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Development of a subsurface landfill fire risk-index

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DEVELOPMENT AND ASSESSMENT OF A SUBSURFACE LANDFILL FIRE RISK-INDEX

by

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Dedications

I would like to dedicate this manuscript to my parents, Gazi Shahabuddin and Shahana Akter Zaman.

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Foremost, I would like to express my sincere appreciation to my thesis advisor Professor Dr. Rouzbeh Nazari of the Civil and Environment Engineering Department at Rowan University for giving me opportunity to work in this research project and enough freedom to explore different methods in my research works. I would like to thank Dr. Jess Everett for his guidance and suggestions throughout my thesis work, which I found really supportive to improve and develop my works towards final output. I am truly grateful to him for his valuable comments on this thesis. I consider the skills and knowledge, I have acquired through this process are my future assets. Now I am confident enough to solve any challenges I need to confront in future.

This work was supported through United States Department of Agriculture (USDA) under Solid Waste Management Grant Programs.

Finally I would like to thank my parents and my husband for their unwavering love and support through this endeavor. I must express my profound gratitude to my husband for supporting me with continuous encouragement throughout the whole process. This achievement would not have been possible without them.

Abstract

Samain Sabrin
DEVELOPMENT AND ASSESSMENT OF A SUBSURFACE LANDFILL FIRE RISK-INDEX
2017-2018
Dr. Rouzbeh Nazari, Ph.D.
Master of Science in Civil Engineering

Landfill subsurface fires create environmental hazards by emitting potentially dangerous particulates into the atmosphere and damaging liners, potentially contaminating surrounding soil and groundwater aquifers with leachate. Currently, the only means of detecting underground fires are physical tests. This paper is used to describe an index that can be employed to track fire risk across a landfill. The landfill parameters analyzed for fire risk susceptibility in Chapter 1 include residual nitrogen concentration, oxygen exceedance, methane concentration, carbon monoxide level, methane and carbon dioxide ratio and monitoring well temperature. Incorporating these factors, a landfill fire index ranging from 1 to 10 was developed in Chapter 2 that can be utilized by waste disposal facility operators to avoid fire incidents, fatalities, and environmental damage. A high index value indicates a high level of risk for landfill subsurface fire. Landfill operators can use the index to take preventive measures that reduce the economic and environmental costs of landfill fires.

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Chapter 1

Abstract

The subsurface environment of any landfill is composed of several gases which are the bi-products of the chemical reactions inside landfills. The most available and influencing gases in subsurface environment contained by any landfill are methane, carbon dioxide, nitrogen, oxygen and carbon mono-oxide. These gases are monitored by every landfill which is a requirement imposed by Federal laws in United States for the sake of safety and protection of environment and community health. Additionally the control and monitoring of the mentioned gases are moderately related with controlling subsurface temperature. Most landfills have history of experiencing subsurface exothermic reactions during their operational lifespan. The research works in chapter 1 inspect how subsurface temperature is governed by the mentioned soil gases and examine the temperature ranges in terms of general parameters for landfill fires mentioned by (Thalhamer 2013) and (Estabrooks 2013); and operational standards legislated by United States Environmental Protection Agency (US EPA).

1.1 Introduction

Landfills are an essential component of modern consumption oriented societies. Solid waste landfills are large-scale containment systems, engineered to isolate solid waste from the environment and limit its harmful effects on surrounding communities. In the United States, 258 million tons of consumer solid waste are estimated to be produced per year, and 52.7% of this is buried within landfills (EPA 2014). The amount of municipal solid waste (MSW) produced in the United States has risen substantially over decades, from 208.3 million tons in 1990 to 250.4 million tons in 2011 (USEPA 2013), while the number of landfills has significantly decreased, from about 8,000 in 1988 (USEPA 2001) to about 1,908 in 2011 (USEPA 2013). This decrease in the number of landfills is generally due to stricter regulations imposed by the EPA regarding landfill gas emissions, leachate collection, safety regulations, and content of landfills, leading to the growing size of the remaining landfills to accommodate the increased production of MSW (U.S. Fire Administration 2002) and resulting in larger waste piles with smaller surface to volume ratios. When self-heat from natural biodegradation processes exceeds heat dissipation through the surface of a solid waste landfill, temperatures may be reached that lead to spontaneous ignition (Moqbel 2009).

This research is primarily focused on municipal solid waste landfills and subsurface fire events. Landfills are susceptible to fires due to their unique composition and construction. According to NFIRS data, an average of 8,400 landfill fires are reported to the Fire Service every year in United States (U.S. Fire Administration 2002). Landfill fires can be divided into surface fires or subsurface fires. Surface fires ignited over newly buried or non-compacted solid waste, can stem from a variety of different reasons, including: the dumping of undetected smoldering materials, landfill gas control systems, human error, construction and maintenance work, spontaneous combustion, deliberate fires to reduce landfill volume, and deliberate arson fires (U.S. Fire Administration 2002). A subsurface event is defined as any combustion below the surface and within the waste mass that is not visible on the surface, such fires may go undetected for years, hence the extent of landfill damage is difficult to determine. This can consume large amounts of waste, causing internal structural damage that may result in sections of the landfill collapsing while personnel are trying to contain the fire (Foss-Smith 2010). When temperatures are high enough to initiate a smoldering event, resulting air pollutants include, but are not limited to, carbon monoxide (CO), volatile organic compounds (VOCs) (e.g., benzene and methyl-ethyl ketone), polycyclic aromatic hydrocarbons (PAHs), and semivolatile organic compounds (SVOCs), each of which can pose serious dangers to welfare of human health and environment (Martin et al. 2012; Stark et al. 2012; Szczygielski 2007; Bates 2004; Nammari et al. 2004). Subsurface landfill fires may cause damage to the liner and leachate collection system.

Most subsurface events have no visible flame or burn slowly, making detection more difficult than with surface landfill fires. There is no easy way to directly detect an underground fire, however some fires can be confirmed by checking the areas of settlement over a short period of time, monitoring smoke or smoldering odor, observing levels of CO exceeding 1,000 parts per million (ppm), detecting temperature increase in the gas extraction system, beyond 140°F, or well temperatures surpassing 170°F (Thalhamer 2006).

The definition of elevated subsurface temperatures are delineated differently by different landfill owners, researchers, consultants and regulators (Jafari et al. 2017). Previous works on elevated landfill temperatures discussed controlling temperature by optimization of methane production and waste decomposition (Rees 1980), investigated thermal aspects of MSW landfills as a function of climate region and operational conditions (Yeşiller et al. 2005), inspected periodic temperature and gas production for MSW (Hanson et al. 2005), and analyzed slope stability using elevated temperature and increased gas and liquid pressures (Hanson et al. 2009). The literature described in chapter 1 discusses unsafe range of subsurface temperature that can pose significant risk to landfill consistency, in respect to safe and unsafe ranges of soil gases from gas collection system in landfills. After a systematic analysis of risk factors effecting the corresponding subsurface elevated temperature indicating possible fire in chapter 1, this paper is focused on generating a risk evaluation model and assessing the model in terms of observed temperature data in chapter 2.

1.2 Background

Landfill gas typically contains 45% to 60% methane (CH_4), 40% to 60% carbon dioxide (CO_2), 2% to 5% nitrogen (N_2) and 0.1% to 1% oxygen (O_2) volumetrically as well as small amounts of ammonia, sulfides, hydrogen, carbon monoxide, and nonmethane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride (Williams 2001). Landfill gas is produced in three processes—bacterial decomposition, where most landfill gas is produced by aerobic and anaerobic bacterial decomposition; volatilization, changing liquid or solid wastes into a vapor, e.g. NMOCs from chemicals disposed of in the landfill; and chemical reactions with chemicals present in waste (Williams 2001). Over decades, bacteria decompose landfill waste in four phases: phase I aerobic decomposition (with aerobic bacteria that live only in the presence of oxygen) converting the refuse matters into carbon dioxide and water; phase II anaerobic decomposition in the absence of oxygen; phase III decomposition when certain kinds of anaerobic bacteria consume the organic acids produced in Phase II; Phase IV when both the composition and production rates of landfill gas are relatively constant (Williams 2001) and Phase V when low amounts of organic matter remain and oxygen is reintroduced. Figure 1 represents the chemical processes and the byproducts created through the bacterial decomposition and Figure 2 is used to illustrate the level of gas production in different stages of waste decomposition.

The composition of the gas changes through the phases of decomposition. The landfill gas produced during phase II consists of 20% to 60% CO2, 10% to 20% hydrogen (H2), and 50% to 30% nitrogen (N2). In the third phase, CH4 production begins and the composition of the landfill gas changes to 40% to 60% CO2 and 45% to 60% CH4 with < 1% hydrogen (Martin et al. 2012). An operating landfill can have all four phases operating at the same time, but in different zones. Eventually, gases are produced at a stable rate; however, gases will continue to be emitted for 50 or more years after the waste is placed in the landfill (Crawford & Smith 1985). In a mature landfill, the gas concentrations remain steady and will range from 50% to 70% CH4, and from 30% to 50%. CO2. The biological transition time from phase III to IV ranges from 180 to 500 days depending on actual landfill conditions (Farquhar & Rovers 1973). The rate and volume of landfill gas (e.g., carbon dioxide, methane, nitrogen, and hydrogen sulfide) production are influenced by the characteristics of the waste (e.g., composition and age of the refuse), a number of environmental factors (e.g., the presence of oxygen in the landfill, moisture content, and temperature), and chemicals disposed of in the landfill (Williams 2001). As the landfill's temperature rises, bacterial activity increases, resulting in increased gas production. Increased temperature may also increase rates of volatilization and chemical reactions (Williams 2001).

