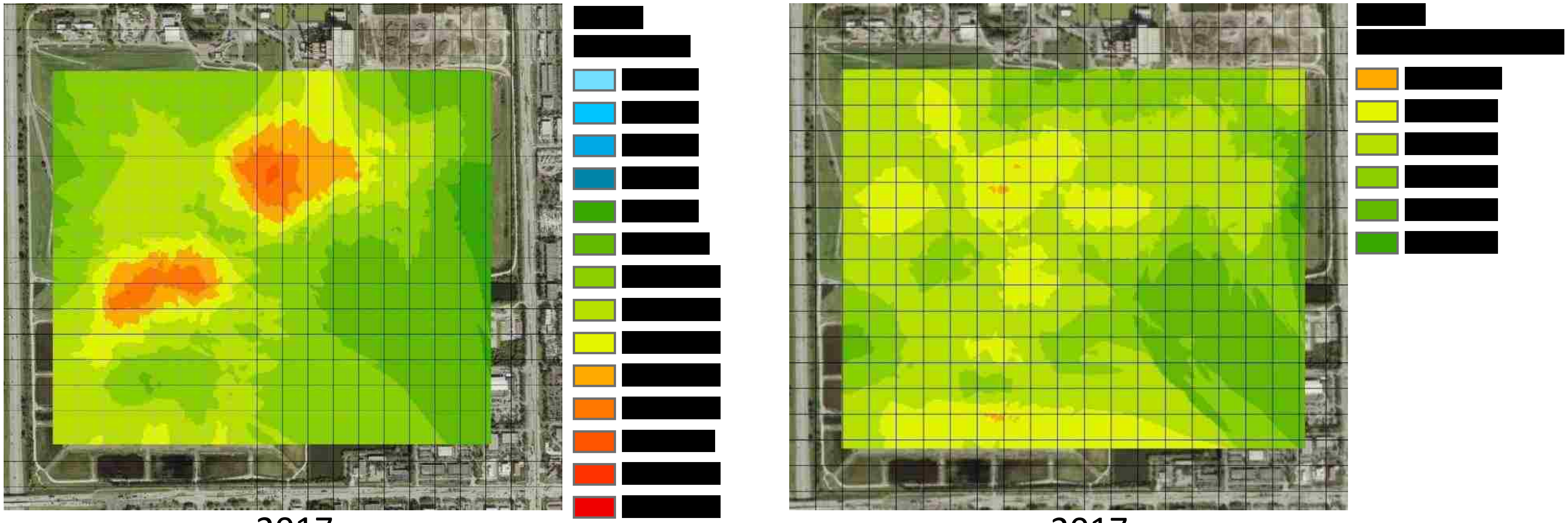

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2017

Figure 30: CH_4 to CO_2 Maps for Landfill G

Summary

Based on the CH_4 to CO_2 maps created for the four ETLFs, it appears that most ETLFs are not experiencing widespread cases of low CH_4 to CO_2 ratios. This contradicts knowledge that ETs reduce CH_4 quality due to methanogen inhibition. However, two of the four ETLFs landfills did not experience gas temperatures above 150°F. Although ETs are distinguished as gas temperatures greater than 131°F, it has not been proven that these temperatures impact CH_4 quality significantly. Instead, as shown by the case study completed for Landfill N, it appears that ETs greater than 150°F are required for this effect.

In addition, similarly to the temperature contour maps, gas transportation does not appear to be occurring between sections of the studied landfills. Landfill N had portions of the landfill that had developed low CH_4 to CO_2 ratios over time; however, this was likely due to the wells being inactive for 3-4 years. As shown earlier, heat propagated from the western section to the eastern section of the landfill, resulting in temperatures greater than 170°F; this high temperature likely caused reduced CH_4 quality.

Furthermore, certain ETLFs had high CH_4 to CO_2 ratios. At Landfill B and Landfill R, CH_4 to CO_2 ratios near or above 2.0 were found throughout multiple acres within the respective landfills. The exact cause for this is unknown; however, the majority of the high CH_4 to CO_2 ratios were located in non-ET sections of the landfill. Landfill R did have CH_4 to CO_2 ratios above 2.0 in sections in which ETs were found. Again, the cause is unknown; this was merely an observation.

CHAPTER SIX: CONCLUSIONS

The benefits of this research relate to landfill gas collection (LFGC), operation and maintenance of LFGC systems, waste management and disposal. Appropriate response to ET scenarios in landfills has not been standardized and are often left up to individual landfill owners/operators. In many cases, they turn off gas wells with ETs; this technique is not proven to reduce gas temperatures, nor does it benefit landfill gas-to-energy systems. Thus, this research was conducted to provide a better understanding of the potential characteristics that may initiate ETs in a landfill. In addition, this research offers a historical database for 22 landfill cells throughout the state of Florida, displaying case-by-case data of gas well temperatures, waste characteristics, landfill geometry and leachate treatment for each landfill.

From the historical gas data analysis, it was determined that a majority (74%) of the studied Florida landfills had ETs within the past couple of years. In addition, it was discovered that at 37% of these ETLFs, ash is disposed (or for a considerable time was disposed) within the landfill either as a cover component or within the working face. This ash could produce exothermic heat if it contacts landfill leachate through hydrolysis and corrosion reactions (Speiser et., al 2000).

After performing detailed analysis regarding ash disposal versus gas temperature in the ash-containing landfills, it was concluded that there is some correlation between ash disposal and temperature increase from gas well readings. As shown in Figures 12-14, landfills that contained ash reported higher maximum temperatures and more ETs when compared to non-ash accepting landfills.

However, there appears to be an optimal ash concentration that leads to ETs. In fact, maximum temperature readings for medium-ash landfills were on-average over 40°F higher than that of high-ash and no-ash landfills. In addition, the percentage of gas wells with ET readings were almost 10% greater for medium-ash landfills than for no-ash landfills, and even greater when compared to the high-ash landfill.

It is likely that this relationship can be attributed to the fact that landfills with significant amounts of ash do not have the interactions between moisture, the fuel (organic material), and the ash needed to produce chemical reactions. Using the same idea, landfills that do not contain ash lack the material needed to initiate chemical reactions between the metals, water, and organics. Therefore, a middle-ground is needed in which both MSW and inorganic materials are present to allow for ETs to occur within a landfill.

When characterizing Florida landfills, several observations were made. ETLF cells in this study tended to be larger than non-ETLF cells both in site area and landfill depth. Due to this increased site area and depth, ETLFs often have more current waste-in-place and a greater waste capacity than non-ETLFs. In addition, it was observed that off-site leachate treatment (through a POTW) is still the primary method of leachate disposal; however, non-ETLFs tend to recirculate leachate more often than ETLFs.

Of significant interest regarding landfill geometry is the landfill depth, as deeper landfills may have higher gas pressures, creating optimal conditions for the development of ETs. In addition, deeper landfills may allow for leachate ponding around and within the gas collection wells. As mentioned above, although most landfill owners utilize off-site treatment through POTWs, 21% of the ETLFs were permitted to recirculate leachate. This recirculation, when coupled with natural rainfall and the depth of the landfill, may promote ponding over time. This ponding could result in slower dissipation of heat and hydrolysis and corrosion reactions when water comes into contact with metals.

When landfills were analyzed on an individual basis, it was found that within ETLFs, ET readings (temperatures greater than 131°F) occurred in many gas wells rather than in a few outlier wells. When researching CH_4 to CO_2 ratios, it was found that approximately 25% of ETLFs had at least half of their ET gas wells experience a CH_4 to CO_2 ratio less than 1 at least 10% of the time. Thus, this indicates that within ETLFs, temperatures greater than 131°F and CH_4 to CO_2 ratios below 1 are somewhat common.

However, there was a noticeable decrease of ET readings found when using an ET threshold of 145°F. In contrast to the previous test, which saw temperature readings greater than 131°F in many gas wells, results from this test indicate that only a few gas wells had temperature readings greater than 145°F. In addition, data points containing CH_4 to CO_2 ratios below 0.8 were rare and limited to a few ET wells.

Cumulative landfill studies suggest that ETs found in wellheads are not predictive of low CH_4 quality within a landfill below a threshold of approximately 150°F, at which point the CH_4 to CO_2 ratio dropped significantly due to assumed methanogen inhibition. If supported by additional testing of other ETLFs, this result would suggest readjusting the wellhead ET threshold from 131°F to something between 145°F and 155°F.

When researching the potential for heat generation and heat propagation throughout ETLFs, it was found that in most ETLFs, minimal heat propagation is occurring. Instead, many ETLFs experience fluctuations of heating and cooling over time. Heat propagation was only found in Landfill N, in which operators turned off their gas wells over many years; thus, it is possible that this may not have occurred had the gas wells been left on. Therefore, it can be concluded that ET gas wells should not be turned off even if landfills are experiencing ETs, as it is necessary to continue to allow for heat to be released by means of the gas wells. Otherwise, the ability to release heat is greatly reduced, creating situations in which heat could propagate between different sections of the landfill; this could result in methanogen inhibition and gas well damage at the "new" ET zones.

Most of the studied ETLFs did not experience widespread cases of low CH_4 to CO_2 ratios, even in ET areas. However, half of the landfills did not experience gas temperatures above 150°F; thus, additional research should be conducted with other ETLFs to accurately determine the range of temperatures that negatively impacts CH_4 quality.

In contrast to current literature, certain ETLFs had high CH_4 to CO_2 ratios. At Landfills B and R, CH_4 to CO_2 ratios near or above 2.0 were found throughout multiple acres within the respective landfills, even in ET zones. Several non-ETLFs also had CH_4 to CO_2 ratios above 2.0 for a few their gas wells. As stated earlier, the cause for this is unknown and it has yet to be determined if this is common at both non-ETLFs and ETLFs. However, it does bring up another potential avenue for additional research to determine if these cases are oddities or if many landfills report similar conditions.

CHAPTER SEVEN: RECOMMENDATIONS

This research addresses the characterization of Florida landfills with ETs. In this study, it appears that ETs are a common occurrence within Florida landfills, with more than half of the studied landfills reporting ETs. However, this study was a first look at the potential for ETs based on a combination of landfill characteristics, types of waste disposed, leachate treatment methods, and other characteristics. In addition, this study utilized ArcGIS software to determine the potential for heat propagation over time within a landfill, as well as the impact on CH_4 to CO_2 ratios. Limited information was found regarding the consequences associated with a landfill reporting ETs over a long time period. Therefore, the following recommendations have been developed which would expand upon the analyses conducted in this study and further knowledge that has been concluded in this project.

- Field studies should be conducted on additional ash samples from ET landfills that dispose of ash or utilize it at as a landfill cover component. Using instruments such as mid-infrared (MIR) spectroscopy or X-ray Fluorescence would allow us to understand the elemental composition of these other ash samples. This can lead to the creation of a database that could be used to predict whether a particular ash sample would be likely to be involved with exothermic reactions leading to ETs if disposed of or used as a cover component.
- Additional communication with landfill owners/operators to disclose specifically where ash or other “special wastes” were disposed of within each landfill. Knowing the precise location of where this waste is disposed would allow for a better understanding of what might be causing ETs within particular sections of each landfill. This in turn would make the information gathered from temperature contour

maps more meaningful.

- Future legislation should define the characteristics of an ETLF to allow landfill owners to clearly diagnose whether their landfill is experiencing ET symptoms.
- Further research on the reactions that may be causing a few non-ETLFs to have low CH_4 to CO_2 ratios, as was the case in this study. In addition, studies should be conducted at ETLFs to determine if many have high CH_4 to CO_2 ratios, or if the results from this study represent outliers or oddities.
- Research on a landfill-by-landfill basis to accurately determine a range of gas temperatures that consistently reduces CH_4 quality through the inhibition of methanogens.
- Continued use of ArcGIS software to map additional landfills to research the possibilities for heat propagation over time and the influence of ETs on the CH_4 to CO_2 ratio.
- Open discussion with landfill owners/operators to provide leachate quality data for both ETLFs and non-ETLFs. Leachate quality data are very limited in OCULUS, as landfills are not required to send leachate quality data to FDEP. However, leachate with high organic compounds can be an indicator of ETs, as it can support the possibility of pyrolysis of organic waste. Thus, open sharing of this information is important to allow for ET scenarios to be documented and corrected.
- Communication with landfill owners/operators regarding problems that surfaced during the time in which ETs were recorded.

In addition, as mentioned earlier, it is recommended that gas wells should be left on even if landfills are experiencing ETs, as it is necessary to allow for gas to be released by means of the gas wells. Heat propagation may only occur significantly in landfills that consistently turn off their gas wells, especially if ETs have been experienced.