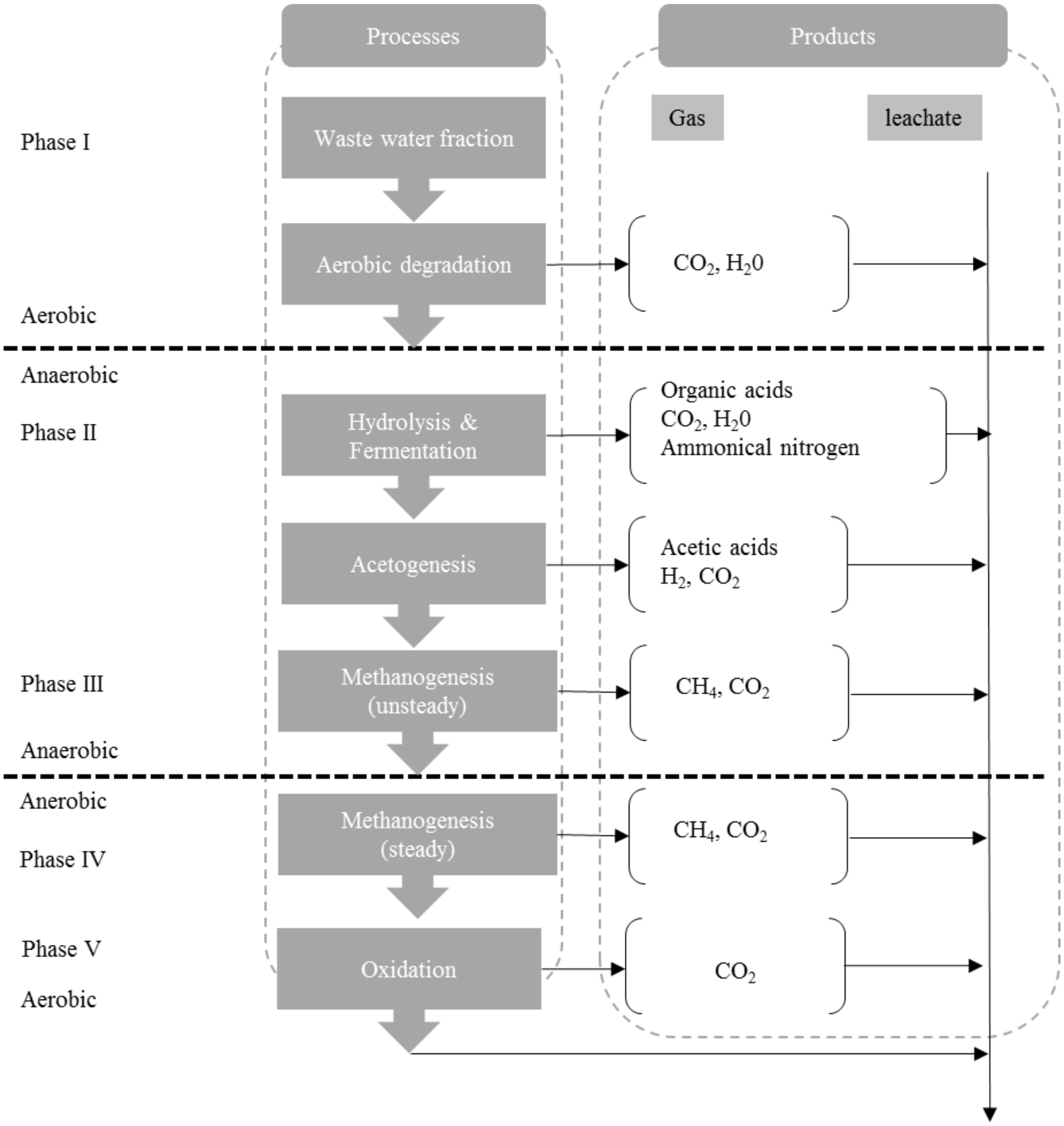
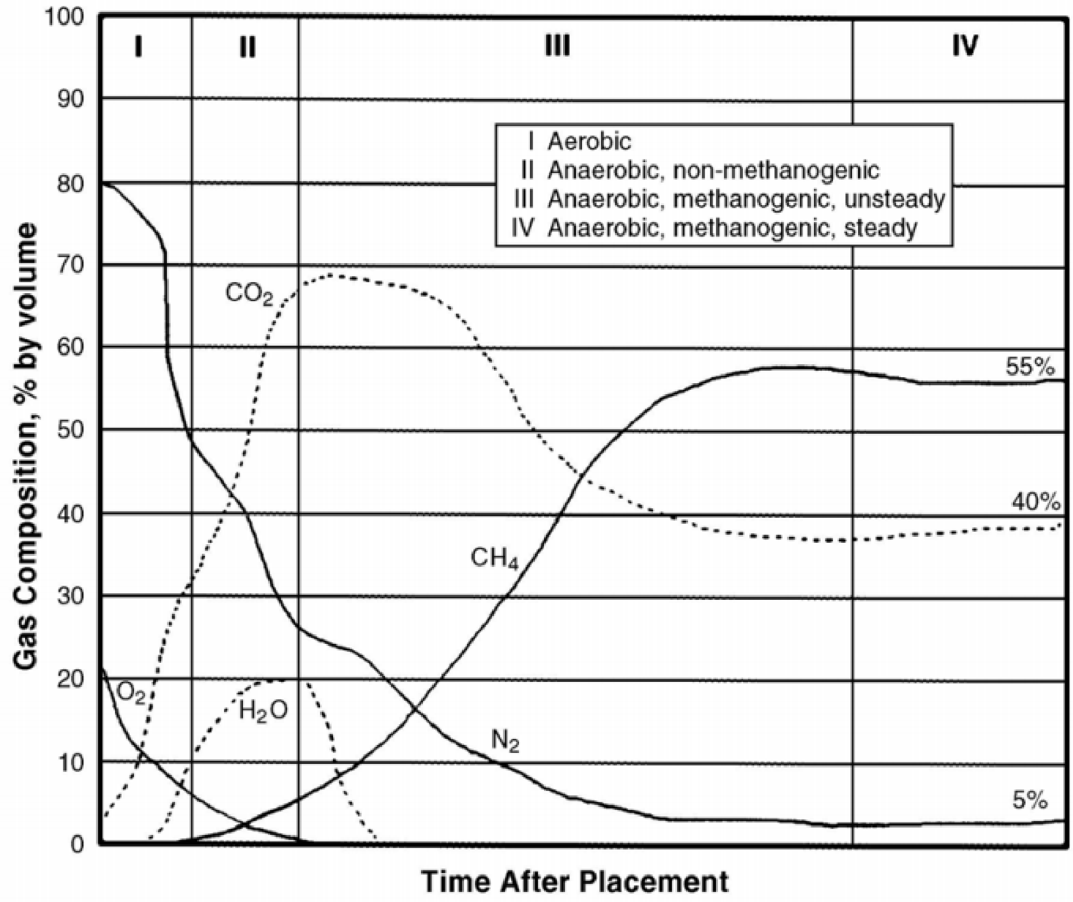


Figure 1. Chemical processes and the byproducts in bacterial decomposition.



Note: Time scale (total time and phase duration) of gas generation varies with landfill conditions (i.e., waste composition and anaerobic state).

Figure 2. Level of gas production in different stages of waste decomposition (Source: Robertson 2005).

MSW landfills undergo aerobic decomposition to produce carbon dioxide, water, and heat (Meraz and Domínguez 1998). As available oxygen is consumed, aerobic decomposition changes to anaerobic with the resultant production of methane, carbon dioxide, and heat. Aerobic and anaerobic transformation of organic waste can be expressed by the reactions in Equation (1) and (2), respectively (Meraz and Domínguez 1998).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \; ; \; \Delta H = -2{,}815 \; kJ/mol \tag{1}$$

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \; ; \; \Delta H = -145 \; kJ/mol \tag{2}$$

Comparing the enthalpies of both reactions, heat generated in anaerobic decomposition is approximately 5% of the heat produced from the aerobic reaction (Meraz and Domínguez 1998). As a result, waste temperatures in aerobic conditions are in the range of 140–176°F (Haug 1997; Lefebvre et al. 2000; Merz and Stone 1970; Hudgins and Harper 1999), while anaerobic landfills typically have temperatures ranging from approximately 77–113°F (Yesiller et al. 2005; Hanson et al. 2009). Accumulation of heat by aerobic biodegradation or another exothermic process with the intrusion of oxygen provides the necessary conditions to initiate and sustain subsurface combustion of MSW (Fire 1996). Based on the tetrahedron of combustion theory (Fire 1996), four conditions must be present for combustion to occur: (1) a fuel source, e.g., paper products in MSW; (2) an oxidizer, e.g., oxygen from air intrusion; (3) an energy source, e.g., heat generated from aerobic decomposition or other exothermic reaction; and (4) a self-sustaining chain reaction of combustion, e.g., charred waste. In MSW landfills, the reactant that can be readily controlled is air intrusion, so it is imperative to limit air intrusion. Subsurface combustion typically propagates in landfills through smoldering combustion, which occurs directly on the surface of a solid fuel (Martin et al. 2012). Incomplete smoldering combustion of cellulose yields carbon dioxide, carbon monoxide, water vapor, and heat (Huggett 1980), as shown in Equation (3).

$$C_6H_{10}O_5\,(s) + 5.7O_2\,(g) \rightarrow 5.4CO_2\,(g) + 0.6CO\,(g) + 5H_2O\ ;\ \Delta H = -2{,}440\ kJ/mol$$

(3)

Smoldering combustion does not proceed to completion because the amount of oxygen is limited, but it can propagate at low oxygen levels, e.g., <3% volume-to volume ratio (v/v) (Kirk and De Haan 2013; Pitts 2007). Smoldering combustion has been documented to persist within an MSW landfill between 212 and 248°F (Ettala et al. 1996). In other cases, the temperature range observed during smoldering combustion in MSW landfills have ranged up to 392 to 572°F and even as high as 1292°F (Lönnermark et al. 2008; Ruokojärvi et al. 1995). Bergström and Björner (1992) measured a range of 176–446°F in a deep subsurface fire. Research has shown sustained temperatures as low as 185°F have impacted the service life and integrity of landfill gas extraction systems, leachate control systems, covers, and materials in composite liner systems (Rowe et al. 2010). During periods of elevated temperature, landfill gas quickly changes from predominantly methane (50–60% v/v) and CO_2 (40–55% v/v) to CO_2 (60–80% v/v) with the ratio of CH_4 to CO_2 falling below 1, hydrogen (10–35% v/v), and CO (>1,500 ppmv) (Jafari et al. 2017).

It is also important to understand that refuse temperature controls the quality and quantity of landfill gas generated (Hanson et al. 2009; Crutcher and Rover 1982). The gas extraction system in landfills is designed to remove methane to limit environmental hazards as well as controlling odor emissions. According to Thalhamer (2013), some parameters have been established to diagnose the presence of smoldering fires: increased temperatures in the landfill gas control systems and waste mass, temperatures over 170°F; decreased methane production; elevated concentrations of volatile and semi-volatile organic compounds; carbon monoxide concentrations above 1,000 ppm; smoldering odors or smoke emanating from the landfill; combustion residue in the landfill gas control systems; and unusually rapid and excessive landfill settlement. The association between CO and subsurface combustion has been observed in many articles (Ettala et al. 1996; Frid et al. 2010; Bates 2004; Martin et al. 2012; Stearns and Petoyan 1984; Sperling and Henderson 2001). Carbon monoxide is generated during smoldering combustion when insufficient oxygen is present to allow complete combustion and generation of water vapor and CO_2 (Shafizadeh and Bradbury 1979; Quintiere et al. 1982; Pitts et al. 1994; Ohlemiller 1995). According to Estabrooks (2013), more than 20% residual nitrogen is a good indicator of aerobic conditions and the potential for subsurface heating events. Table 1 displays the ranges of residual nitrogen as described by Estabrooks (2013).

Table 1

Residual Nitrogen (RN_2) ranges for Landfill's (Estabrooks 2013)

RN Percentage	Indications
0-12%	Normal operating range for internal extraction system in most landfill
16-20%	Considered necessary for controlling side slope emission, perimeter migration or where other compromise is needed
>20%	Implies aggressive landfill gas extraction that can lead to aerobic condition

The procedures to detect, evaluate, and mitigate a landfill fire vary in the literature. According to US EPA, recommended ranges for oxygen, methane, temperature are considered to be <5%, 45 to 60% and less than <130°F, respectively and the presence of carbon monoxide up to 2000 ppm is considered an action level (the level of concentration when exceeded is considered sufficient to warrant regulatory or remedial action) (Robertson & Dunbar 2005). SWANA considers oxygen <1%, methane 45 to 58%, and temperature <125°F as normal ranges; and recommends an action level of trace CO <25 ppm to take preventive measures against subsurface smoldering events (SWANA 1997). Table 2 is shown to simplify information on landfill operations and prevention of fires. However, these physical tests are inadequate because they can be used only when the fire has already caused damage to the landfill and surrounding environment. A risk index is needed that relates these parameters to the risk of future fire, to predict and prevent fire outbreaks.

Table 2

Important documents regarding landfill operations and prevention of fires in U.S. (Thalhamer 2013)

Document	**Recommended /Allowed Oxygen Intrusion**	**Normal Methane Range**	**Tempe-rature Action Range**	**Carbon Monoxide (CO) Action Level**	**Symptoms/Indications of a Smoldering Event or Comments**
SWANA	Ideal 0 to 0.5% <1%	Normal 45 to 58%	Typical range is 60ºF to 125°F Action 125ºF to 140°F	Trace <25 ppm	• CO is an indicator of the possible presence of a subsurface fire • 165°F is the temperature limit for PVC • CO is a byproduct of incomplete combustion and hence an indicator of a possible subsurface fire • Landfill fire may be tested by monitoring CO • Best way to treat a LFG fire is to starve the fire of oxygen • High residual N2 levels may indicate a landfill fire • If oxygen is sufficiently high (around 10% or greater) the LFG can be in the combustible range within the collection piping.

Table 2 (continued)

Document	**Recommended /Allowed Oxygen Intrusion**	**Normal Methane Range**	**Tempe-rature Action Range**	**Carbon Monoxide (CO) Action Level**	**Symptoms/Indications of a Smoldering Event or Comments**
US EPA	Typical 0.1 to 1% Max. <5%	Normal 45 to 60%	Action Level >130°F	0 to 2,000 ppm	• High residual N2 levels may indicate a landfill fire • If oxygen is sufficiently high (around 10% or greater) the LFG can be in the combustible range within the collection piping • Landfill fires can occur from the excessive influx of ambient air into the landfill wastes. • Underground landfill fires generally occur when ambient air is drawn into the landfill. • There must be data demonstrating that the elevated parameter(s) does not cause fires or significantly inhibit anaerobic decomposition of the waste (40 CFR §60.753)

1.3 Methodology

This research is based on quantitative statistical methods which incorporate landfill gas data collection (such as methane, carbon dioxide, oxygen and balance gas), categorizing the factors (gases) in terms of safe ranges, statistical tests to ascertain each factor’s influence on temperature and finally developing a risk index in chapter 2. The statistical tests in chapter 1 involve assessing the impact of all parameters in different temperature ranges by applying the Conditional Inference Trees algorithm (Hothorn et al. 2015), then analyzing the influence of various gas parameter combinations on subsurface temperature. Finally, the probability of temperature ranges with respect to possible parameters combinations were investigated using Naïve Bayes Conditional Probability (Lowd and Domingos 2005).

1.4 Data Collection

This research uses a collection of archived data for the above mentioned parameters from Bridgeton Sanitary landfill, Missouri. Bridgeton was permitted on Nov. 18, 1985, and ceased accepting waste on Dec. 31, 2004 when the waste mass encompassed approximately 52 acres with approximately 240 feet below the ground's surface and a total waste thickness of 320 feet. This landfill is regulated by the Missouri Department of Natural Resources' Solid Waste Management Program (SWMP). The landfill first informed SWMP about elevated temperatures in some gas extraction wells on Dec. 23, 2010, as well as smoldering and odor issues. Since 2013, a website (https://dnr.mo.gov/bridgeton/BridgetonSanitaryLandfillReports.htm) provides public access to commonly requested reports and data files related to subsurface smoldering events and odors at and around Bridgeton Landfill.

Figure 3 displays the geographical location of the study area and Figure 4 shows the location of all the gas extraction wells from which subsurface gas samples are collected. The data regarding gas and well's temperature data are available on a weekly and monthly basis. Weekly gas well data contains the basic parameters of methane, carbon dioxide, oxygen and balance gas concentration and temperature data, while monthly data includes only methane, carbon dioxide, oxygen, nitrogen, hydrogen and carbon monoxide without temperature data. Since temperature is most important parameter for data analysis, weekly data containing 18469 observations from gas collection wells, gas interceptor wells and temperature monitoring probes for the time period of June, 2013 to October, 2016 are used here. Table 3 shows a sample of collected data.

Figure 3. Geographical map overview of Bridgeton Landfill in Missouri, USA.

Table 3

Sample gas-well data for Bridgeton Landfill

Well Name	**Date Sampled**	**CH_4**	**CO_2**	**O_2**	**Balance Gas**	**Temperature (°F)**	**Residual N_2**	**Ratio (CH_2: CO_2)**
GEW-40	6/3/2013 9:31	47.9	51.6	0	0.5	100	0.5	0.93
GEW-41R	6/3/2013 9:35	57.3	42.2	0	0.5	116	0.5	1.36
GEW-41R	6/3/2013 9:36	56.8	41.1	0	2.1	116	2.1	1.38
GEW-42R	6/3/2013 9:39	53.3	39.9	0	6.8	112	6.8	1.34
GEW-43R	6/3/2013 9:45	57.4	42.5	0	0.1	96	0.1	1.35

Based on the discussion in section 1.2, residual nitrogen and the methane to carbon dioxide ratio are significant parameters for predicting gas well temperature. These two parameters can be calculated from the collected data. Residual nitrogen is the portion of nitrogen that remains unused during aerobic decomposition. Over-pulling of gas through the gas collection system and air infiltration results in the presence of excess nitrogen. When the vacuum in the gas collection system pulls in more air, oxygen in the air kills methanogens and creates aerobic conditions. During this state of decomposition, oxygen is consumed and the nitrogen that is also present in the air is left inside the landfill.

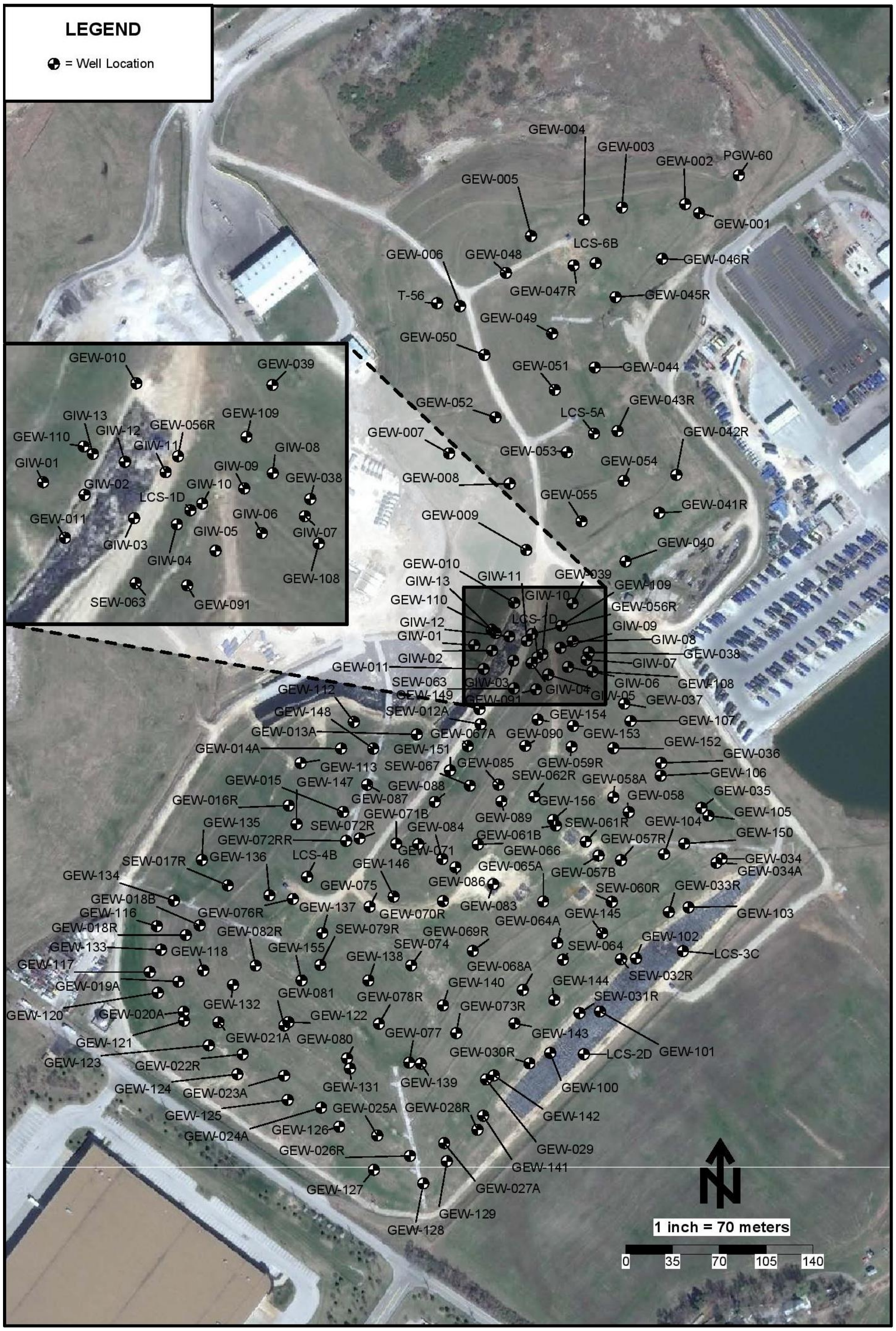


Figure 4. Location of Gas extraction wells in Bridgeton Landfill.

A report provided by the Solid Waste Association of America states that CH_4, O_2 and CO_2 are the key parameters to determine balance gas concentration which primarily indicates the amount of nitrogen; and the normal ratio of N_2 to O_2 is approximately 3.76 (SWANA 1997, Estabrooks 2013). Residual nitrogen can be calculated using a simple gas equilibrium equation, e.g., if a gas well measures CH_4 (32.5%), CO_2 (28.1%), O_2 (3.7%), then balance gas (100- 32.5 – 28.1 -3.7 = 35.7%) and the normal nitrogen can be calculated by taking the typical ratio (3.76) multiplied by oxygen composition (3.7%), 3.76 * 3.7 = 13.912 %. Residual nitrogen (RN_2) can then be measured by subtracting normal nitrogen composition (13.912%) from balance gas (35.7%) which yields a residual nitrogen composition of 21.8% (Estabrooks 2013).

1.5 Analysis

1.5.1 Categorizing the variables. Before analyzing the Bridgeton landfill dataset, it is vital to investigate the correlation of the considered parameters on temperature and to test their effect on temperature. For this purpose the gas data was categorized based on the normal and safe ranges for gases according to 40 CFR §60.753 and for temperature a safe limit of less than 176 °F (Martin et al. 2012; Thalhamer 2013). The safe limit for residual nitrogen was considered less than 20% (Estabrooks 2013). This creates dichotomous variables denoting two categorical variables for each parameters: safe and unsafe. Table 4 shows the parameters and their categorization rule.

Table 4

Categorization of factors based on documents

Parameters	categorization rule	Categories	References
Methane	Safe range: 45 to 60%	safe	40 CFR §60.753
	Unsafe range: < 45% and >60%	unsafe	
Oxygen	Safe range: <5%	safe	40 CFR §60.753
	Unsafe range: >5%	unsafe	
Ratio (CH_4:CO_2)	Safe range: >1	safe	Thalhamer 2013
	Unsafe range: <1	unsafe	
Temperature	Safe range: <176°F	safe	Thalhamer 2013
	Unsafe range: >176°F	unsafe	
Residual Nitrogen	Safe range: <20%	safe	Estabrooks 2013
	Unsafe range: >20%	unsafe	

For each parameter methane, ratio between methane and carbon dioxide, oxygen, residual nitrogen, temperature and carbon monoxide--there are 2 possible events. Each sampling event can be described as a combination of safe or unsafe values of six parameters. The total number of possible samples events is two raised to the number of parameters. In the case of 5 factors, the possible number of events will be 2^5 or 32.

1.5.2 Testing each variable's effect on temperature. As the data for carbon-monoxide are not available for Bridgeton Landfill, the other available gas parameters have been analyzed. First, the individual gas conditions' effect on temperature was examined using boxplots. Figure 5 shows temperature range for four factors, each with two conditions (safe = 0 and unsafe = 1). The box plot displays the distribution of data in terms of five numbers: minimum, first quartile, median, third quartile, and maximum. The median (middle quartile) marks the mid-point of the data and is shown by the line that divides the box into two parts. 50% of samples fall in the range of samples from first to third quartile, the inter-quartile range, which is represented as the box. Twenty-five percent of the samples fall above the third quartile, while another twenty-five percent fall below the first quartile. The data points located 1.5 times outside the interquartile range above the third quartile and below the first quartile are considered as outliers and are shown as open circles. The third quartile and median values for temperature were observed higher in unsafe range than safe range for three factors, but not oxygen. The EPA oxygen safe range was associated with a higher temperature range than the unsafe range, in contrast to the literature review described in section 1.2. The reason could be because of relationship with other parameters or how this particular landfill was operated.