APPENDIX A: LANDFILL DESIGN CHARACTERISTICS

Table A-1: Landfill Geometry (by landfill)

Landfill Letter	Elevated or non-elevated	Ash Acceptance	Site Area (acres)	Current Landfilled Area	Design Landfill Depth (feet)	Current Landfill Depth (feet)	Well Depth (feet)
A	No	No	81	43	290	210	100
B	Yes	No	957	190	225	160	100
C	No	No	53	25	100	---	---
D	No	Yes	234.5	196.7	135	85	---
E	No	No	276	139	130	---	---
F	Yes	Yes	360	224.1	200	---	150
G	Yes	Yes	531.5	252	225	200	---
H	No	No	500	82.2	140	---	---
I	Yes	Yes	520	280	160	140	115
J1	Yes	No	5000	---	120	---	75
J2	Yes	No	301.1	65	134	---	75
K	Yes	No	1400	232	130	130	100
L	Yes	Yes	320	110	135	135	90
M	Yes	No	320	50	147	---	---
N	Yes	Yes	115	115	105	105	---
O	Yes	N/A	140	53	90	90	80
P	No	No	60	31.6	85	75	45
Q	No	No	316	118	85	---	---
R	Yes	Yes	158	34	144	---	---
S	No	No	---	61.1	93	---	70
T	Yes	Yes	144	---	225	225	---
U	No	No	39	21	77	77	---

Table A-2: Leachate Treatment (by landfill)

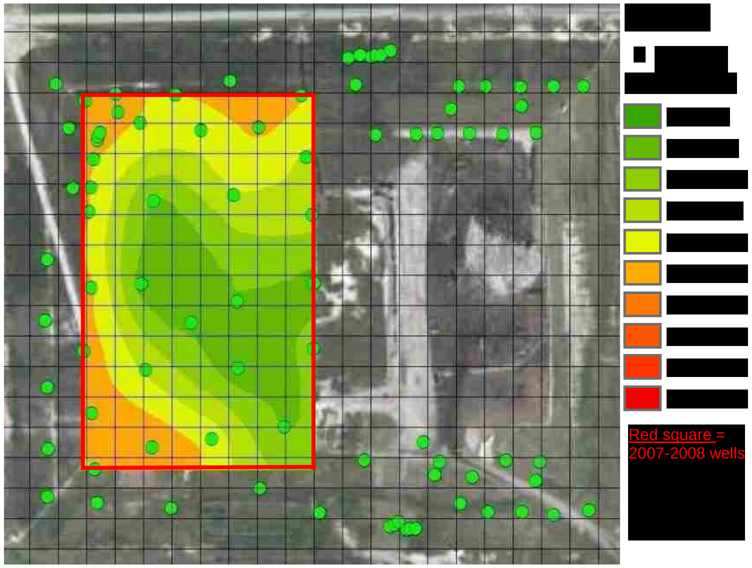
Landfill Letter	**Elevated or non-elevated**	**On-site Treatment**	**Off-site Treatment**	**Discharge Method**
A	No	Recirculation	POTW	Tanker Truck
B	Yes	Aeration	POTW	Force Main
C	No	No	POTW	Pumped
D	No	Biological Treatment	If needed	Tanker Truck
E	No	No	POTW	Force Main
F	Yes	Recirculation	POTW	Tanker Truck
G	Yes	No	POTW	Pumped
H	No	Recirculation	POTW	Pumped/Tanker Truck
I	Yes	Recirculation	POTW	Tanker Truck
J1	Yes	No	POTW	Sewer
J2	Yes	No	POTW	Sewer
K	Yes	No	POTW	Tanker Truck/ Manhole
L	Yes	Aeration/Oxidation	POTW	Force Main
M	Yes	Ammonia	POTW	Sewer
N	Yes	SBR/Recirculation	POTW or Spray Pond	Tanker Truck
O	Yes	No	POTW	Tanker Truck
P	No	Recirculation	POTW	Gravity main
Q	No	No	POTW	Lift Station
R	Yes	No	Deep Injection Well	Pumped
S	Yes	No	POTW	Pumped
T	Yes	No	POTW	Tanker Truck
U	No	Recirculation or leachate pond	If needed	Pumped

Table A-3: Landfill Design Capacity (by landfill)

Landfill Letter	Elevated or non-elevated	Landfill Design Capacity (tons)	Waste in Place (tons) - 2016	% of Landfill Capacity Used
A	No	5,330,000	4,963,126	93
B	Yes	25,617,853	24,059,347	94
C	No	4,793,670	2,164,662	45
D	No	---	---	---
E	No	11,613,892	4,989,551	43
F	Yes	81,478,722	18,869,026	23
G	Yes	84,293,492	66,943,666	79
H	No	6,059,598	5,049,921	83
I	Yes	21,695,852	16,534,665	76
J1	Yes	64,559,937	29,964,963	46
J2	Yes	64,559,937	29,964,963	46
K	Yes	45,000,000	9,758,586	22
L	Yes	18,346,266	10,648,257	58
M	Yes	21,184,000	18,079,734	85
N	Yes	18,214,658	13,229,551	73
O	Yes	3,372,600	2,589,128	77
P	No	2,800,000	1,450,000	52
Q	No	22,841,000	10,824,791	47
R	Yes	50,207,093	15,516,855	31
S	No	25,908,750	5,106,424	20
T	Yes	76,680,202	19,396,292	25
U	No	3,438,494	3,217,017	94

APPENDIX B: LANDFILL CONTOUR MAPS

Landfill N



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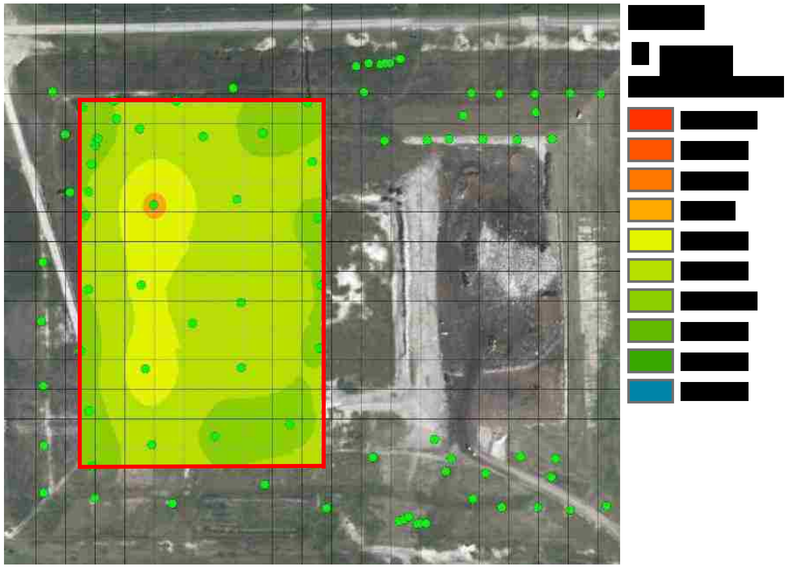
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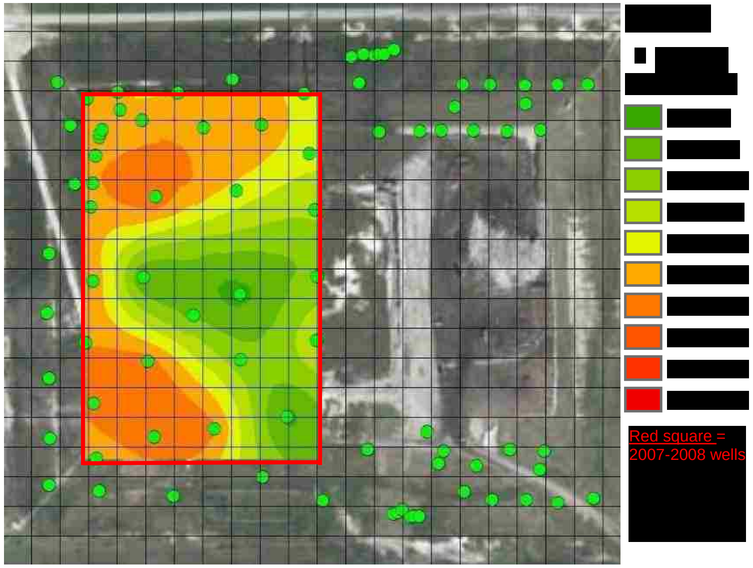

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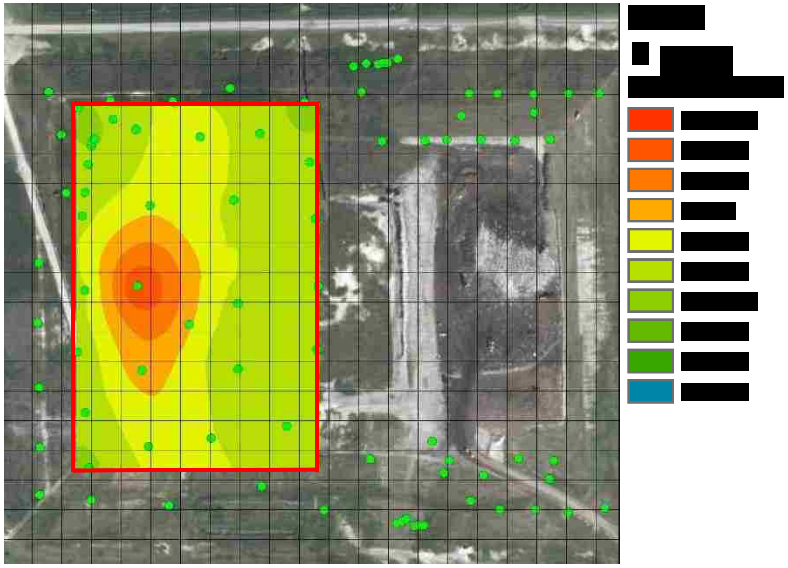
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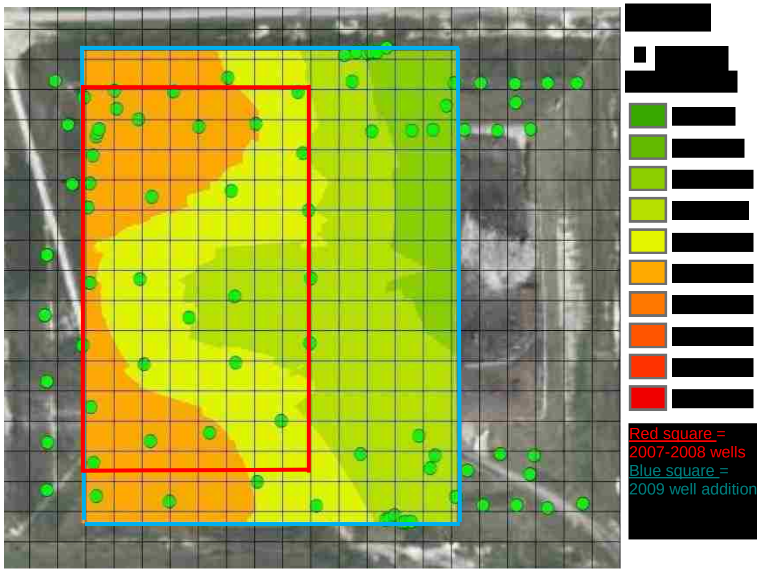

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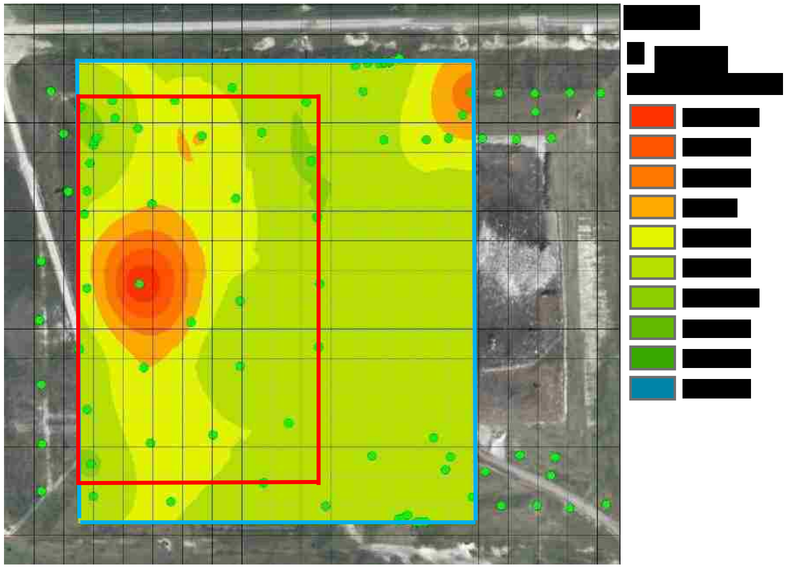

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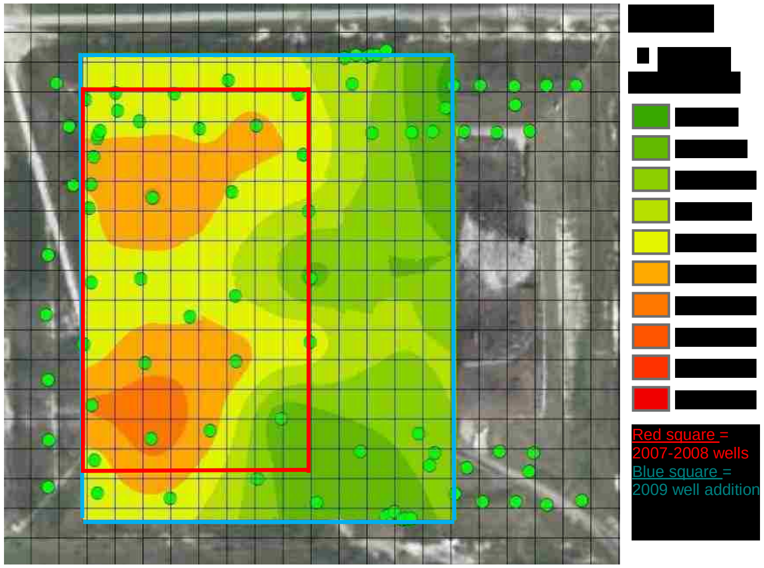

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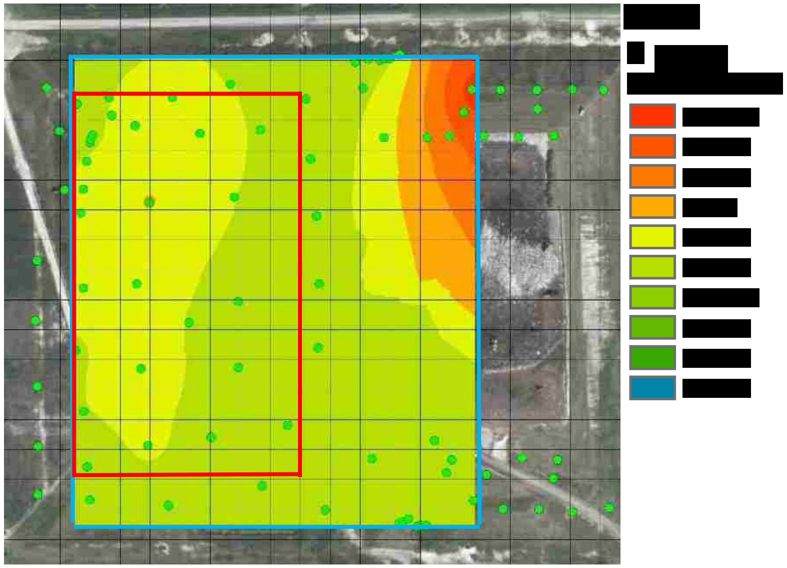

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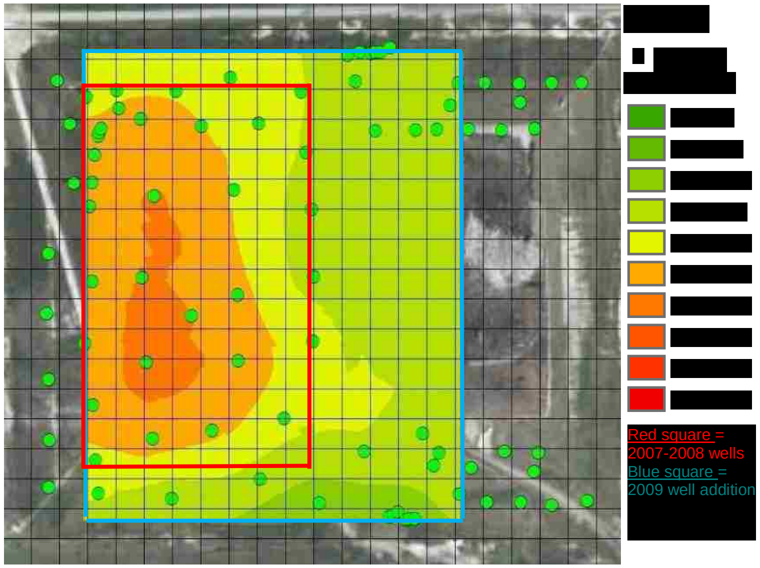

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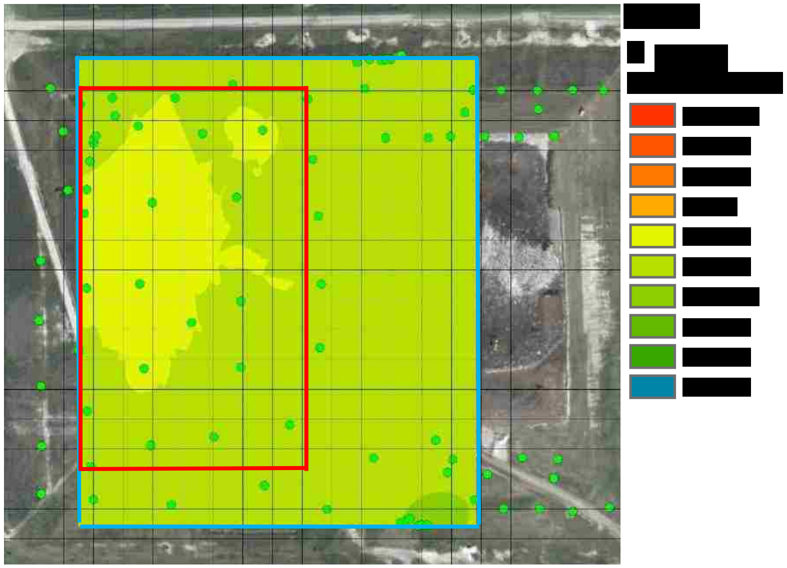

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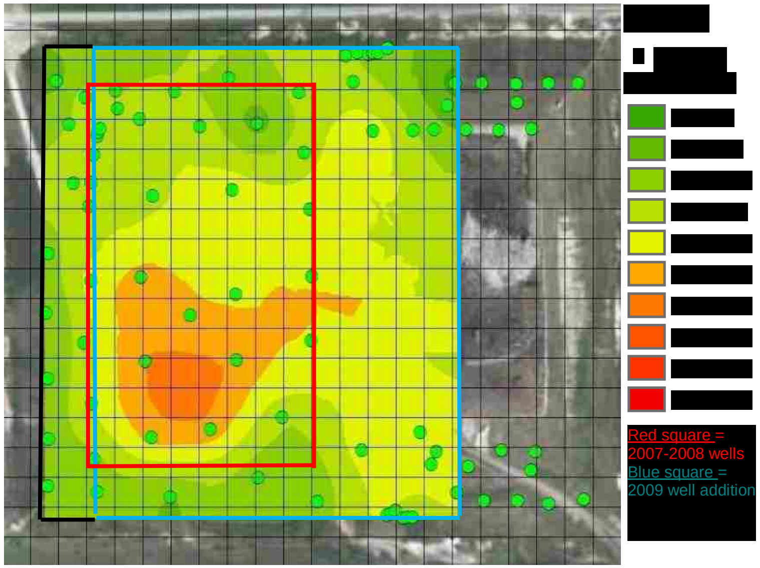

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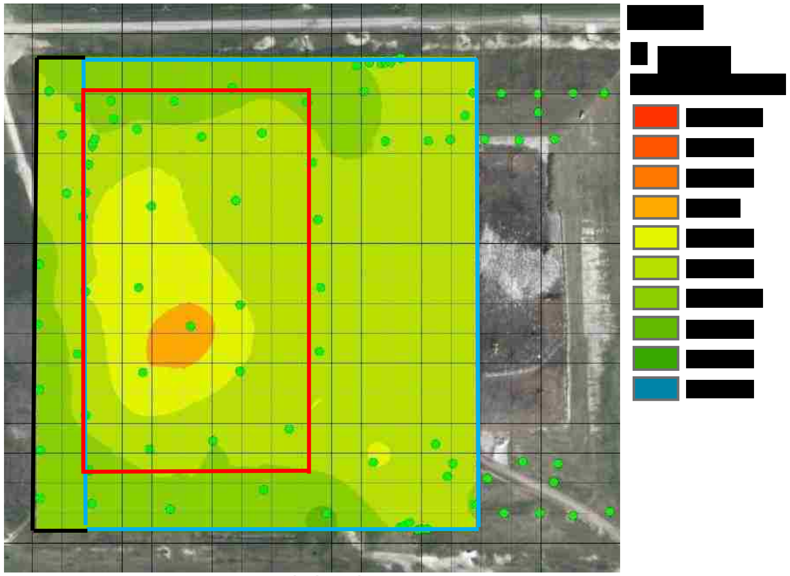

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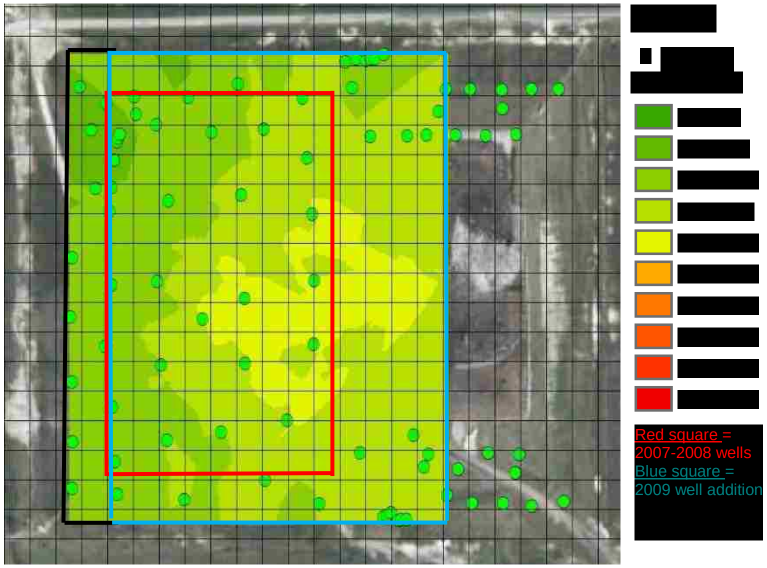
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Red square = 2007-2008 wells
Blue square = 2009 well addition
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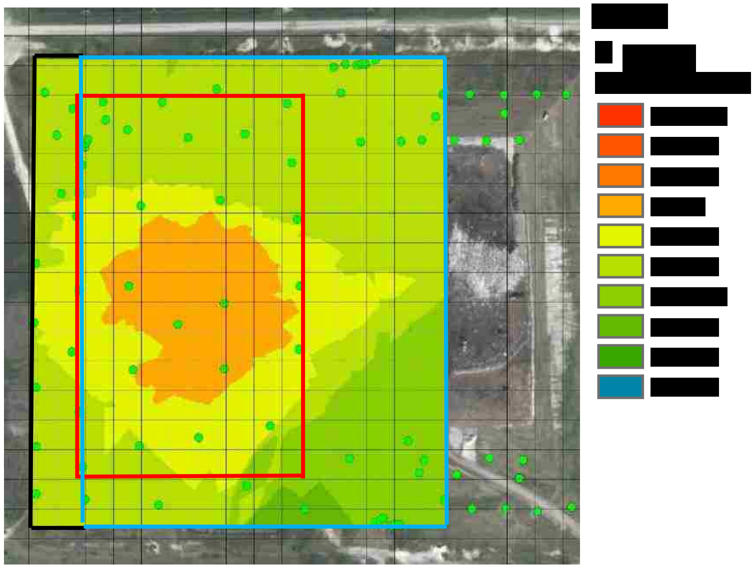
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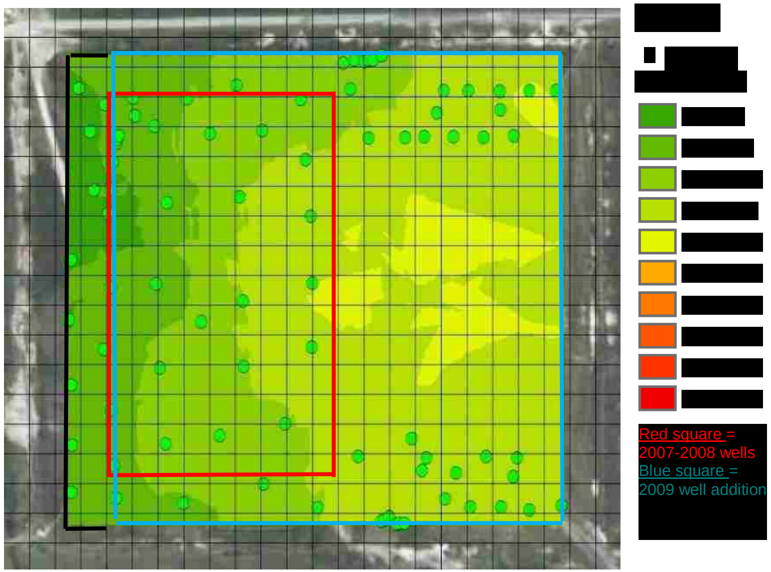
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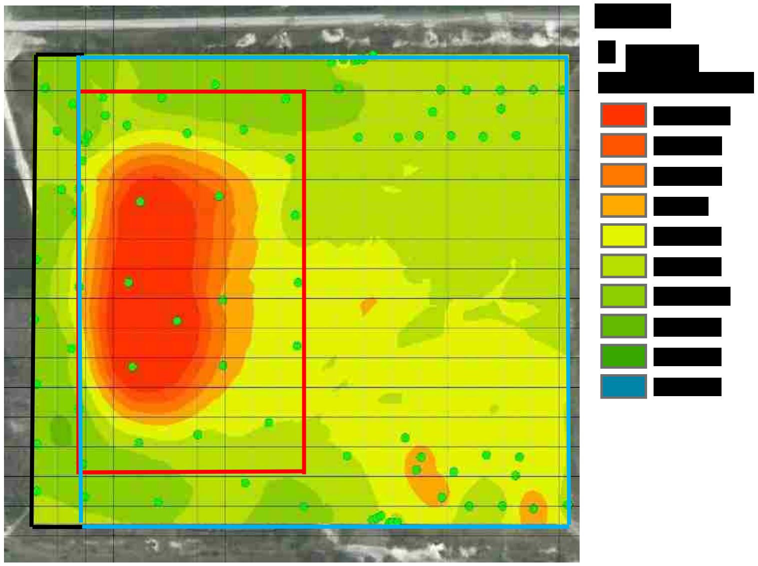
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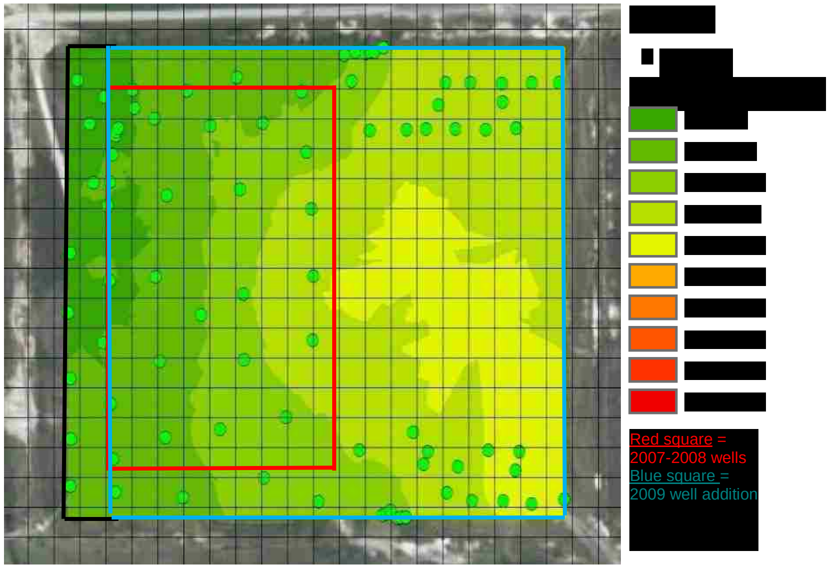

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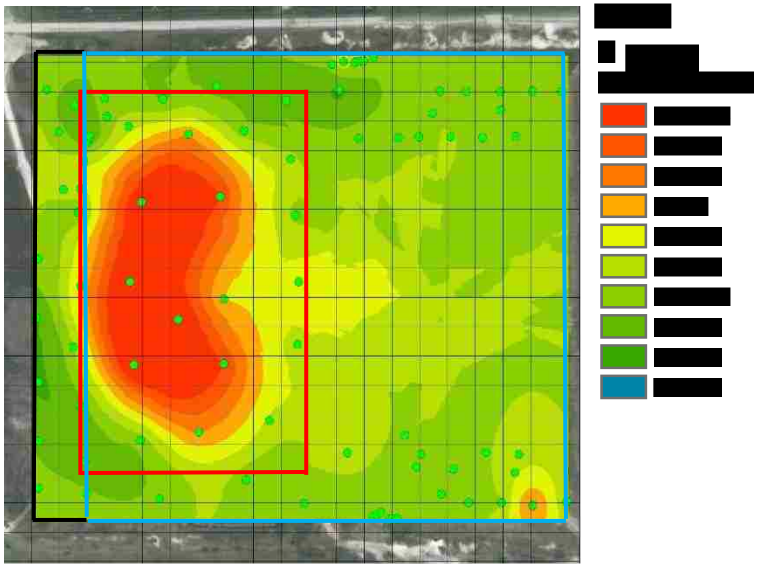