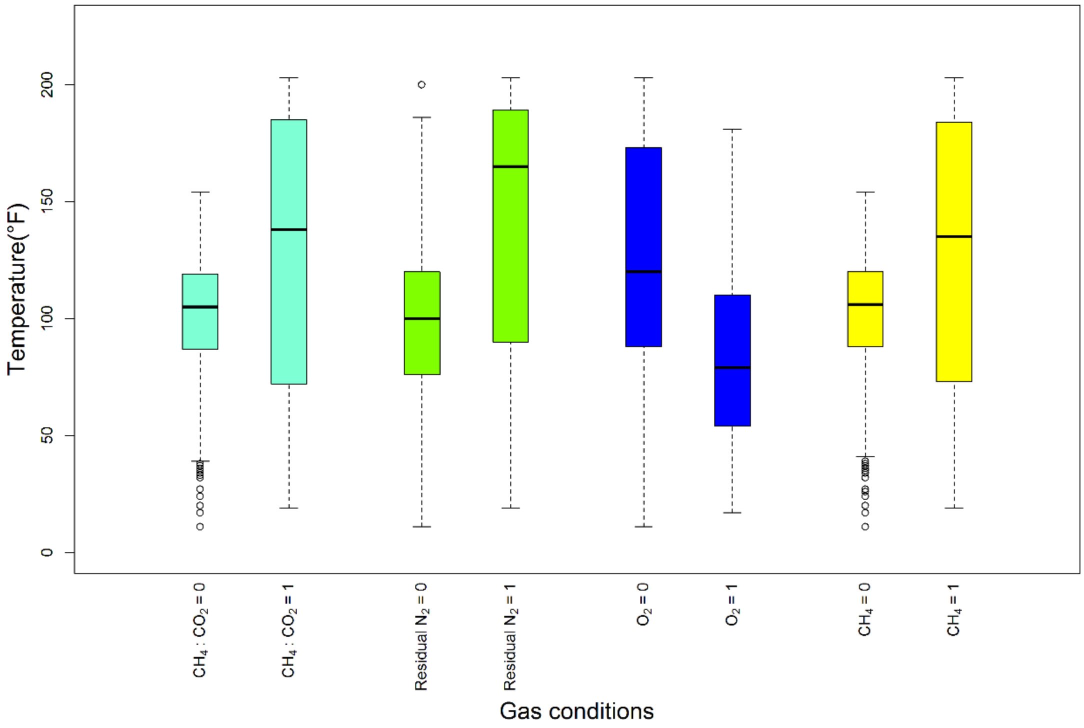


Figure 5. Temperature in different Gas conditions.

1.5.3 Testing variables' effect on temperature with decision tree. The impact of all the parameters on different ranges of subsurface temperature was investigated by applying the Conditional Inference Trees algorithm (Hothorn et al. 2015) on 18,469 observations. Before applying the algorithm, all the parameters were classified as to safe and unsafe range, while temperature was classified as 'under 131°F', '131-176°F', '176-200°F' or '200-300°F'. Figure 6 presents a tree with all possible splits with significance level less than 0.05 and the name of parameters for best splits in the circles with corresponding p-values. The levels of the parameters are stated on the branches and the bar plots at the bottom show the proportions of four temperature ranges in each end node containing all observations with a combination of features.

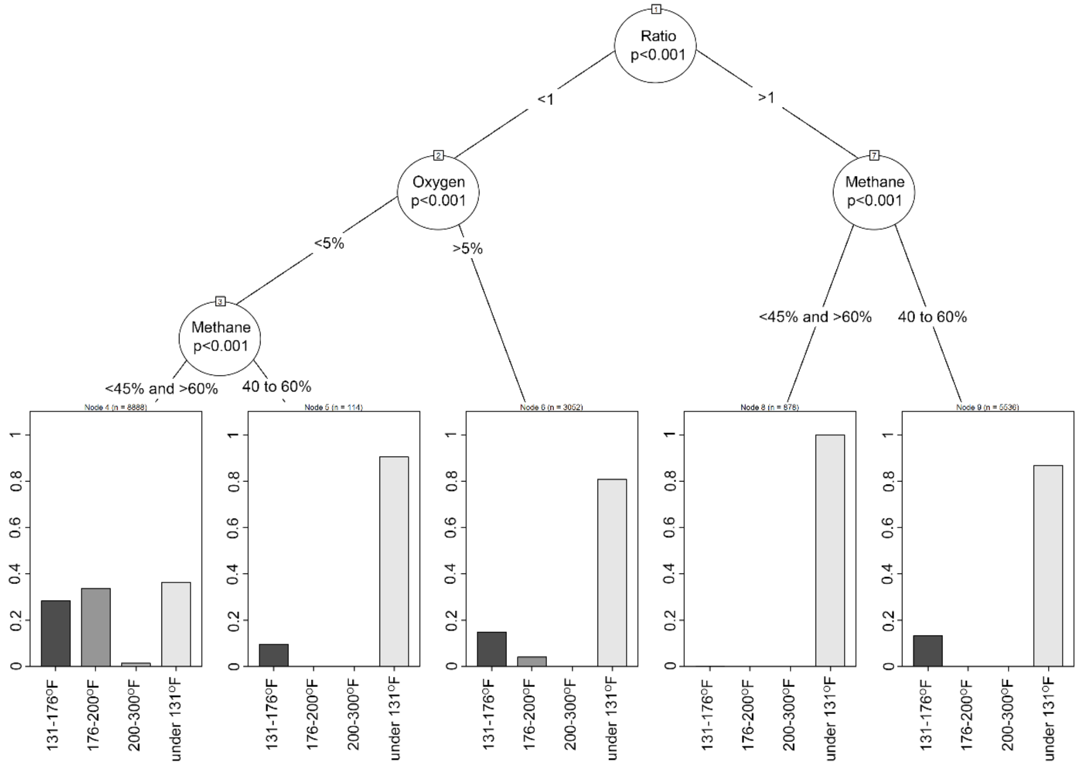


Figure 6. Result from applying Conditional Inference Trees on temperature ranges.

Among four parameters, the covariate showing the largest association with temperature ranges is the ratio between methane and carbon dioxide, with a significance level less than 0.001. The 1st tree branch, with ratio <1, has high association with oxygen (significance level, $p < 0.001$), while the branch with ratio >1 has the largest association with methane (significance level, $p < 0.001$). The tree shows the branch with a ratio less than 1, oxygen less than 5% and methane with <45% and >60%, has a higher number of incidents in the temperature ranges of '131-176°F', '176-200°F' and '200-300°F' than any other branches. The 2nd highest number of incidents in the temperature range 176-200°F is observed in the branch with ratio <1 and oxygen >5%. The tree branch with ratio >1 and methane with 45 to 60% has the third highest number of incidents in the temperature range of 131-176°F, with approximately 720 observations. Therefore high temperature ranges do not always associate with the unsafe ranges of all parameters, rather they vary with parameter combinations.

1.5.4 Effect of variable combinations on temperature. To understand how various gas parameter combinations influence subsurface temperature, a boxplot of temperature versus different events is provided in Figure 7, where 0 is safe and 1 is unsafe. Figure 7 shows that some of the combinations show similar temperature ranges, while in other cases they significantly vary in the range. In four cases, such as (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0,Temperature=0), (CH_4=1, CH_4:CO_2=1, RN_2=1, O2=0, Temperature=0), (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=1, Temperature=0), and (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=1, Temperature=0), the temperature ranges are wider. The widest inter-quartile temperature ranges are observed in these combinations and the top positive quartile value is observed in (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0, Temperature=1). Only one data-point is observed in (CH_4=1, CH_4:CO_2=0, RN_2=1, O_2=1, Temperature=0) combination. Four of the combinations (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0, Temperature=1), (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0, Temperature=1), (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=1, Temperature=1), (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=1, Temperature=1) always give temperature greater than 170°F; while rest of the combinations produce safe temperatures with more than 75% probability of temperatures under 170°F. Moreover there are seventeen other combinations where no boxplot was created due to the absence of these events in the sample data, implying these combinations are rare or do not occur. Similar gas parameters combinations are observed in three combinations pairs. For example (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0, Temperature=0) and (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0, Temperature=1) combinations show similar gas combination with both safe and unsafe temperature range which indicates that the gas parameters have insignificant effect on temperature for these two combinations. The insignificant effect of gases are also observed for gas combination of (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0) and (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=1).

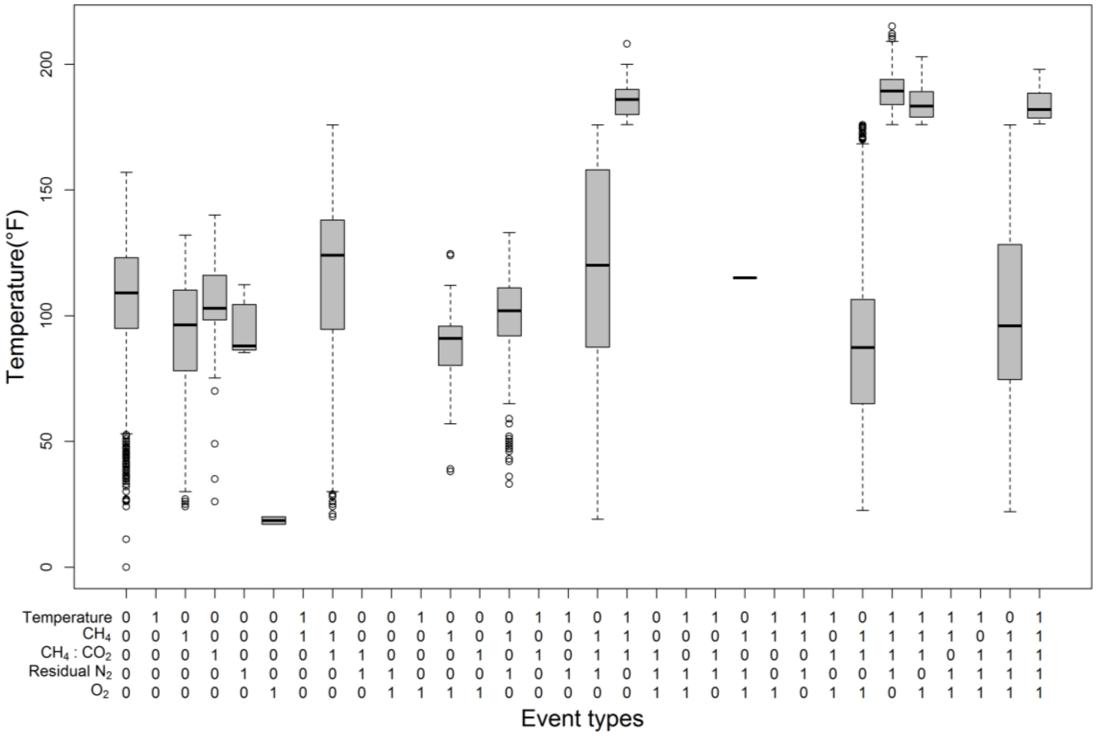
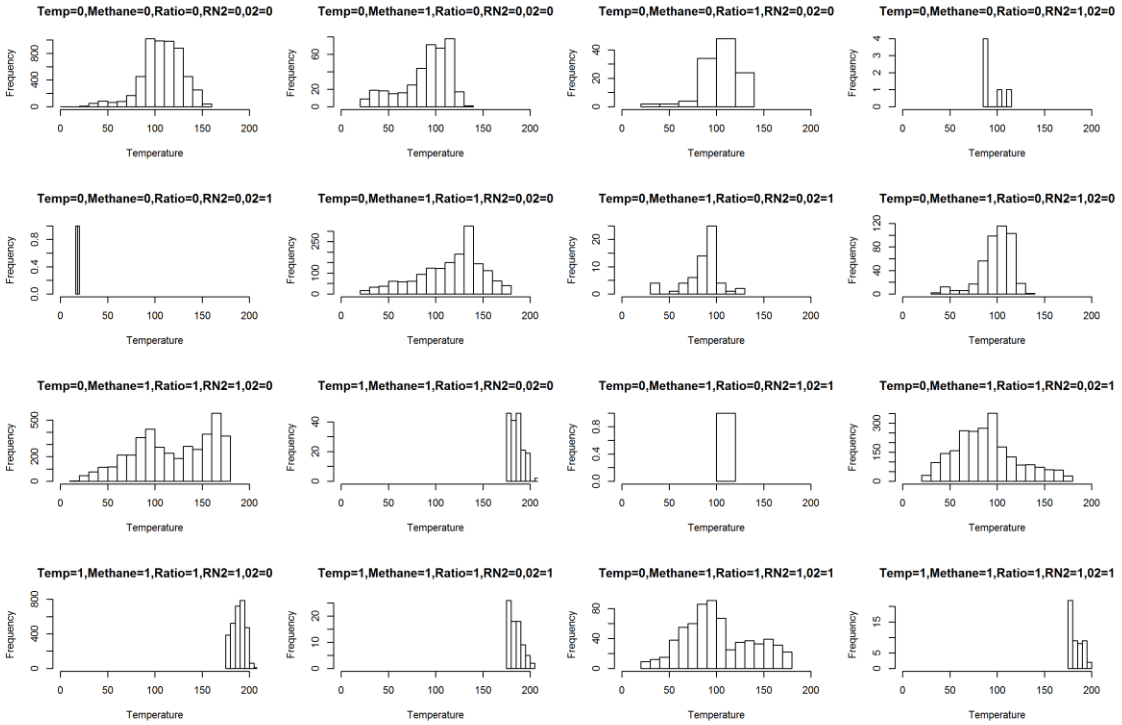


Figure 7. Temperature in different event conditions.