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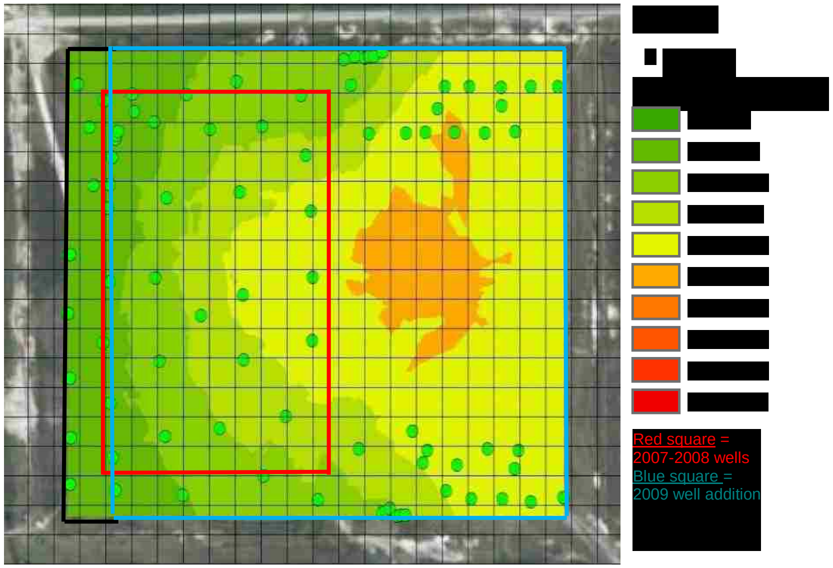

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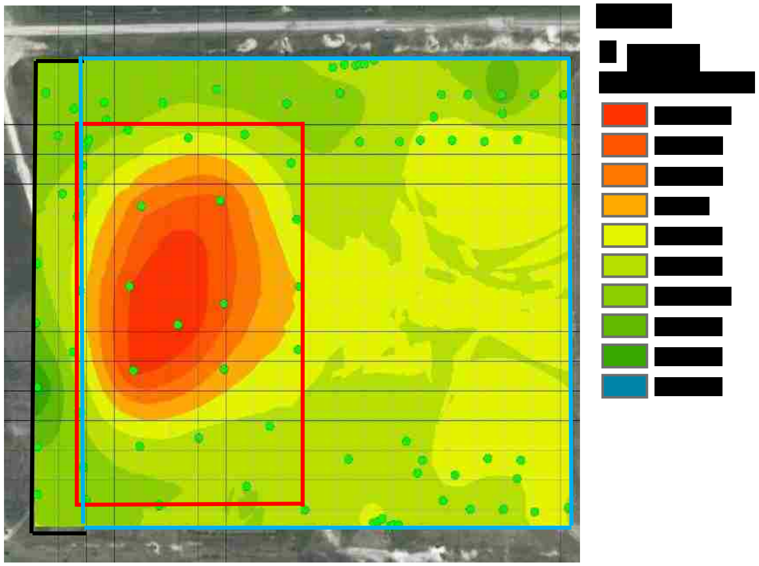

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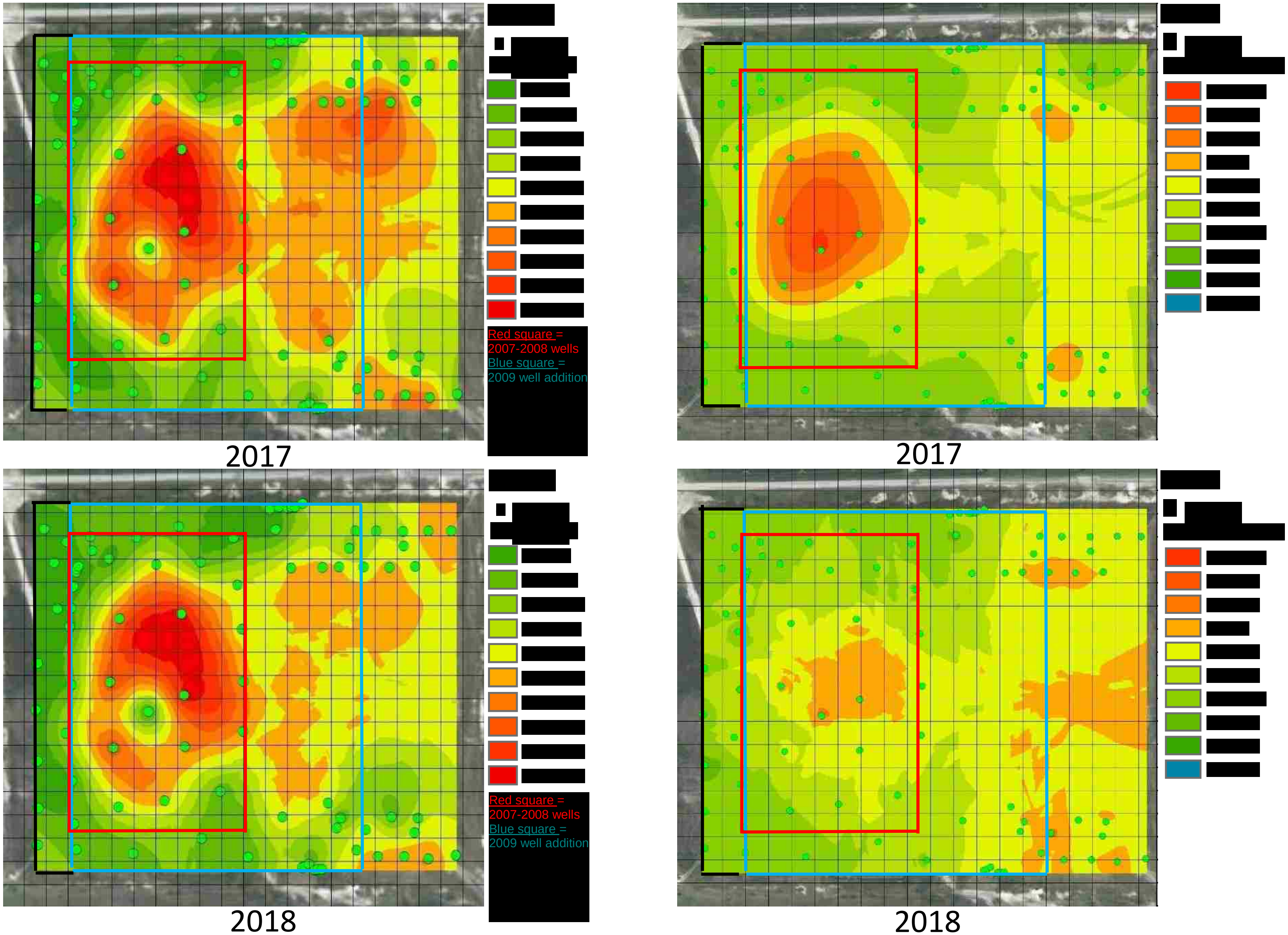

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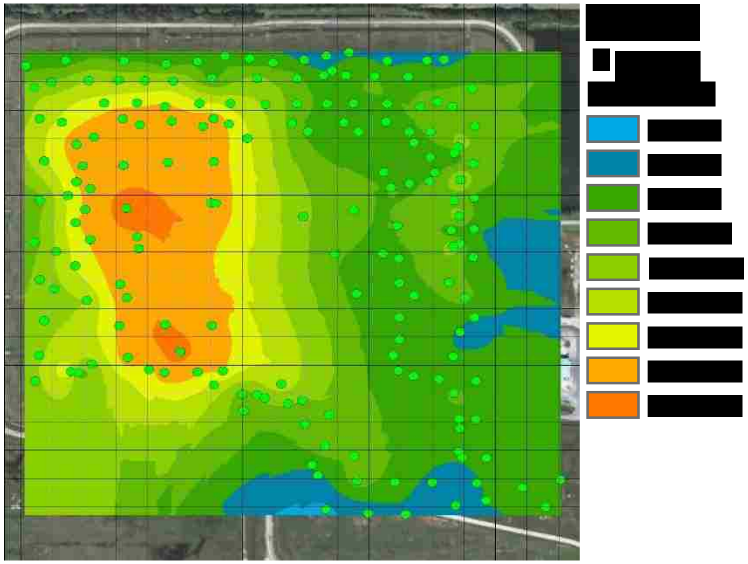
Figure B-1: Temperature Contour Maps and CH_4 to CO_2 Maps for Landfill N (2007-2018)

Landfill B



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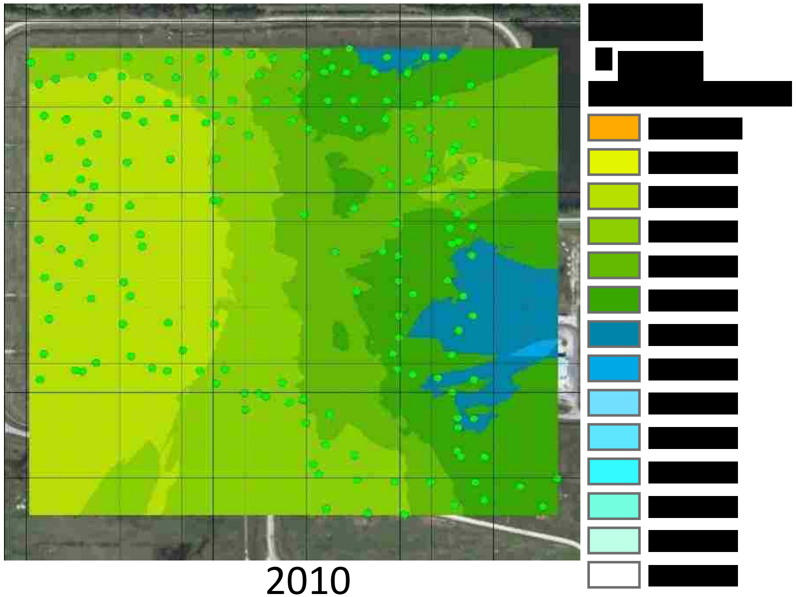

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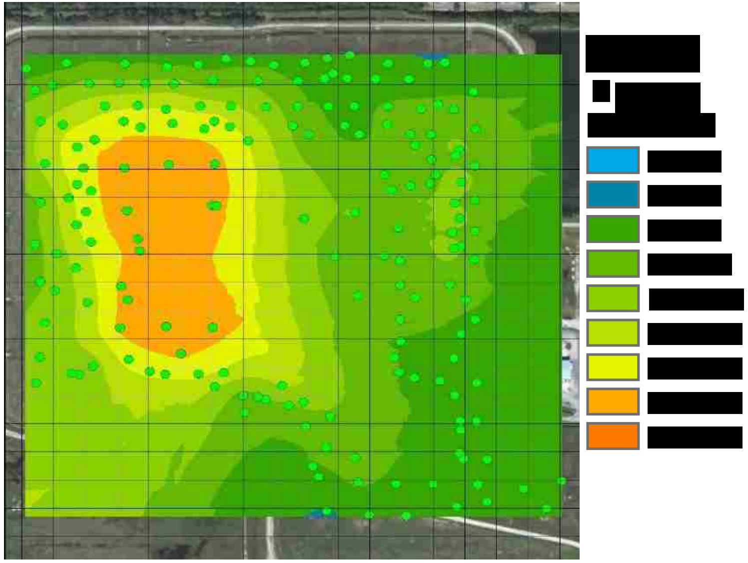

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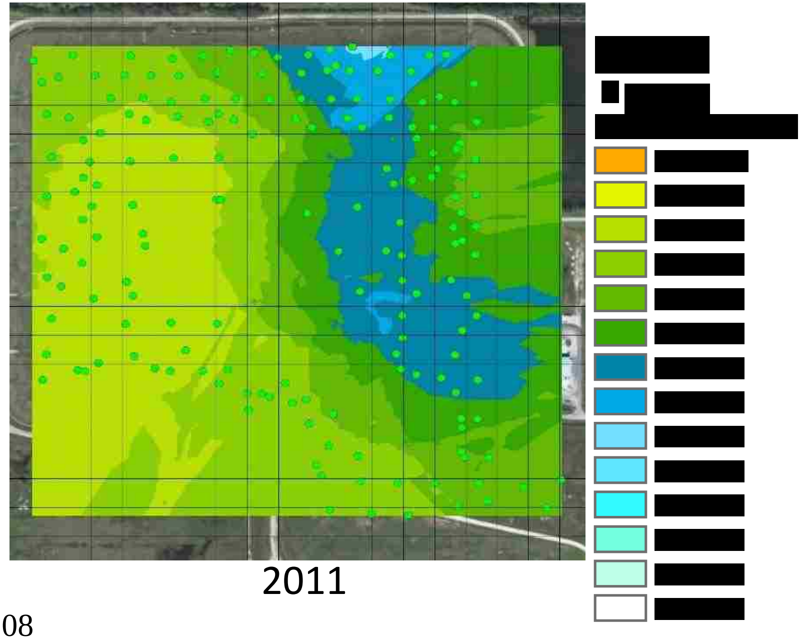

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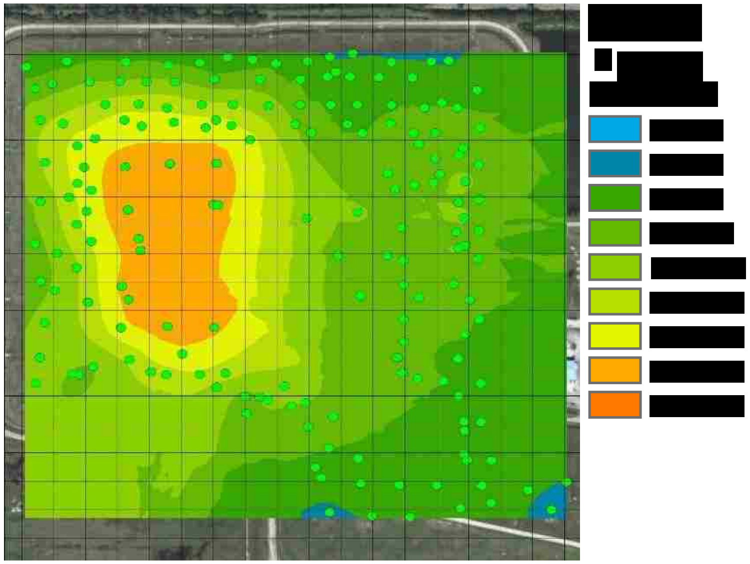