A group histogram can plot the frequency and variance of temperature for different combinations. Figure 8 presents the distribution of temperature in each case, including the peaks, spread, and symmetry. The histogram shows data with different peaks, frequencies, often non-normal and with outliers. In some cases histograms have multiple peaks.

The question is to test whether the mean temperature range actually differs with respect to the combinations. A nonparametric test method, the Wilcoxon rank-sum test (Haynes 2013) enables the interpretation of the difference between these events. The Wilcoxon rank-rum test is robust against the non-normality of the sample distribution and the presence of outliers. This test was applied on all the combinations, with the null hypothesis of no difference between any two events. The two-sided (nondirectional) test resulted in p-value less than 0.05 for all the cases except two combinations (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0, Temperature=1) and (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=1, Temperature=1) with a p-value of 0.4188 meaning these two events share significant similarity in means and spreads.


Temp=0,Methane=0,Ratio=0,RN2=0,02=0
Temp=0,Methane=1,Ratio=0,RN2=0,02=0
Temp=0,Methane=0,Ratio=1,RN2=0,02=0
Temp=0,Methane=0,Ratio=0,RN2=1,02=0
Temp=0,Methane=0,Ratio=0,RN2=0,02=1
Temp=0,Methane=1,Ratio=1,RN2=0,02=0
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Temp=0,Methane=1,Ratio=0,RN2=1,02=1
Temp=0,Methane=1,Ratio=1,RN2=0,02=1
Temp=1,Methane=1,Ratio=1,RN2=1,02=0
Temp=1,Methane=1,Ratio=1,RN2=0,02=1
Temp=0,Methane=1,Ratio=1,RN2=1,02=1
Temp=1,Methane=1,Ratio=1,RN2=1,02=1

Figure 8. Temperature distribution in different combinations.

Furthermore, the probability of four temperature ranges (under 131°F,131-176°F, 176-200°F, 200-300°F) were analyzed on the given conditions of different combinations of four gas parameters in series of methane, ratio between methane and carbon di-oxide, residual-nitrogen and oxygen. Figure 9 displays a gradual upward trend for 176-200°F range in these four combinations of 1_1_0_1, 1_1_0_0, 1_1_1_1 and 1_1_1_0; a decreasing trend for ‘under 131°F’ range is observed. Only the 1_1_1_0 combination gives the probability of 3% in 200-300°F range. Hence the graph shows the combination with 1_1_1_0 has the most potential to correspond to high temperature ranges, instead of the 1_1_1_1 combination where all the gas parameters are in unsafe range. Combinations with 1_1_1_0, 1_1_1_1, 1_1_0_0, 1_1_0_1, 1_0_1_0, 1_0_1_1 have more than 15% probability in 131-176°F range. Therefore, gas combinations with 1_1_1_0, 1_1_1_1, 1_1_0_0, 1_1_0_1 should be considered as risky combinations; and 1_0_1_0, 1_0_1_1 gas combinations correspond to medium risk which indicate tendency to proceed to the risky combinations.

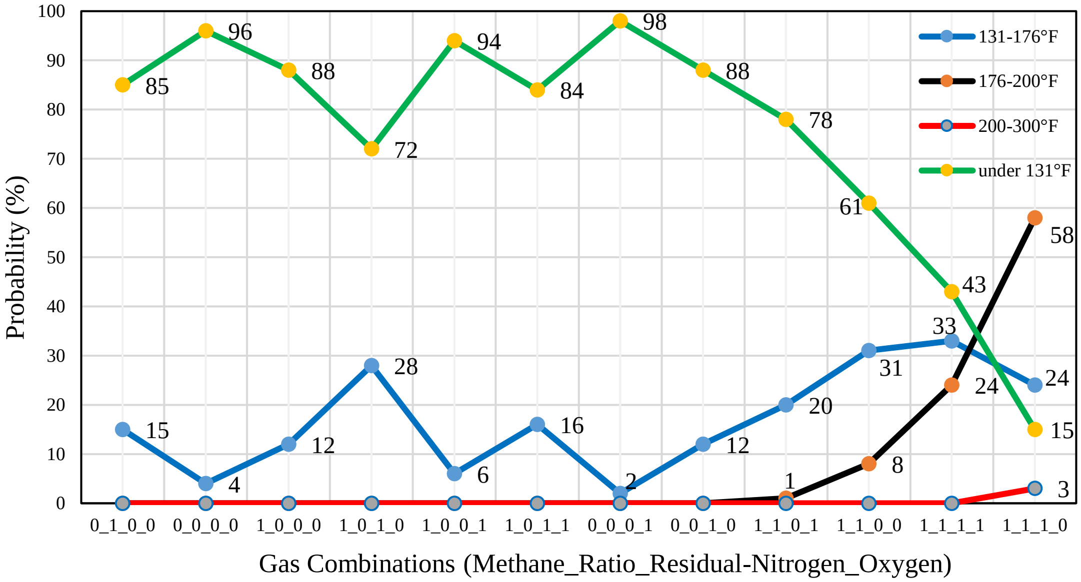


Figure 9. Naïve Bayes Conditional Probability on gas combinations.

1.6 Discussion and Conclusion

The primary goal of study in chapter one is to explore the effect of soil gases on elevated landfill temperature over a threshold. Regulatory agencies have provided regulations regarding acceptable ranges of these subsurface gases and temperature. In this study, a temperature threshold of 176°F was selected because the temperature range during any normal biological decomposition processes was observed up to 176°F; and thresholds for some of the gas parameters were selected according to 40 CFR §60.753, Thalhamer (2013) and Estabrooks (2013) . From the statistical analysis conducted above some points can be concluded such as:

- Events of unsafe temperature were observed more in the unsafe range for methane, ratio between methane and carbon dioxide, residual nitrogen, but not for oxygen.
- Based on the conditional inference tree algorithm, the ratio between methane and carbon dioxide among four parameters shows the largest association with temperature. The probability of events ranging from 131°F to 300°F were most often observed with ratio less than 1, oxygen less than 5% and methane with <45% and >60%.
- Gas parameters have insignificant effect on the events with gas combinations of (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0), (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0) and (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=1). This indicates that there are other missing confounding variables effecting these three combinations.
- Based on Naïve Bayes Conditional Probability, only the (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0) combination shows high probability in 200-300°F range, while a gradual upward trend for 176-200°F range is observed in these four combinations of (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=1), (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0), (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=1) and (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0).
- High temperature ranges do not always associate with the unsafe ranges of all parameters, rather it varies with parameter combinations.
- A three step process can be employed for evaluating risk related to landfill subsurface fire. Step 1 begins with checking temperature range if it is within

unsafe range, then other parameters should be controlled to bring temperature into safe range; if temperature is within safe range, the landfill authorities should proceed to step 2. Step 2 includes checking gas combinations. If one of the four combinations of (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=1), (CH_4=1, CH_4:CO_2=1, RN_2=0, O_2=0), (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=1) and (CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0) occurs, other preventive measures should be taken. Step 3 involves checking gas-wells with 'nearby' combinations of (CH_4=1, CH_4:CO_2=0, RN_2=1, O_2=0) and (CH_4=1, CH_4:CO_2=0, RN_2=1, O_2=1) corresponding to medium risk, monitoring those gas-wells locations more closely or more often to ensure that gas combinations do not end up in one of the risky combinations.

The data set used for this analysis does not contain carbon mono-oxide which is the most important parameter regarding landfill subsurface fire incidents and the spacing of observation times are not constant. To improve analysis result, some important parameters such as carbon mono-oxide, leachate collection, and pressure can be included. The research methodology described in Chapter 1 can be repeated on thresholds for the parameters based on different regulatory agencies for example US EPA, SWANA, ISWA and USACE. The results from these regulatory agencies can be compared to observe the effect on unsafe temperature condition.

Chapter 2

Abstract

The first chapter focused on examining soil gas parameters that influence temperature in the subsurface landfill environment. Using several statistical methods, it was observed that events of elevated subsurface temperature are governed by different combinations of safe and unsafe ranges of considered parameters, i.e., ranges of gas parameters suggested by United States Environmental Protection Agency (US EPA), Thalhamer (2013) and Estabrooks (2013). The second chapter establishes a method to calculate risk index associated with different gas and temperature combinations, considering the strength of the relationships between each possible combination and subsurface temperature. The risk assessment equation incorporates event intensity for each possible combination which is the sum of the unsafe parameters within each combination. The associated risk index for a possible combination of soil gas parameters can be calculated with the product of its strength of affiliation with temperature and its event intensity. The risk index calculated for all the combination were normalized to range from 0 to 10. After implementing the algorithm on the existing dataset, the temperature ranges in terms of each risk indices and risk types were inspected with a decision tree algorithm.

2.1 Introduction

Elevated temperatures in both surface and subsurface environments are experienced by almost all types of landfills during their lifecycle. These heating events have been reported by several categories of landfills, i.e., for example municipal solid waste landfills, industrial waste landfills, construction demolition debris landfills and sanitary dumps (Martin et al. 2012; Sperling and Henderson 2001; Hogland and Marques 2003; Ettala et al. 1996; Riquier et al. 2003; Øygard et al. 2005; Nikolaou 2008; Merry et al. 2005; Koelsch et al. 2005; Frid et al. 2010). Some landfills often experience random events of surface fire, while other landfills encounter and go through hardships of regulating subsurface fire events. Surface fire incidents mostly occur in the profuse presence of energy and oxygen burning in between the surface level and up to 5 feet below ground, while other fire events take place below ground level extending down to 100 feet depending on site and geological conditions (Thalhamer 2013). In the United States such smoldering events frequently occur during the period of late spring and fall with the change in barometric air pressure (Thalhamer 2011). Often subsurface fire incidents can ignite due to several other reasons such as arson, hot load, chemical reaction or equipment which are often regarded as operational fires are generally managed by the operating facilities and recorded in the facility logbook, if mandated by regulations. (Thalhamer 2013). Some of these incidents may need support from local fire departments to be controlled, but do not create significant public attention. Merely around 1-2% of such reported fire incidents involve specialized response, expertise, additional environmental oversight, and/or repairing by the landfill's engineering control systems, of which only about 10% turn out to be a major environmental dilemma (Thalhamer 2011).

The presence of subsurface heating events can damage the consistency of inner landfill system, i.e., cover and liner systems (Lewicki 1999; Øygard et al. 2005; Jafari et al. 2014; Stark et al. 2012). When subsurface temperatures become high enough to ignite waste, such events can cause thermal dilapidation of municipal solid waste, posing substantial hazards to the environment by releasing by-products from incomplete combustions, reduced sulfur compounds, harmful di-oxin, furans and particulate matters to the atmosphere (Nammari et al. 2004; Ruokojärvi et al. 1995; Lönnermark et al. 2008; Chrysikou et al. 2008).