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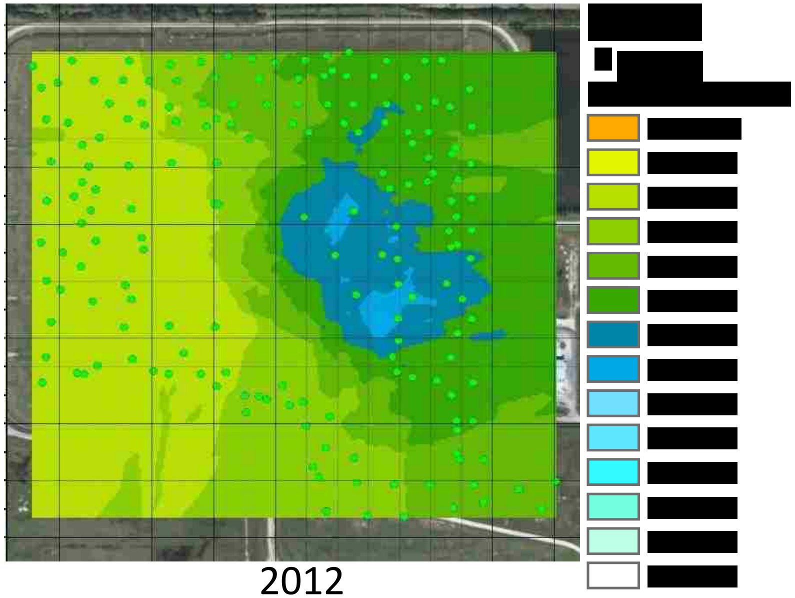

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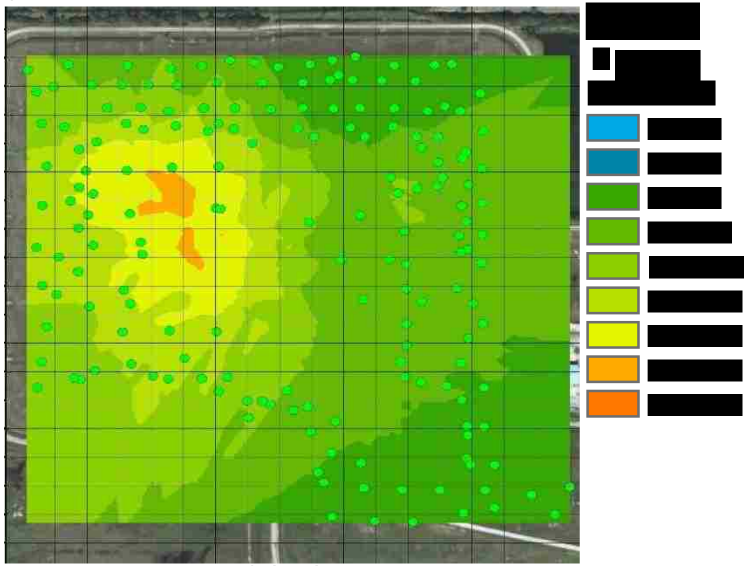

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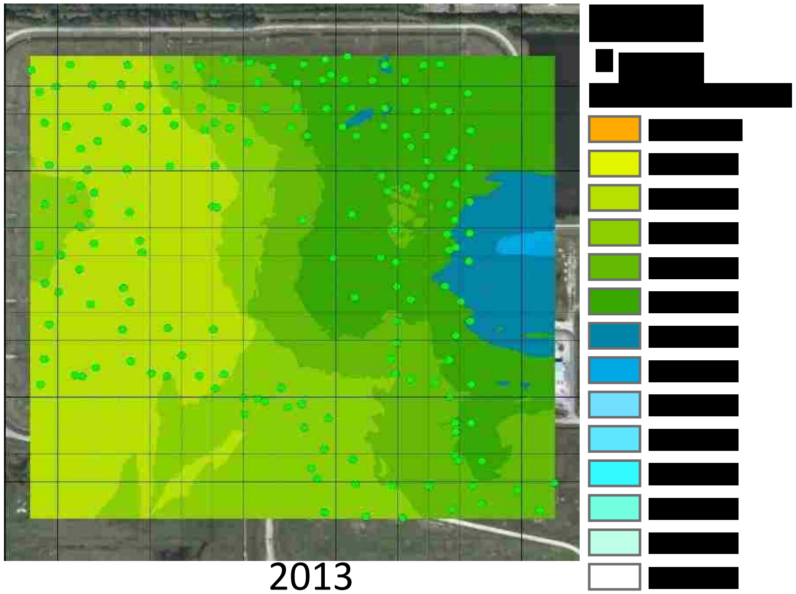

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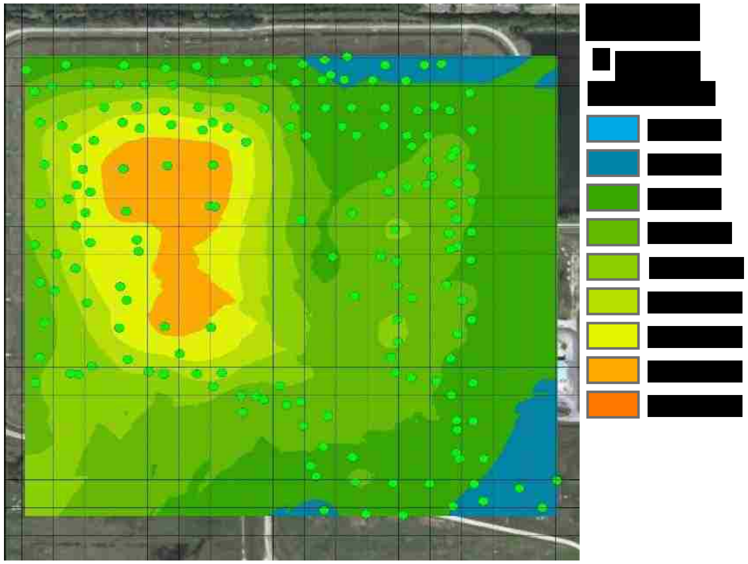

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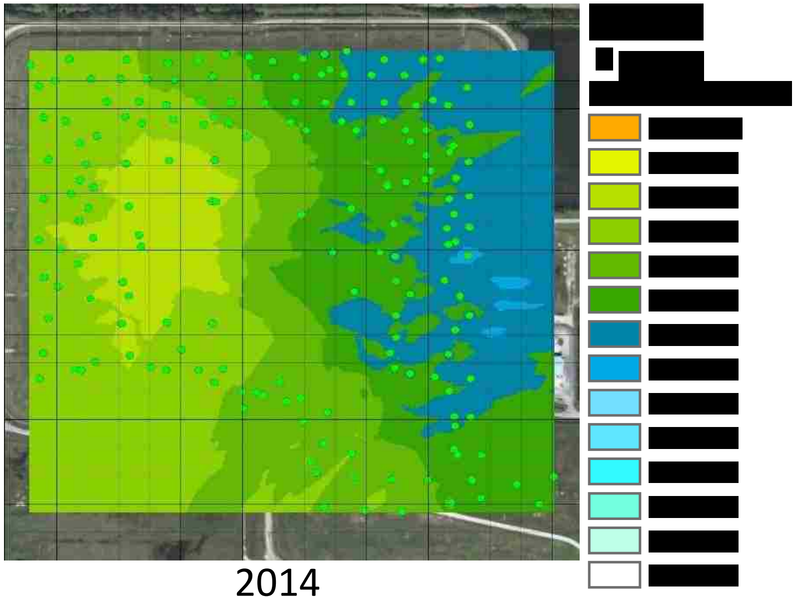

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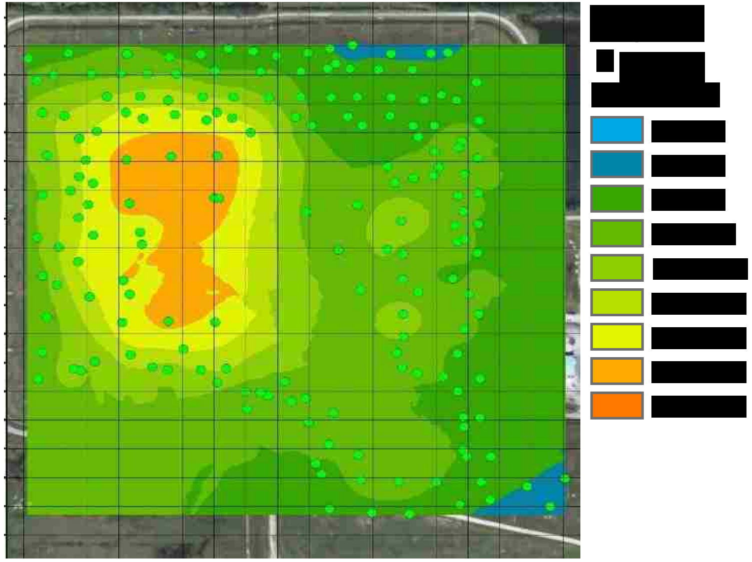

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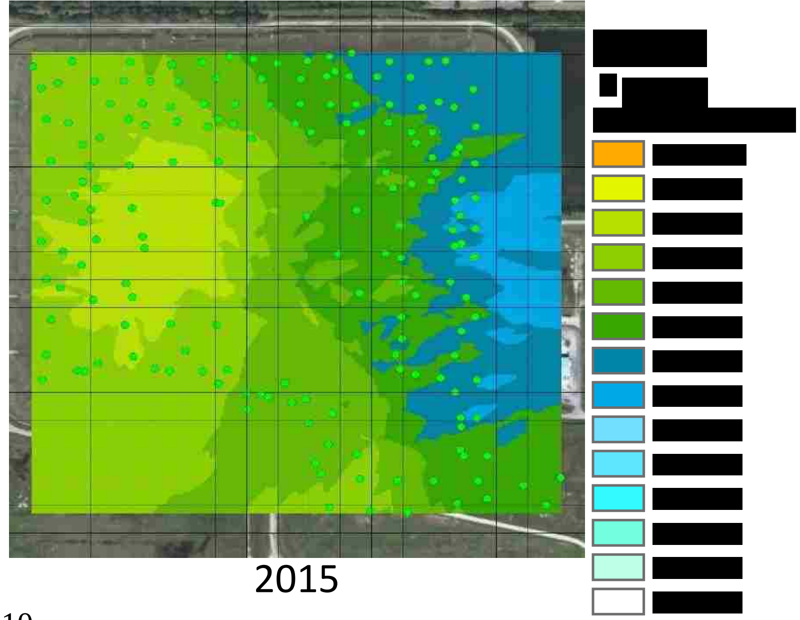

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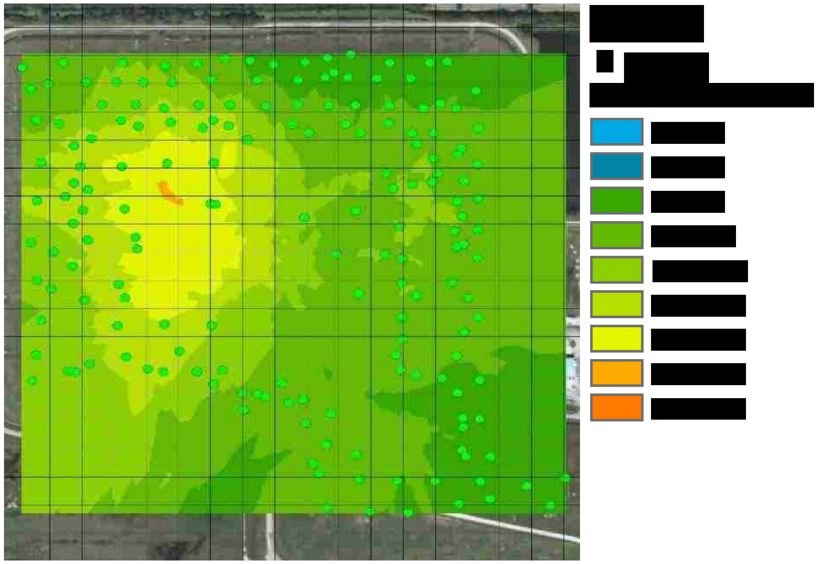

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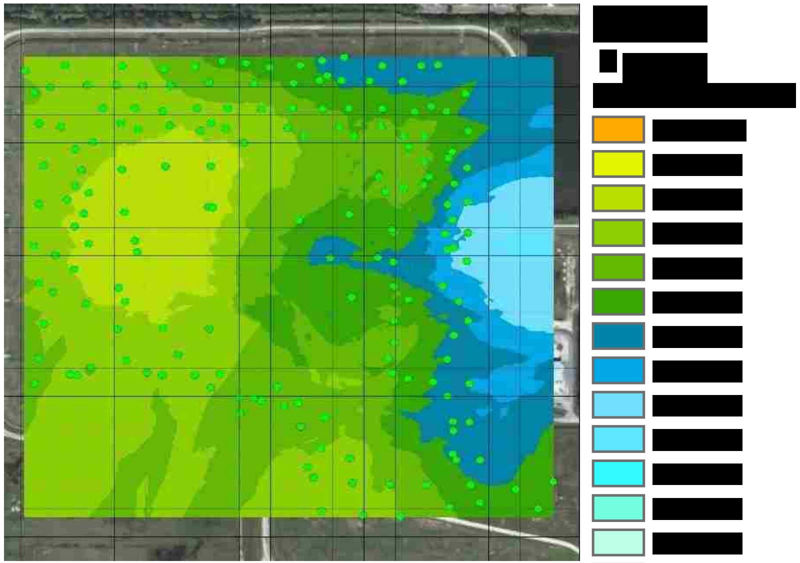

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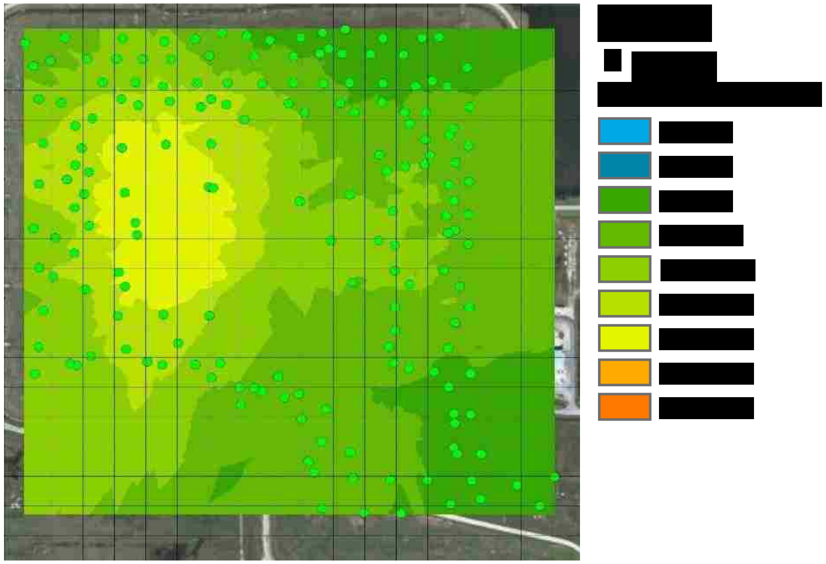

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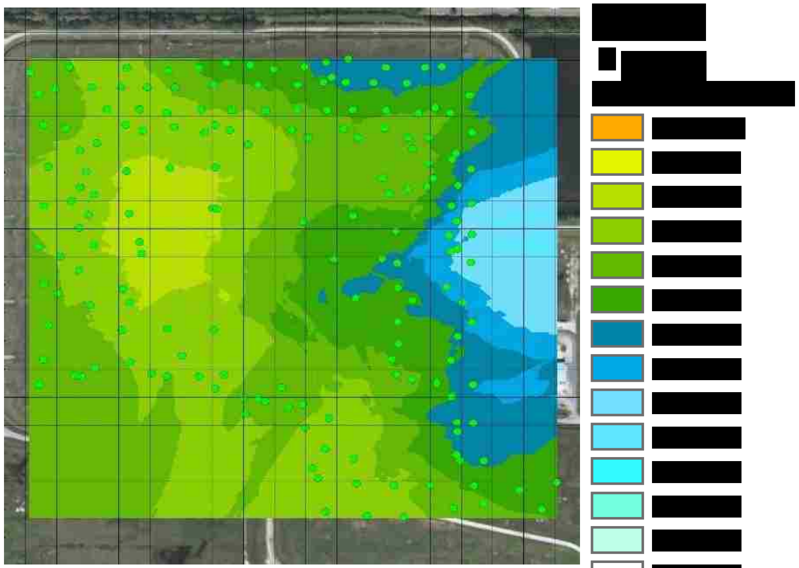

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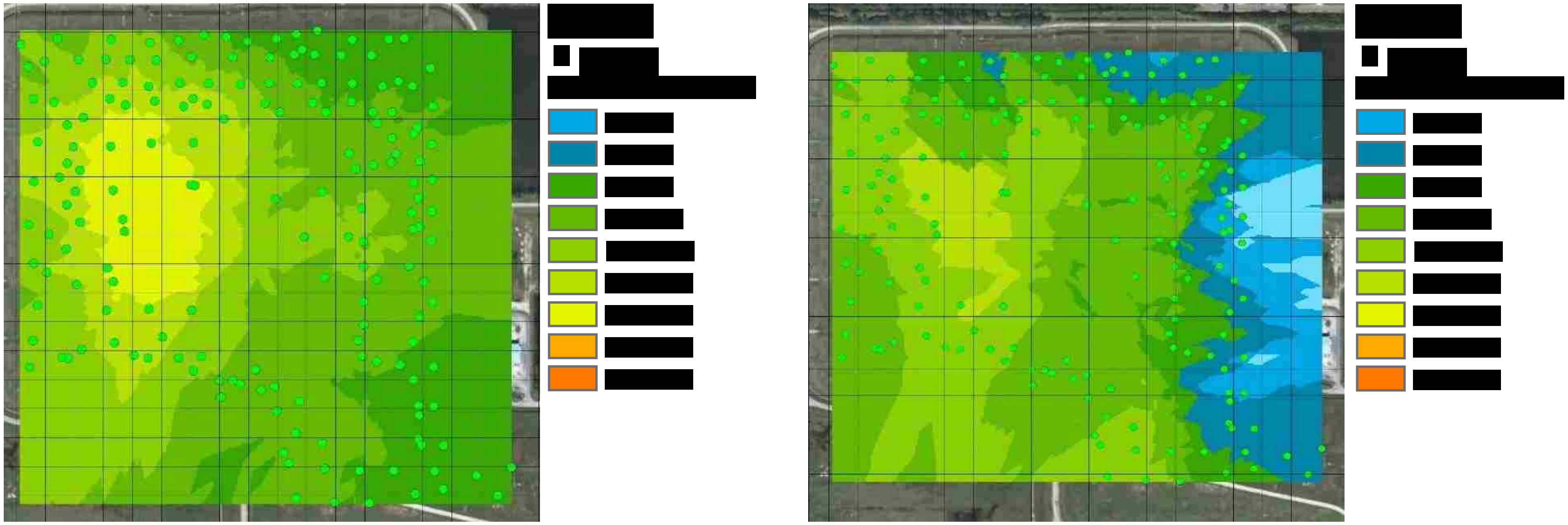

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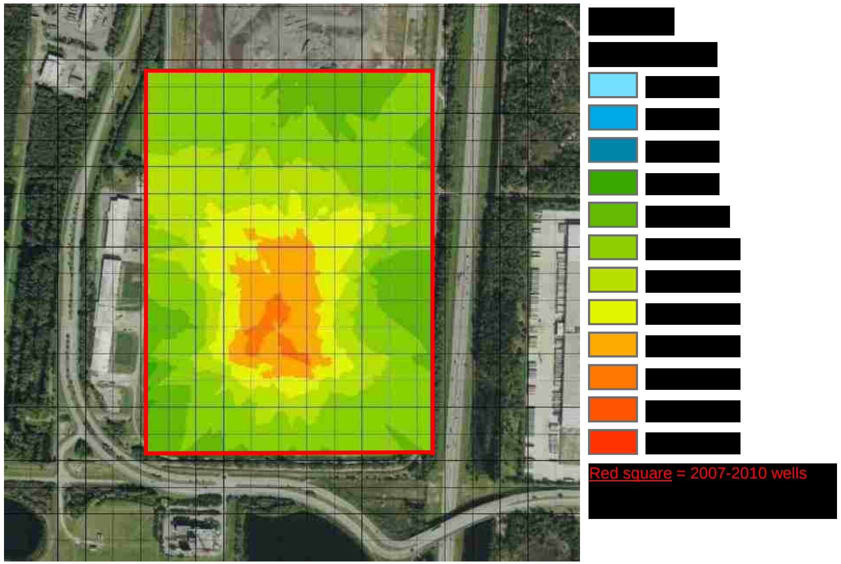
Figure B-2: Temperature Contour Maps and CH_4 to CO_2 Maps for Landfill B (2010-2018)

Landfill R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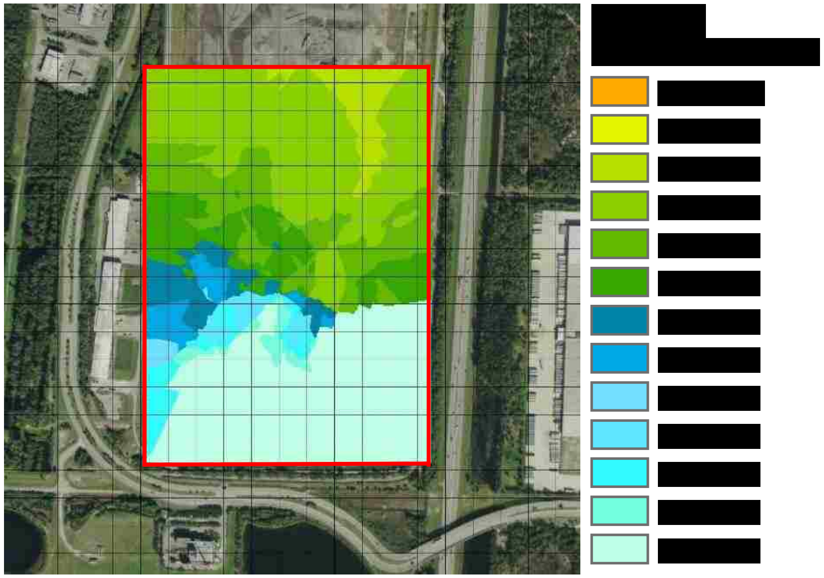
Red square = 2007-2010 wells [redacted]

2007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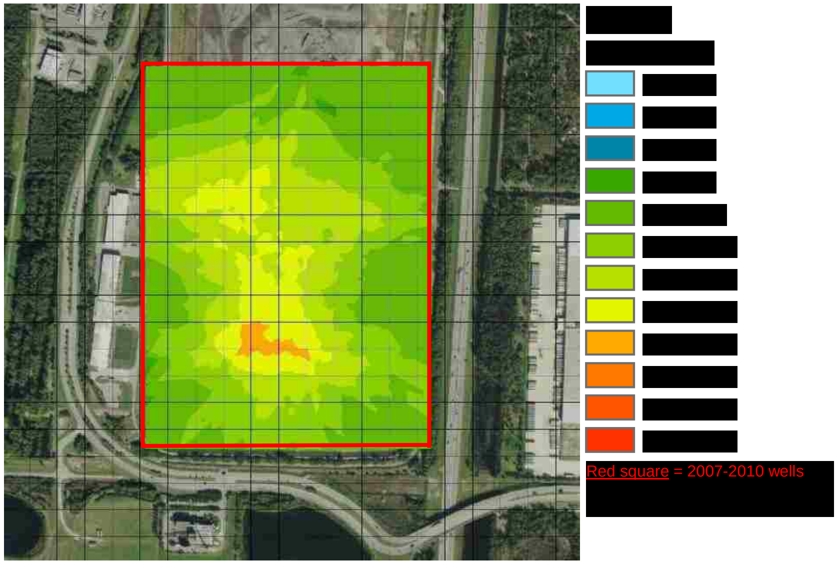
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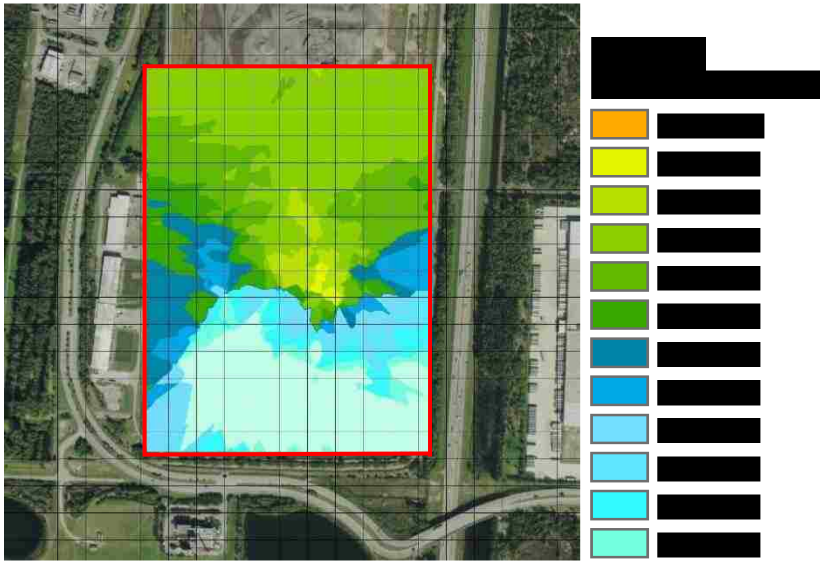
Red square = 2007-2010 wells [redacted]

2008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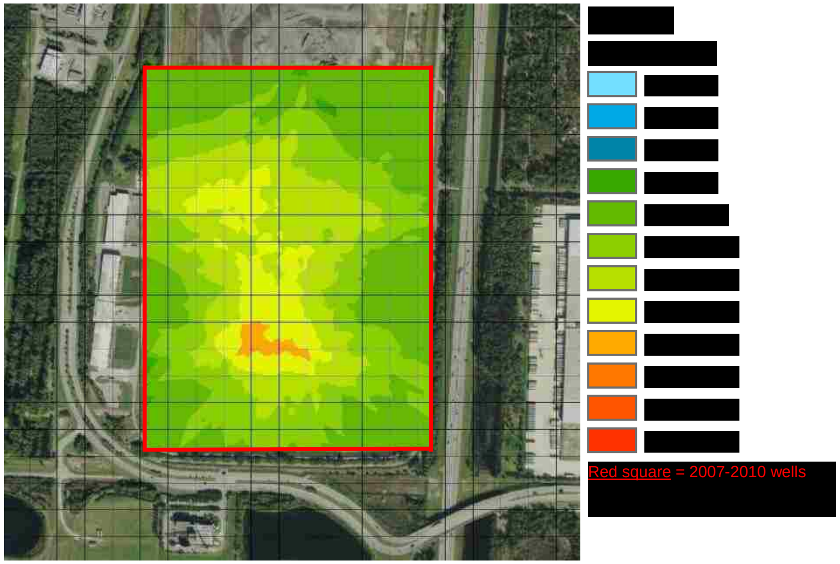

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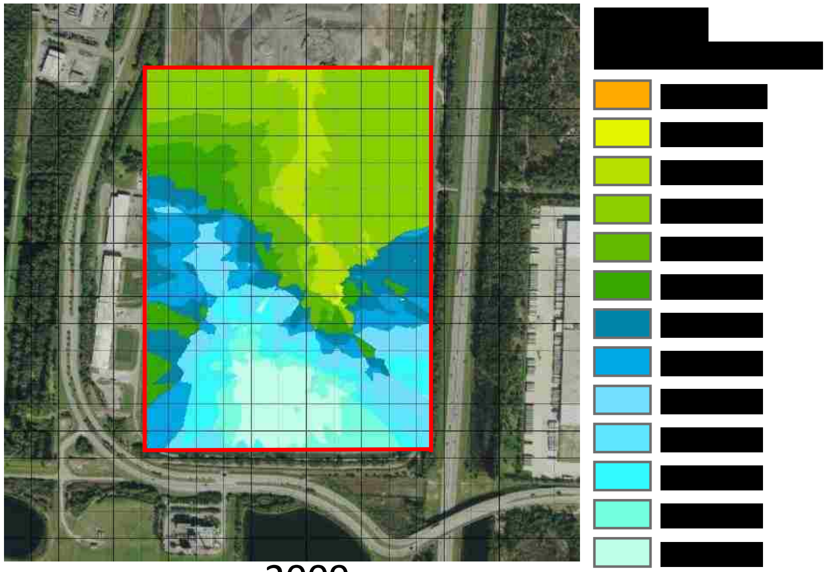