Ways to prevent subsurface landfill fire include landfill management and regulation and methane gas detection and collection (Hanson et al. 2009). To rapidly detect subsurface landfill fires, landfill operators, consultants, and regulatory agencies have used infrared imagery, geophysical (electric and electromagnetic) techniques, visual observations (surface settlement, smoke, and steam), and monitoring of waste temperatures, gas composition and temperature, and leachate quality (Stearns and Petoyan 1984; Lewicki 1999; Riquier et al. 2003; Sperling and Henderson 2001; Riviere et al. 2003; Ohio 2011; Crawford and Smith 2016). From the analysis works of chapter 1 involving how subsurface temperatures are effected by soil gases, chapter 2 assesses risk categories or magnitude associated with possible combinations of safe and unsafe ranges of considered soil gases. For example, the US EPA utilizes risk assessment methods to identify the nature and intensity of ecological receptors and human health risks (https://www.epa.gov/risk). In similar way, a risk assessment framework can be a useful tool for all categories of landfills to identify potential danger from elevated subsurface temperatures (EST) and the operating facilities can observe the progression of risk categories over periods of time. Thus, they can take proper actions by controlling governing parameters behind EST, employing regular observation of subsurface landfill fire risk assessment.

2.2 Risk Assessment for Landfills

A risk assessment is a safety management system that promotes the prevention of environmental hazards by increasing awareness of hazards and risks. This can be used to identify significant threats responsible for landfill fire. These evaluations can be used by the landfill personnel in deciding what control measures need to be enacted to reduce risk to an acceptable level. A risk assessment should be reviewed regularly, whether it be daily, monthly, annually or bi-annually. The 5 steps of a landfill fire assessment are: identifying factors responsible for landfill fires, identifying control measures from different environmental regulatory agencies, evaluating risk using a developed methodology, recording risk assessment data, and forecasting future risk. The first two steps have been described in chapter 1. The statistical methods in chapter 2 involve dependency tests between these factors and temperature, testing correlation between factors and temperature in different situations. Finally, an equation to calculate the risk-index for subsurface heating events is developed and implemented in an existing dataset to check the assessment accuracy. The importance of a landfill fire risk assessment is to limit clean-up costs and reduce risk exposure, by making the landfill personnel aware of possible heating events in present and near future.

2.3 Statistical Dependency Test

It is important to investigate the statistical relationships between the parameters and temperature. The Chi-square test of independence (Argyrous 1997, McHugh 2013) was applied to the categorized sample data. This test can explain whether or not two attributes are associated. The test proceeds with the null hypothesis that any two attributes, in this case any of the categorized gas parameters and temperature are independent which means that the considered gas variables are not effective in controlling temperature. The alternative hypothesis implies the two variables are dependent on each other.

A chi-square statistic is one way to examine the relationship between two categorical variables. The chi-squared statistic is a single number that measures the extent of difference existing between observed counts and the expected counts if there was no relationship in the population. It is appropriate to give a statistical conclusion using a p-value. With computer program such as R, the p-value for the chi-squared statistic can be calculated. A small p-value provides evidence that the null hypothesis should be rejected and to accept the alternate hypothesis concluding a significant association between two attributes.

The Pearson's chi-squared test was performed between categorical gas factors and temperature to compute p-value for a Monte Carlo test (Sham and Curtis 1995) with 2000 random samplings and continuity correction. Since the P-value (0.0004998) is less than the significance level (0.05), the null hypothesis cannot be accepted. Thus, it concludes that there is a relationship between gas parameters (methane, ratio between methane and carbon dioxide, residual nitrogen, oxygen) and temperature.

2.4 Correlation among Factors

The association between gas variables and temperature is proven in the previous section, but inspecting the strength of the association among parameters needs to be determined. The above mentioned, chi-square test only infers the presence or absence of an association between two attributes, it does not measure the strength of association. Furthermore, it does not indicate the cause and effect, the test merely concludes the probability of occurrence of association by chance. However, statistical correlation can be an appropriate tool for inferring strength of association. It is a statistical technique which indicates the strength of relationship between two variable and the type of relationship (positive or negative).

The relationship strength is measured using the coefficient of correlation (r). Its numerical value ranges from +1.0 to -1.0 giving an indication of the strength of relationship. In general, $r > 0$ indicates positive relationship, $r < 0$ indicates negative relationship while $r = 0$ indicates no relationship (or that the variables are independent and not related). Here $r = +1.0$ describes a perfect positive correlation and $r = -1.0$ describes a perfect negative correlation. The strength of the relationship between the variables gets higher with the proximity of coefficient to +1.0 and -1.0. Table 5 is used to describe the strength of the relationship (Cohen 1988).

Table 5

Types of correlation (Cohen 1988)

Value of r	Strength of relationship	Strength Index
-1.0 to -0.5 or 1.0 to 0.5	Strong	4
-0.5 to -0.3 or 0.3 to 0.5	Moderate	3
-0.3 to -0.1 or 0.1 to 0.3	Weak	2
-0.1 to 0.1	None or very weak	1

Correlation is only suitable for investigating the relationship between quantifiable data rather than categorical data. Therefore the statistical correlation test was applied to uncategorized data, i.e., the direct sample data for all factors. To assess the strength of correlation in different cases, 14 datasets were extracted for all possible combinations from the available sample data to correlate them with temperature.

Figure 10 and 11 display scatterplot matrices for all the variables available in the dataset in the lower triangle, with density plots on the diagonal and spearman correlation printed in the upper triangle, for combinations (temperature=0, CH4=0, CH4:CO2=0, RN2=0, O2=0) and (temperature=1, CH4=1, CH4:CO2=1, RN2=1, O2=0) respectively. Variables (methane, carbon dioxide, oxygen, temperature, residual-nitrogen, ratio between methane and carbon dioxide; and balance gas) are printed in the top and right sides of the Figure 10 and 11. Respective variables' units (i.e., percentages for CH4, CO2, O2, residual-nitrogen, balance gas; 0 to 200°F for temperature; 0 to 2.5 for ratio between CH4 and CO2) are written in left and bottom corners. Each variables are plotted against each other. For example, the 2nd square in the 1st column is the individual scatterplot of CH4 and CO2, with CH4 as the X-axis and CO2 as the Y-axis. This same plot showing correlation value between CH4 and CO2 is replicated in the 2nd square of the 1st row. Among 21 correlation values showed in Figure 10 and 11, only four of them (correlation between CH4 and balance gas; O2 and ratio; CH4 and ratio; residual-nitrogen and balance gas) are common in both. The comparison between Figure 10 and 11 indicates the difference between these two combinations. Table 6 shows the correlation coefficient of every parameter with temperature using the Spearman correlation method, a nonparametric measure of rank correlation. The combinations for the parameters in Table 6 are arranged in series of safe (0) and unsafe (1) ranges for temperature, methane, ratio between methane and carbon dioxide, residual nitrogen and oxygen. The types of strength of association are represented by the index in Table 5. The number 1 represents none or very weak association; similarly 2, 3, 4 represent weak, moderate and strong association between parameters, respectively.

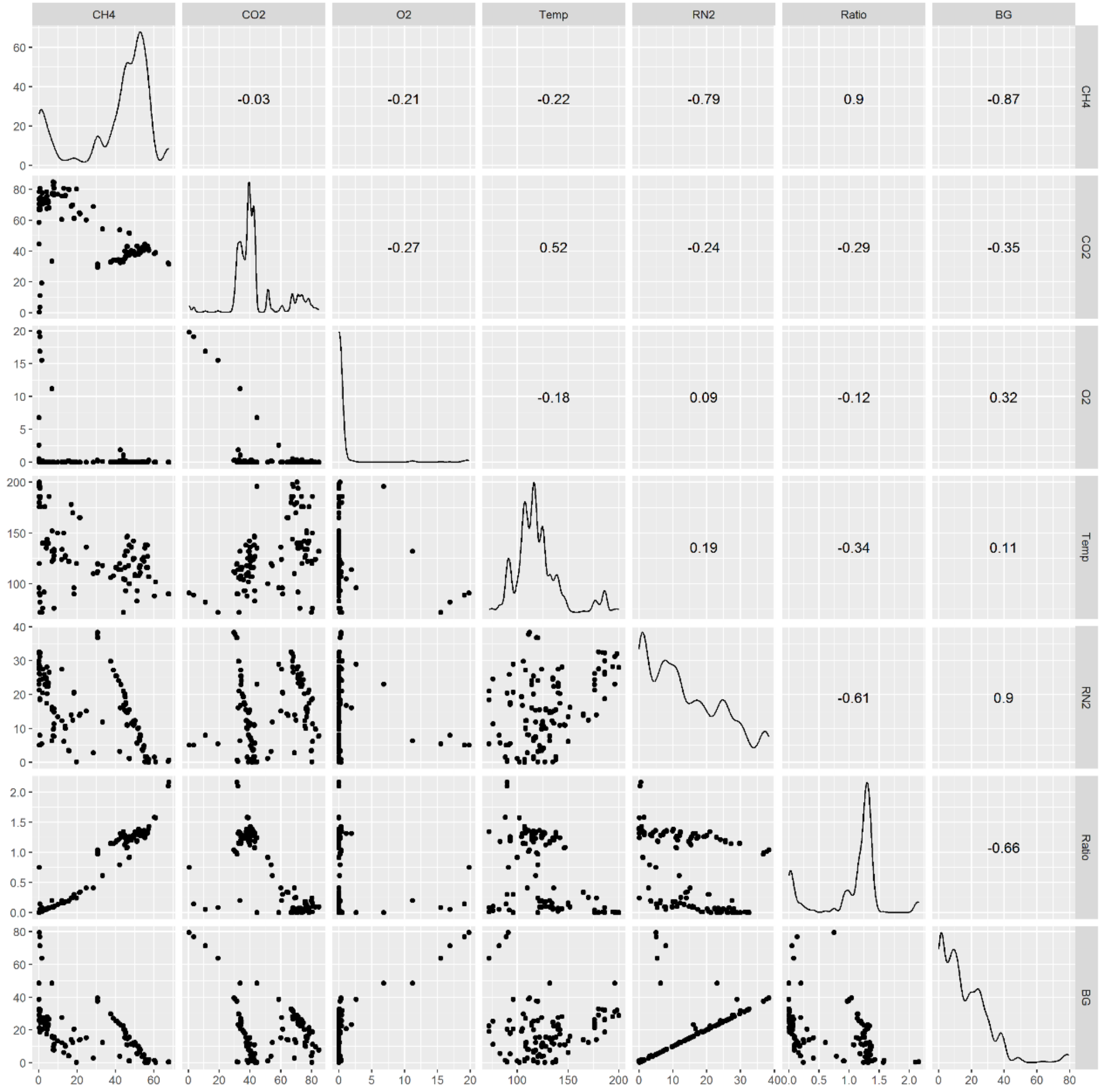


Figure 10. Scatterplot matrix, density plots & correlation for combination (temperature=0, CH_4=0, CH_4:CO_2=0, RN_2=0, O_2=0).