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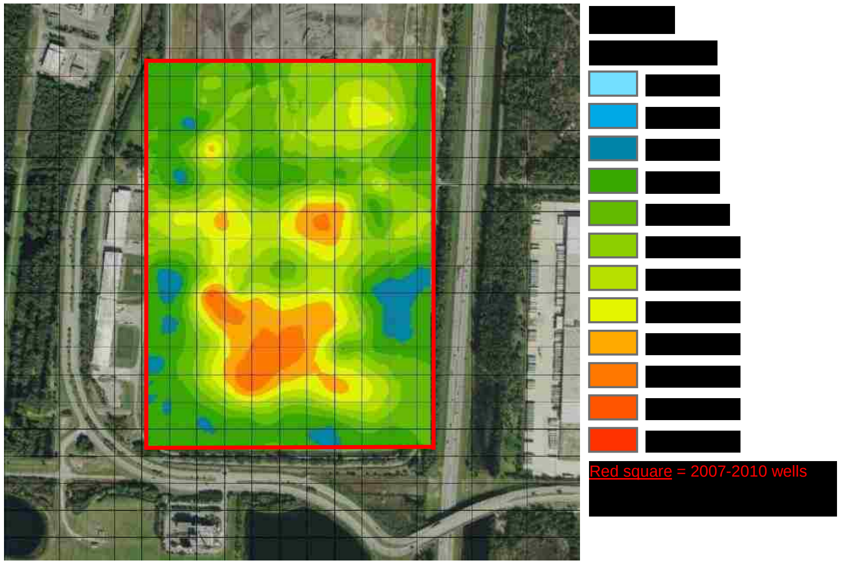

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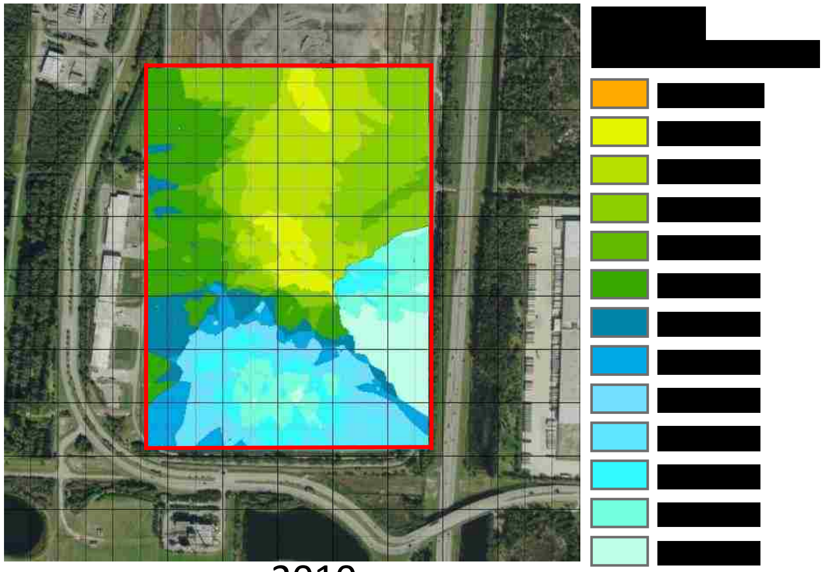

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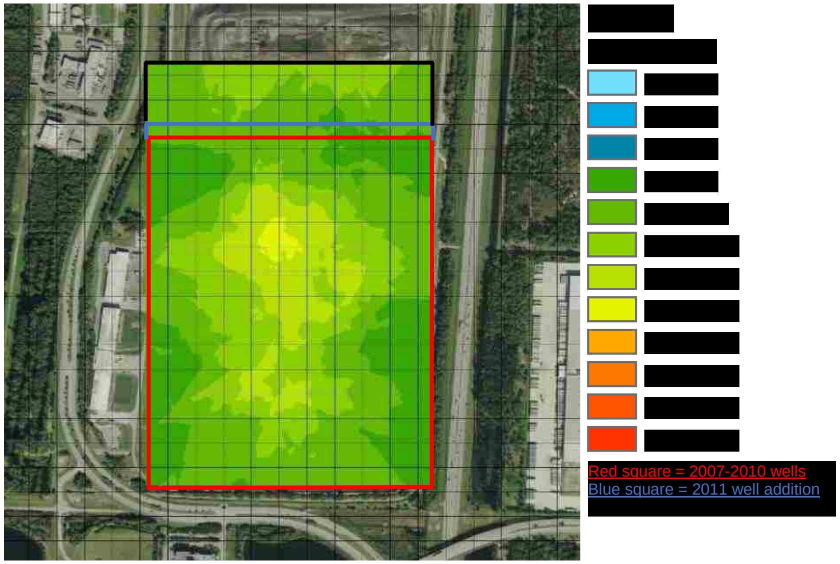

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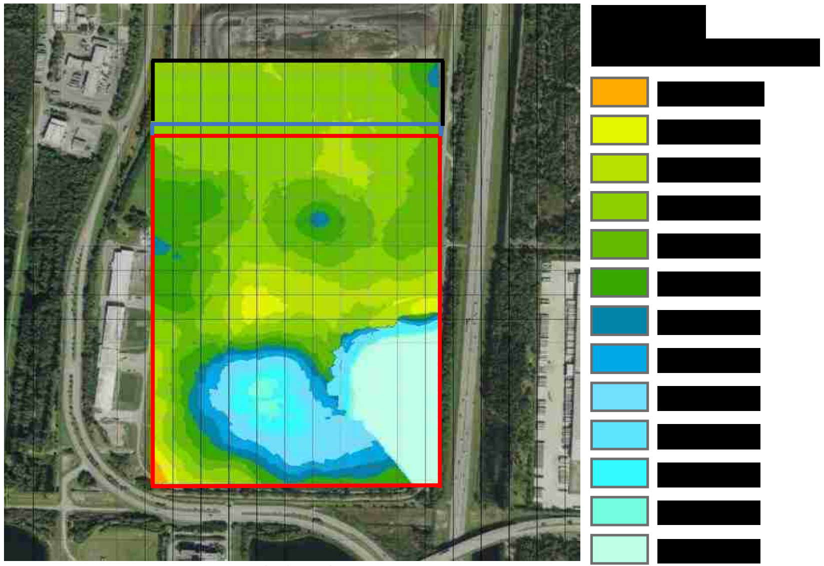

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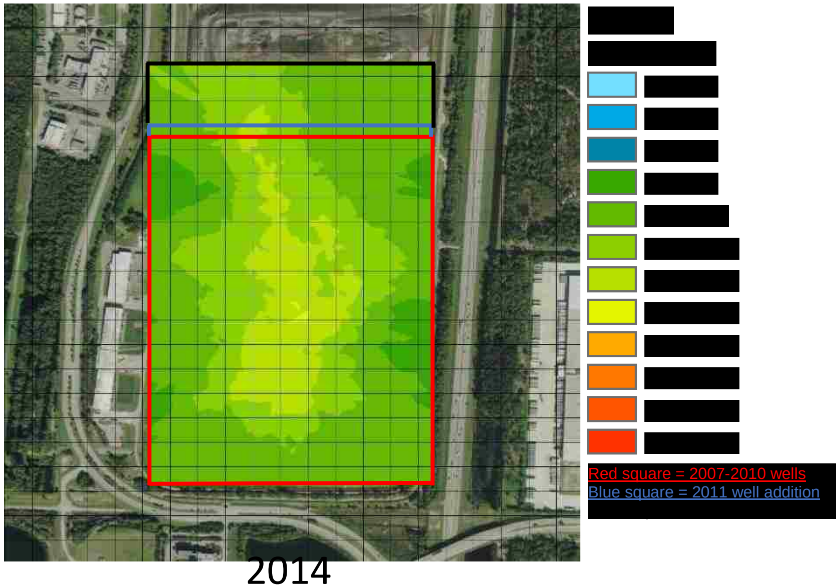

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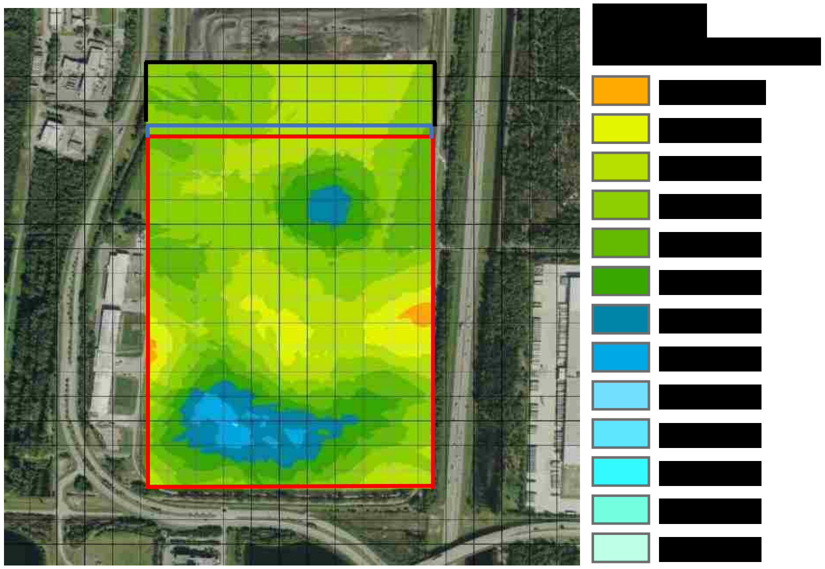

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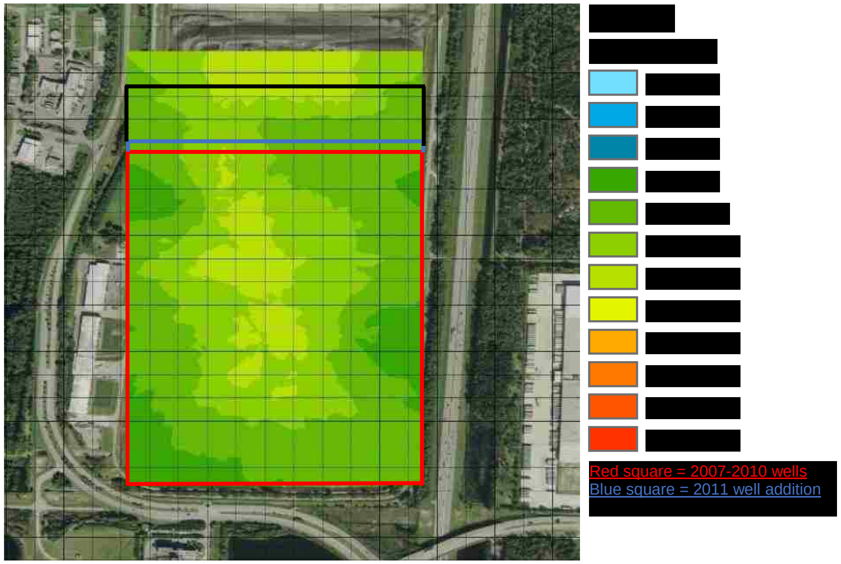

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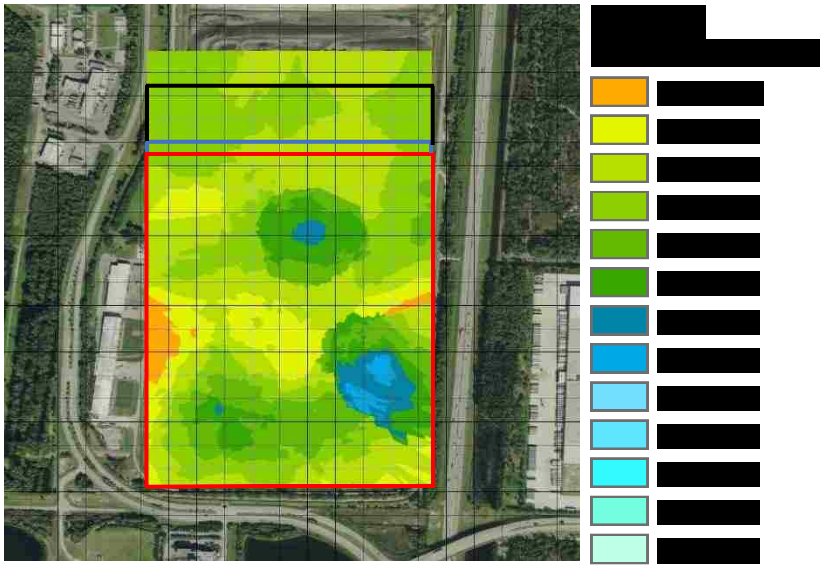

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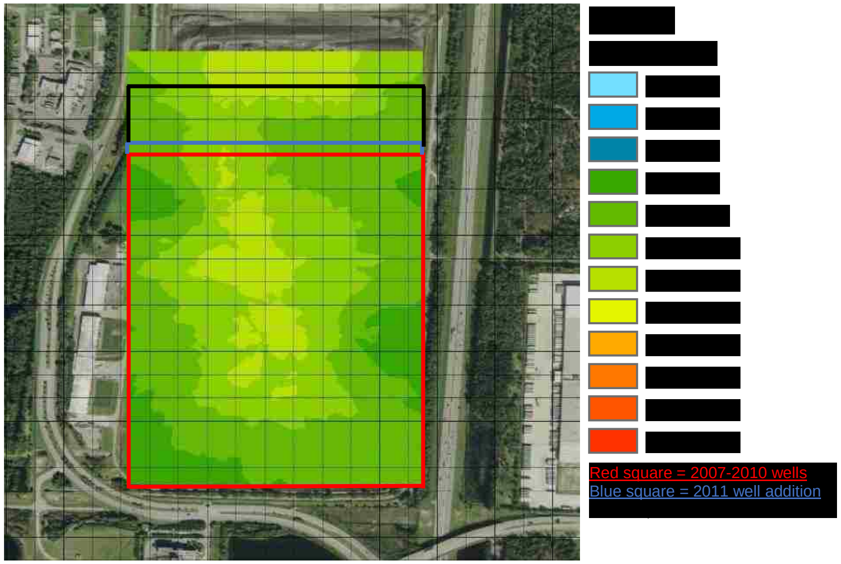