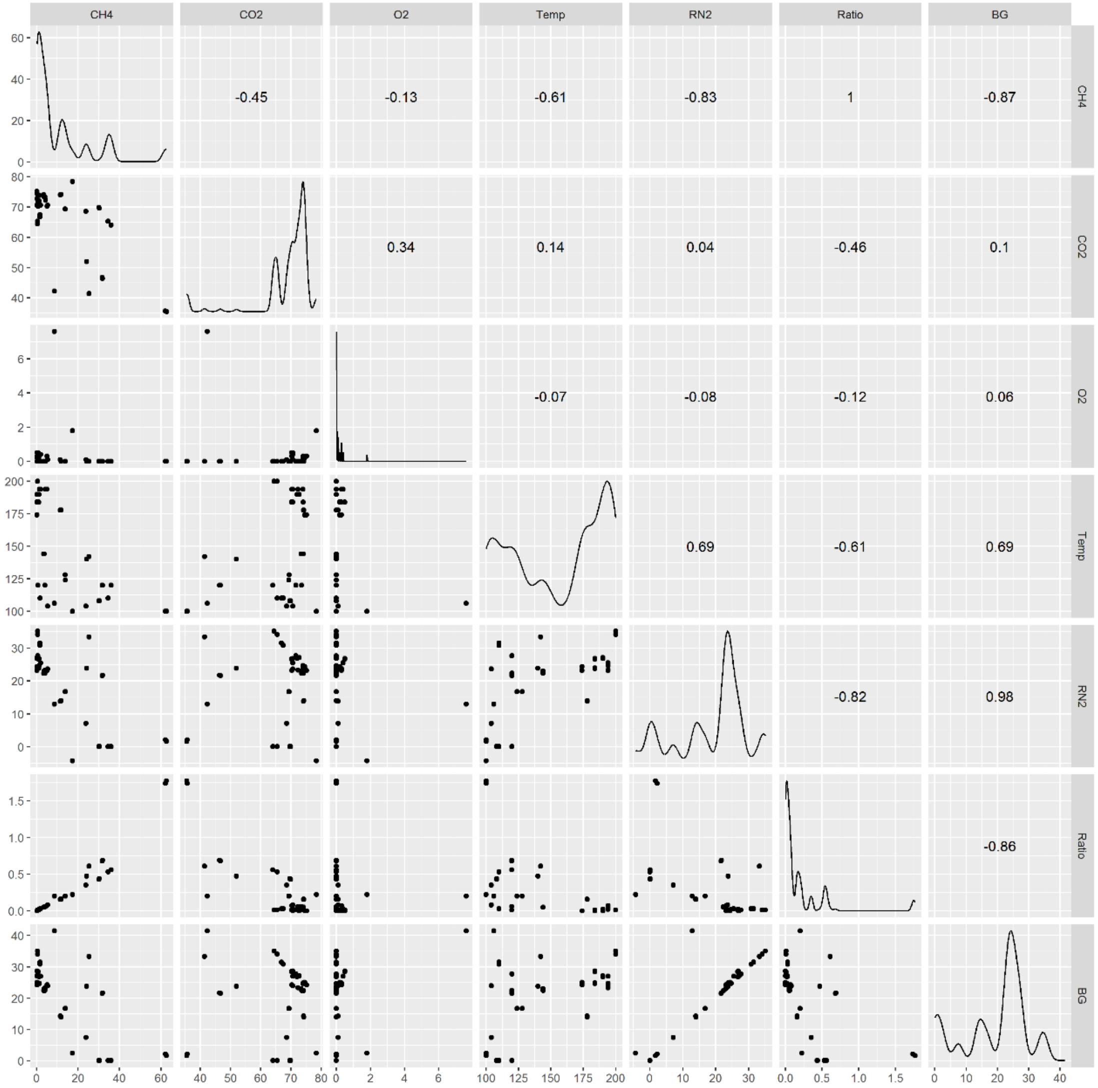


Figure 11. (Temperature=1, CH_4=1, CH_4:CO_2=1, RN_2=1, O_2=0).

Table 6

Strength of Association of the parameters with temperature for all combinations

Combinations	Spearman correlation of parameters with temperature				Strength index of the parameters with temperature			
	CH_4	**Ratio between CH_4 & CO_2**	**Residual N_2**	**O_2**	**CH_4**	**Ratio**	**Residual N_2**	**O_2**
0_0_0_0_0	-0.28	-0.39	0.18	-0.14	2	3	2	2
0_0_0_1_0	0.09	0.14	-0.61	-0.83	1	2	4	4
0_0_1_0_0	-0.33	-0.08	0.32	-0.11	3	1	3	2
0_1_0_0_0	-0.41	-0.49	0.46	-0.11	3	3	3	2
0_1_0_0_1	-0.48	0.12	0.09	0.41	3	2	1	3
0_1_0_1_0	0.04	-0.17	-0.12	-0.07	1	2	2	1
0_1_1_0_0	-0.01	-0.01	0.16	-0.21	1	1	2	2
0_1_1_0_1	0.30	0.29	0.35	-0.26	3	2	3	2
0_1_1_1_0	0.15	0.13	-0.18	-0.13	2	2	2	2
0_1_1_1_1	0.31	0.25	-0.06	-0.11	3	2	1	2
1_1_1_0_0	-0.28	-0.28	0.04	-0.07	2	2	1	1
1_1_1_0_1	-0.55	-0.56	0.02	0.17	4	4	1	2
1_1_1_1_0	-0.38	-0.38	0.04	-0.28	3	3	1	2
1_1_1_1_1	-0.47	-0.46	-0.04	-0.01	3	3	1	1

Comparing the strength indices of all combinations, it is evident that the strength of relationship among factors varies from event to event, even from positive to negative correlation (except the last two combinations which share similar association strengths, as expected from the Wilcoxon rank-sum test for these two cases). The factors tend to affect one another differently from combination to combination. The strong correlation between gases and temperature does not always depend on the extreme unsafe conditions of factors. The gas factors contribute to an event together, not individually. Hence, they should not be taken individually to evaluate temperature. These factors work in groups; their correlation as well as influence on temperature changes through events.

2.5 Development of Risk Index

The test results described in chapter 1 indicate that the parameters should not be considered individually; landfill temperature should not be evaluated by an individual factor's conditions. Each parameter combinations creates a distinct event with a distinct relationship between gases and temperature, and this relationship will vary for another event. Correlation can quantity the strength of association between any individual factor and respective temperature for any given event condition mentioned in Table 6. Therefore, a risk assessment system can be developed using temperature's correlation with the various parameter combinations, as this risk assessment is especially concerned with subsurface fire which is directly fueled by subsurface temperature.

The Risk Index provides a quantitative estimate of the risk associated with elevated temperature for possible combinations of gas parameters. This risk index is developed using the gas collection data set from case study 'Bridgeton Landfill'. It is not the scope of this Risk Index to determine individual risks that a single person is subject to. This assessment utilizes historical gas-well collection and temperature data; assigns a value for their level of hazardousness (safe or unsafe). The next step involves data extraction from archive data for possible combinations of all the parameters.

Risk can have several meanings including i) risk as potential loss; ii) risk as viability, volatility or uncertainty regarding events in the future; and iii) risk as a probability of negative event occurring (Mandel 2007). Risk assessment is the method of estimating quantitative and qualitative risk related to a recognized threat (also called hazard); statistically quantitative risk assessment involves calculations of two components of risk (R): the magnitude of the potential loss (L), and the probability (p) that the loss will occur (Shirey 2007). Most popular definitions and perception of risk are based on probabilities. By using probabilities in estimating risk, significant uncertainty aspects can be overlooked; and events with low probabilities and high consequences are not depicted properly (Aven 2010). The risk assessment described in Chapter 2, incorporates total unsafe parameters and statistical association between temperature and gas parameters. Therefore, an extreme unsafe event and a high correlation with temperature result in a high index indicating high risk for subsurface heating events; while a safe event and a high correlation can result in a risk index near to medium risk category, indicating some level of vulnerability to subsurface heating events.

Event intensity, F, can be defined as the sum of unsafe parameters including temperature for a particular combination. It is increased by 1 to avoid resulting in 0, while calculating for a complete safe event and high association with temperature. As an example of calculation, event intensity is 1 (0+0+0+0+0+1) for a very safe conditions such as CH_4=0, CH_4:CO_2=0, RN_2=0, O_2=0, temperature=0. For a very unsafe conditions such as for a combination of CH_4=1, CH_4:CO2=1, RN_2=1, O_2=1, temperature=1; the event intensity is 6 (1+1+1+1+1+1). Total risk is a collective risk index, which is the average of all the risks that results from all the considered hazardous parameters contributing to an event. It can be expressed mathematically by equation 3; where V_i is the strength index of a single parameter for that particular combination and N is the number of gas parameters. For an event with the (1_1_1_1_1) combination mentioned in Table 3, the calculated risk index R using equation 3 is the average of the collective risk index for CH_4, ratio between CH_4 and CO_2, residual N_2 and O_2; where F= (1+1+1+1+1+1)=6 , N= 4 and $\sum_{i=1}^{N} V_i$ = (3+3+1+1)= 8. Strength indices of the parameters (V_i) for this particular combination were obtained from Table 3. Therefore,

$$R = \frac{6*8}{4} = 12$$

$$Risk\ Index,\ R = \frac{F}{N}\sum_{i=1}^{N} V_i \qquad (3)$$

Table 7

Risk Index associated with a single parameter

			event intensity (F)					
Strength Index (V_i)			1	2	3	4	5	6
-0.1 to 0.1	(none or very weak)	1	1	2	3	4	5	6
-0.3 to -0.1 or 0.1 to 0.3	(weak)	2	2	4	6	8	10	12
-0.5 to -0.3 or 0.3 to 0.5	(moderate)	3	3	6	9	12	15	18
-1.0 to -0.5 or 1.0 to 0.5	(strong)	4	4	8	12	16	20	24

Risk matrix is an organized method that identifies most critical risks to a program and provides a methodology to evaluate possible impacts of a risk or set of risks throughout the program duration (Garvey and Lansdowne 1998). A Risk matrix has been used to define the level of risk by considering the category of correlation with temperature against the category of event intensity. Table 7 displays general risk assessment matrix for a single parameter within a specific combination, where the column number represents event intensity (F) for that combination, rows number represents the strength index (V_i) of that parameter mentioned in Table 5 depending on its strength of association with temperature. The values in the middle cells of matrix are the product of event intensity (F) and strength index (V_i). For a combination (1_1_1_1_1) mentioned in Table 3, event intensity, F= (1+1+1+1+1+1) = 6; and a quantitative risk associated with CH_4 is the product of its strength index ($V_i = 3$) and event intensity ($F = 6$), which results in the risk index of 18.

As the risk calculation process uses accumulative dataset, the parameters' strength indices in each combination are not constant. Therefore, the index scale has been normalized to a scale of 0 to 10 using min-max normalization with equation 4; where R_{min} is the minimum risk index among all the combination and R_{max} is the maximum risk index. The Index values for all event combinations present in the data set (in series of temperature, methane, ratio between methane and carbon dioxide, residual nitrogen and oxygen) have been calculated using equation 3; then normalized to a 0 to 10 scale using equation 4, based on the minimum and maximum values calculated in Table 8. Some combinations share the same index values, meaning those events have similar risk.

$$Risk\ Index, R_N = \frac{R - R_{min}}{R_{max} - R_{min}} * 10 \quad (4)$$

Table 8

Calculated risk index for different combinations

Combinations	R_i, Index Scale (0-20)	R_N, Scale normalized (0-10)
0_0_0_0_0	2.25	0.0
0_0_1_0_0	4.5	2.0
0_1_0_1_0	4.5	2.0
0_1_1_0_0	4.5	2.0
0_0_0_1_0	5.5	2.8
0_1_0_0_0	5.5	2.8
1_1_1_0_0	6	3.3
0_1_0_0_1	6.75	3.9
0_1_1_1_0	8	5.0
0_1_1_0_1	10	6.7
0_1_1_1_1	10	6.7
1_1_1_1_0	11.25	7.8
1_1_1_1_1	12	8.5
1_1_1_0_1	13.75	10.0

The determination of risk type for a risk index whether it is low, medium or high degree of risk, is based on the probability of temperature predicted by risk indices. The indices which predict temperature (under 131°F) with <5% probability define normal condition. The indices predicting temperature (under 131°F) with >5% frequency and temperature (131-176°F) with <20% frequency are considered as low risk indices. The indices giving >20% frequency in predicting temperature (131-176°F) are regarded as medium risk indices, while the indices predicting temperature (176°F-300°F) are associated with high level of risk. Table 9 displays the prediction probability (in percentage) of four temperature ranges: ‘under 131°F’, ‘131-176°F’, ‘176-200°F’ and ‘200-300°F’ by all risk indices and the associated risk categories. Table 10 summarizes the indices and risk types; where the green box (R_N = 2.8, 3.9) represents normal condition, while the yellow box (R_N = 0, 2, 6.7) shows the low risk level, the orange box (R_N = 5) shows the medium risk level and the red box (R_N = 3.3, 7.8, 8.5, 10) shows a high level of risk.