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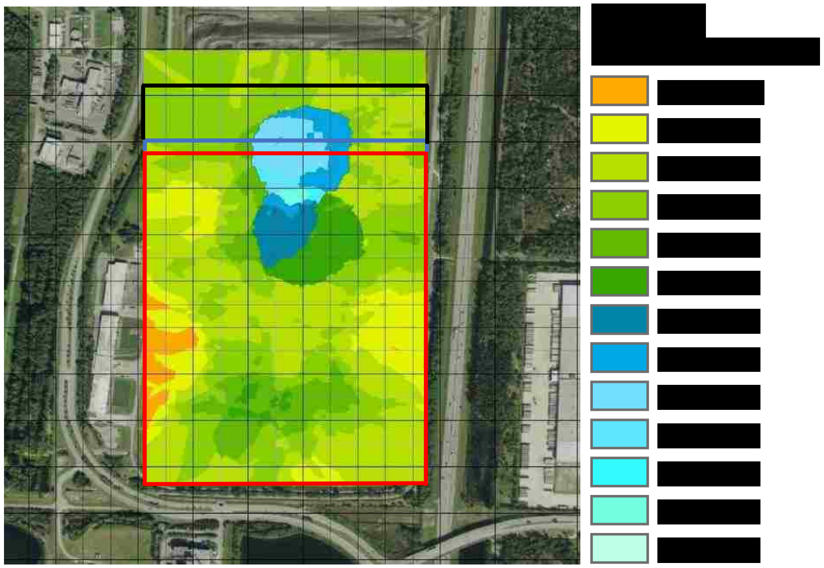

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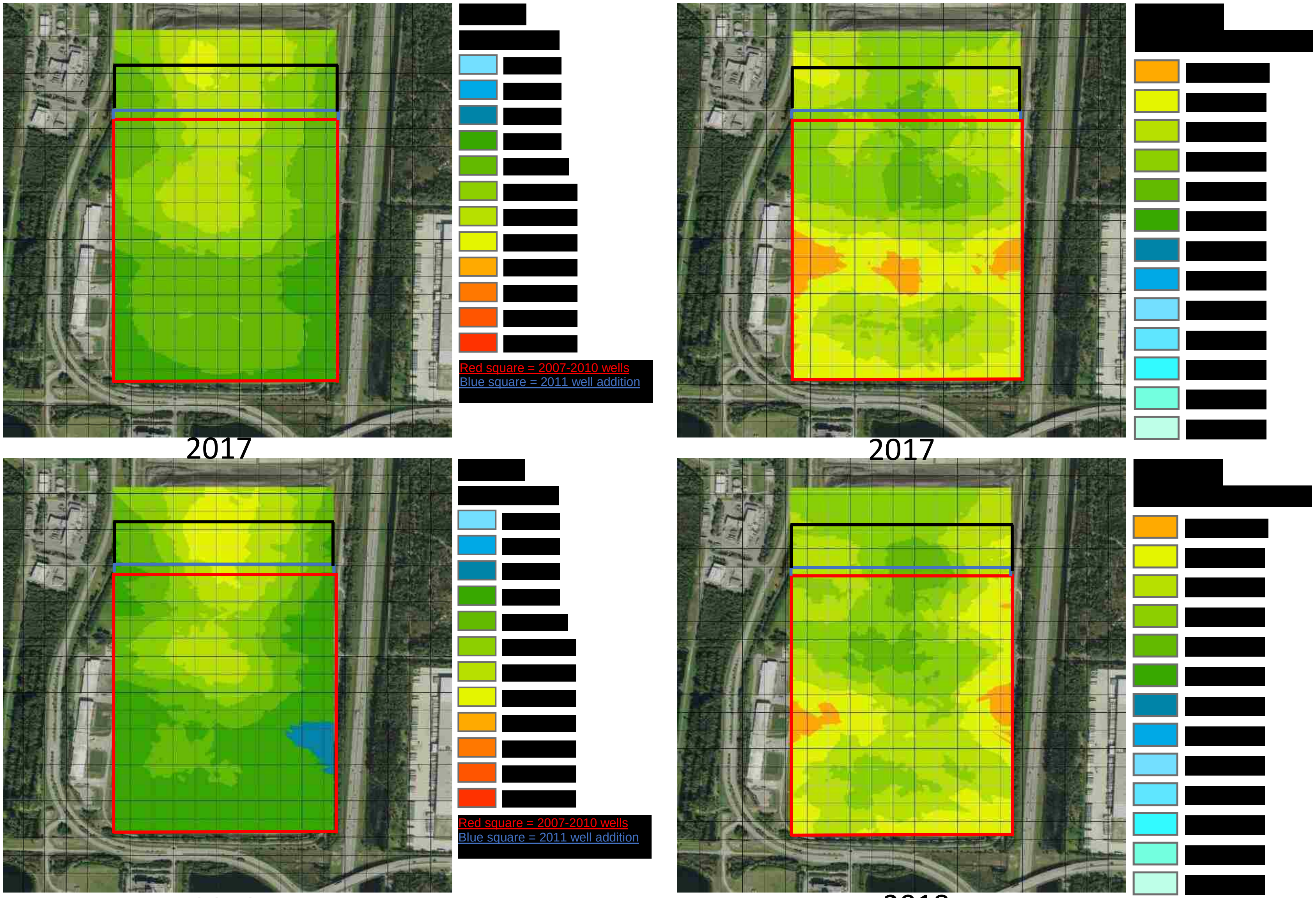
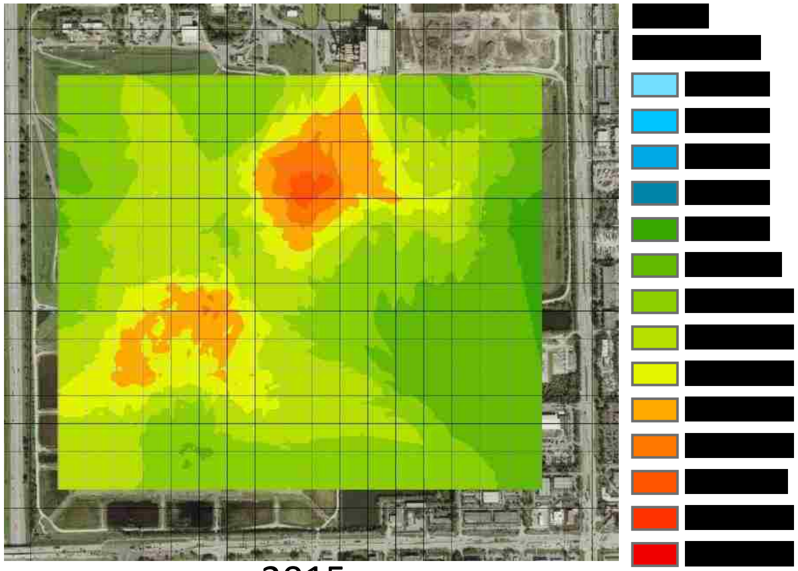


Figure B-3: Temperature Contour Maps and CH_4 to CO_2 Maps for Landfill R (2007-2018)

Landfill G



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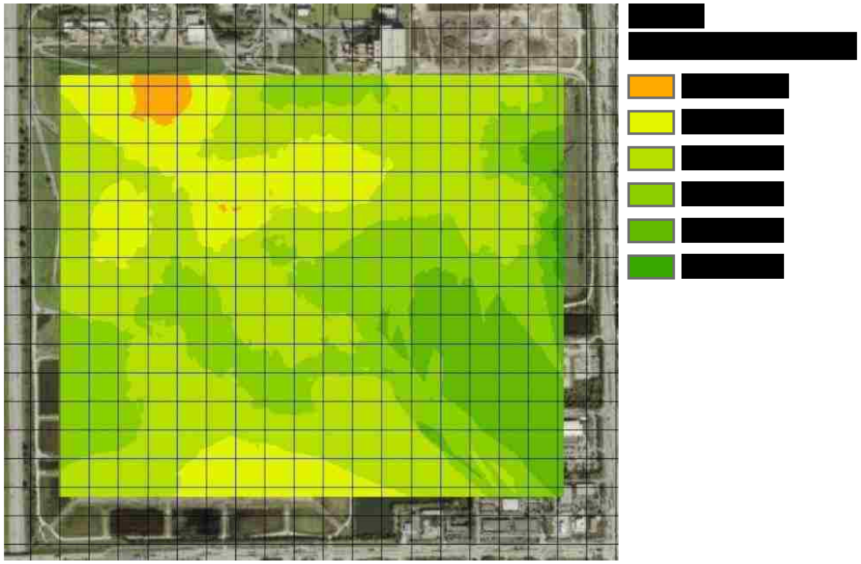

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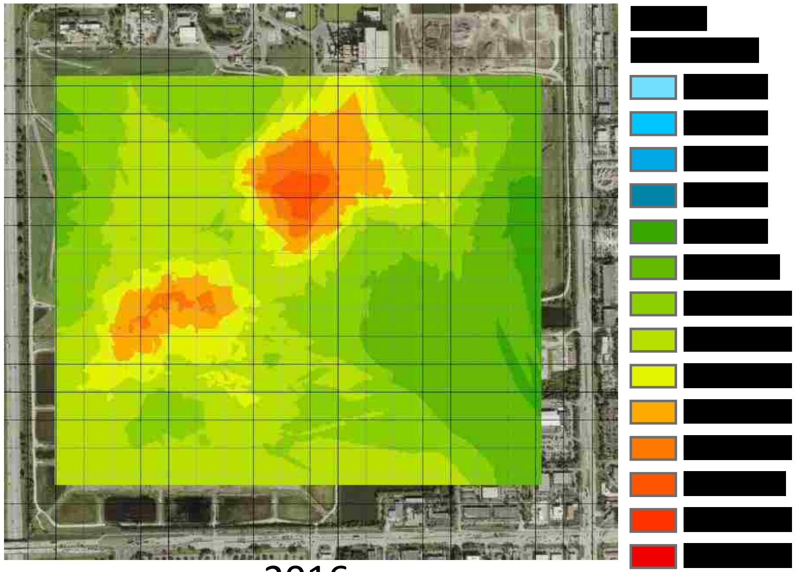

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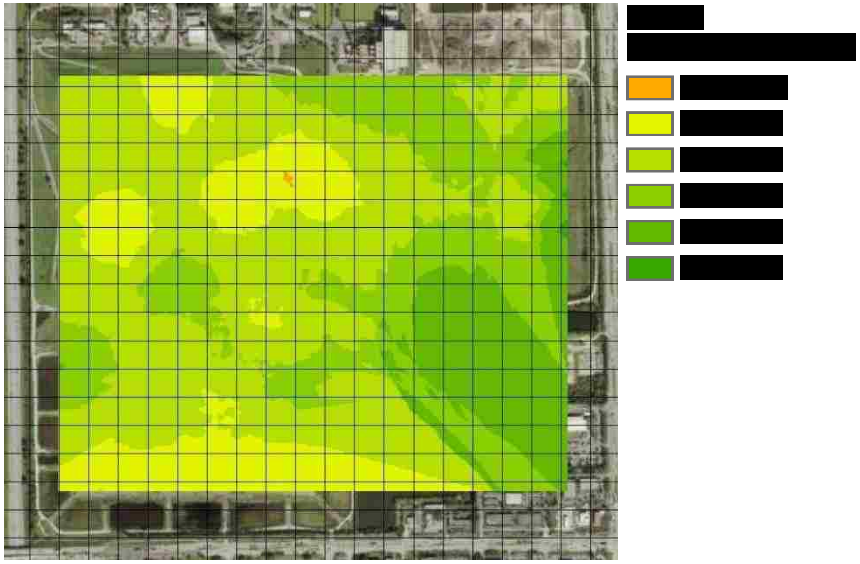

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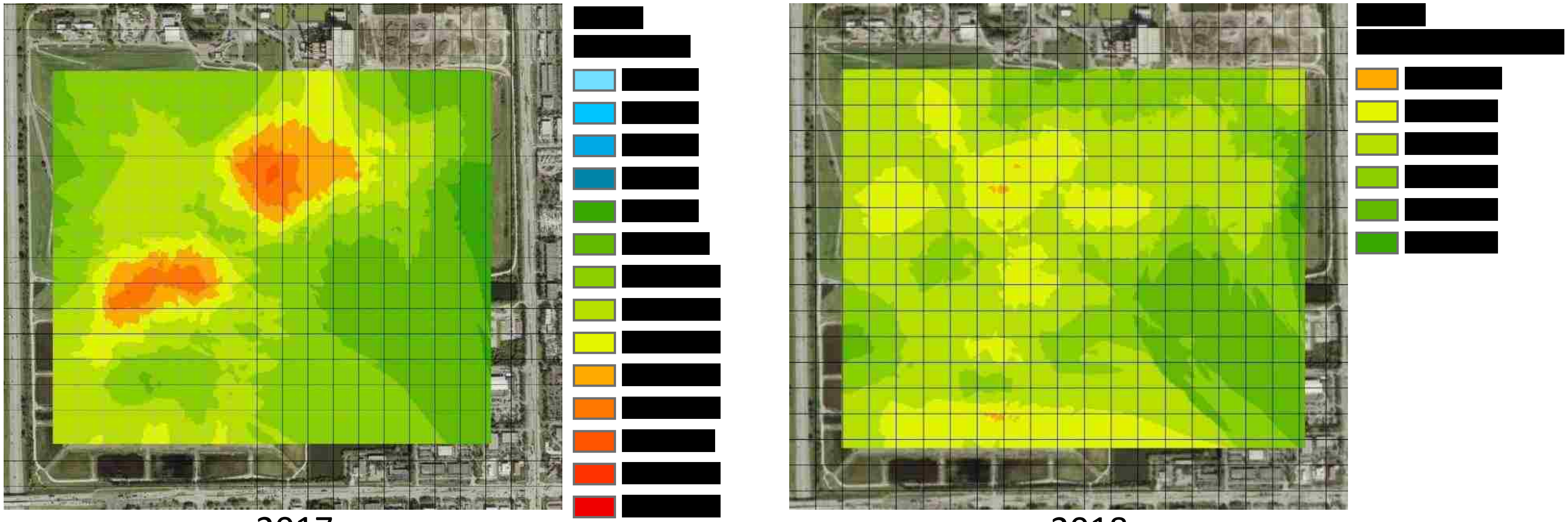

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2017

2018

Figure B-4: Temperature Contour Maps and CH_4 to CO_2 Maps for Landfill G (2015-2017)

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