Table 9

Risk Index table

	Probability of predicting temperature ranges (%)				
Risk Index	under131F	131-176F	176-200F	200-300F	Risk
0	41.8	19.8	0.0	0.0	Low
2	13.0	18.4	0.0	0.0	Medium
2.8	3.4	0.0	0.0	0.0	Low
3.3	0.0	0.0	5.4	4.2	High
3.9	0.5	0.0	0.0	0.0	Low

Table 9 (continued)

	Probability of predicting temperature ranges (%)				
Risk Index	under131F	131-176F	176-200F	200-300F	Risk
5	19.8	49.5	0.0	0.0	Medium
6.7	21.5	12.3	0.0	0.0	Low
7.8	0.0	0.0	90.6	94.4	High
8.5	0.0	0.0	1.6	0.0	High
10	0.0	0.0	2.4	1.4	High

Table 10

Risk Types and Indices

Risk types	Risk Index (R_N)
Normal risk	2.8, 3.9
Low risk	0, 2, 6.7
Medium risk	5
High risk	3.3, 7.8, 8.5, 10

Temperature was added as a parameter in the calculation of risk index, because of insignificant effect of gases on three gas combinations. Albeit with the inclusion of temperature in calculation process, risk indices still do not progress sequentially with risk categories. Instead of starting from normal condition, risk indices 0 and 2 are observed as ‘low risk’ and risk index 3.3 is marked as ‘high risk’. The normal condition is observed in risk indices 2.8 and 3.9. The index scale does not track temperature sequentially which implies that the probability of resulting in unsafe temperature sequentially is dependent on specific parameter combinations. Inclusion of confounding variables in calculation process is expected to resolve the issue.

2.6 Implementing Risk Index

In this section, the previously developed risk index model is used to assess real field scenarios at Bridgeton landfill. The time duration for the assessment is chosen for four months from January to April 2015, to check how index predicts elevated temperature.

The index assessment method is evaluated for gas-wells suitable with temperature less than 131°F (scenario 1), wells with consistent high temperature more than 176 °F (scenario 2) and wells with fluctuating temperatures (scenario 3) for the chosen time period. Gas wells fitting the assumptions of three scenarios were selected from the maximum monthly temperatures spatial maps showing wells temperature (i.e. Figure 12), in the gas-well field data available in the website (https:/dnr.mo.gov/bridgeton/BridgetonSanitaryLandfillReports.htm). Figure 13, 14, 15, 16, 17 and 18 are used to plot risk indices, risk types and temperature time-series. The plots outlines the indices (0, 2, 2.8, 3.9, 6.7) giving indication of normal and low-risk, based on the developed index method. For understanding the type of situation, risk types are added on the plots where numbers 2, 4, 6 and 8 represent normal, low, medium and high level of risk respectively. Gas wells (GEW-29, GEW-65A, GEW-139 and GEW-140) in Figure 15 and 16 had consistent high temperature (more than 176°F), during those four months. The index of 7.8 and 8.5 fall in the range of high risk of heating events. On the contrary, gas wells (GEW-137, GEW-131, GEW-11 and GEW-120) with unstable temperature in Figure 17 and 18, show shifting index values. It is observed that occasionally the index values deviate before temperature. The index can be improved by including more influencing factors, such as carbon monoxide.

Finally, to inspect how the Risk types predicts different temperature ranges such as ‘under 131°F’, ‘131-176°F’, ‘176-200°F’ and ‘200-300°F’, the Conditional Inference Trees algorithm (Hothorn et al. 2015) is applied on the observed temperatures from original dataset with calculated Risk types. It is evident from Figure 17 that in more than 95% of the observations, high risk type predicts temperature range of 176-200°F (with significance level, $p < 0.001$). In more than 40% cases ($p < 0.001$), temperature (131-176°F) is predicted by Medium risk type, which is <20% in low risk type. In almost 100% cases ($p < 0.001$), normal condition gives temperature range under 131°F. However, further research on the forecasting ability of the risk index and risk types is expected to improve on these results.

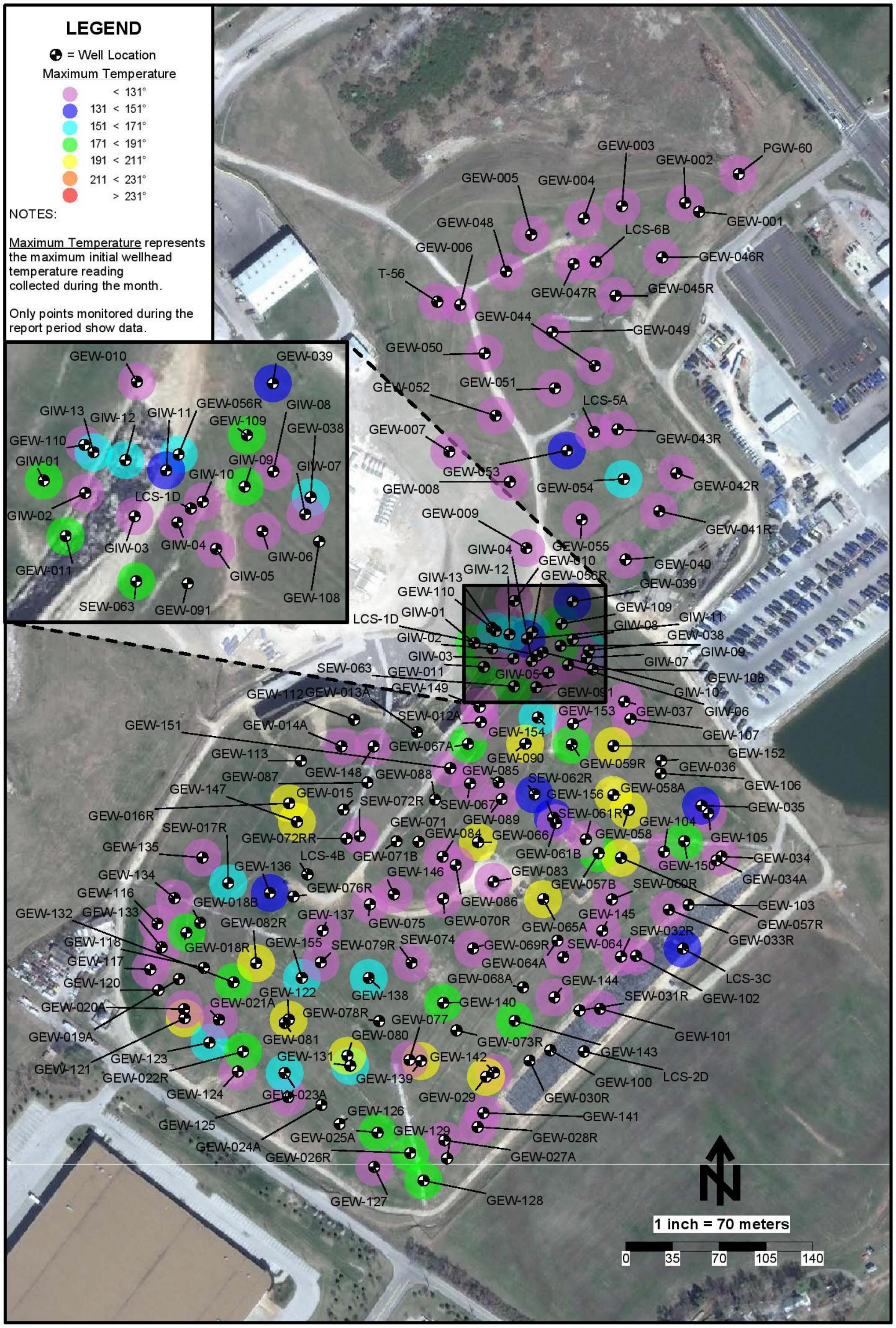
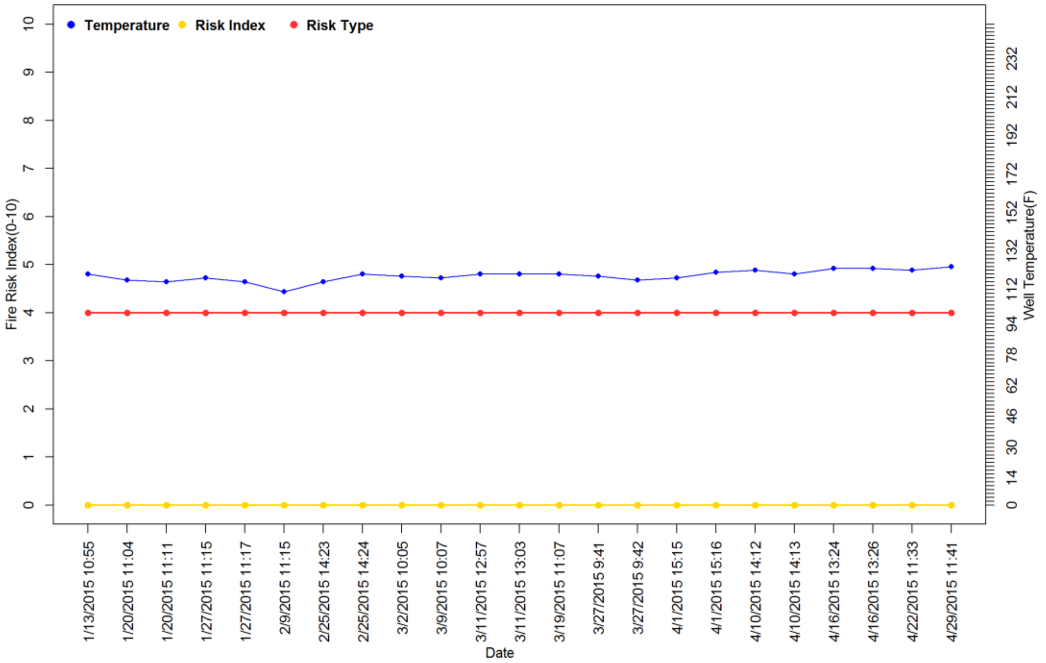


Figure 12. Example of spatial map showing maximum monthly (January 2015) gas well temperatures (source: https:/dnr.mo.gov/bridgeton/BridgetonSanitary LandfillReports.htm).

GEW-51



GEW-55

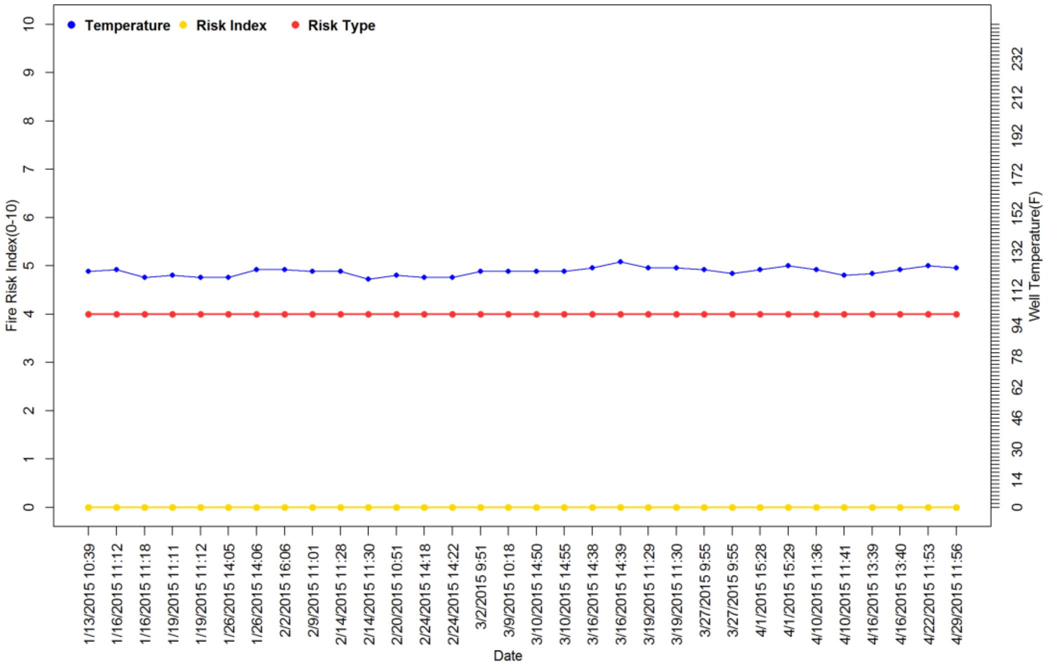


Figure 13. Risk Index and types for Gas wells (GEW-51 and GEW-55) with low temperature less than 131°F. (Note. 2, 4, 6 and 8 for risk types represent normal, low, medium and high level of risk respectively)

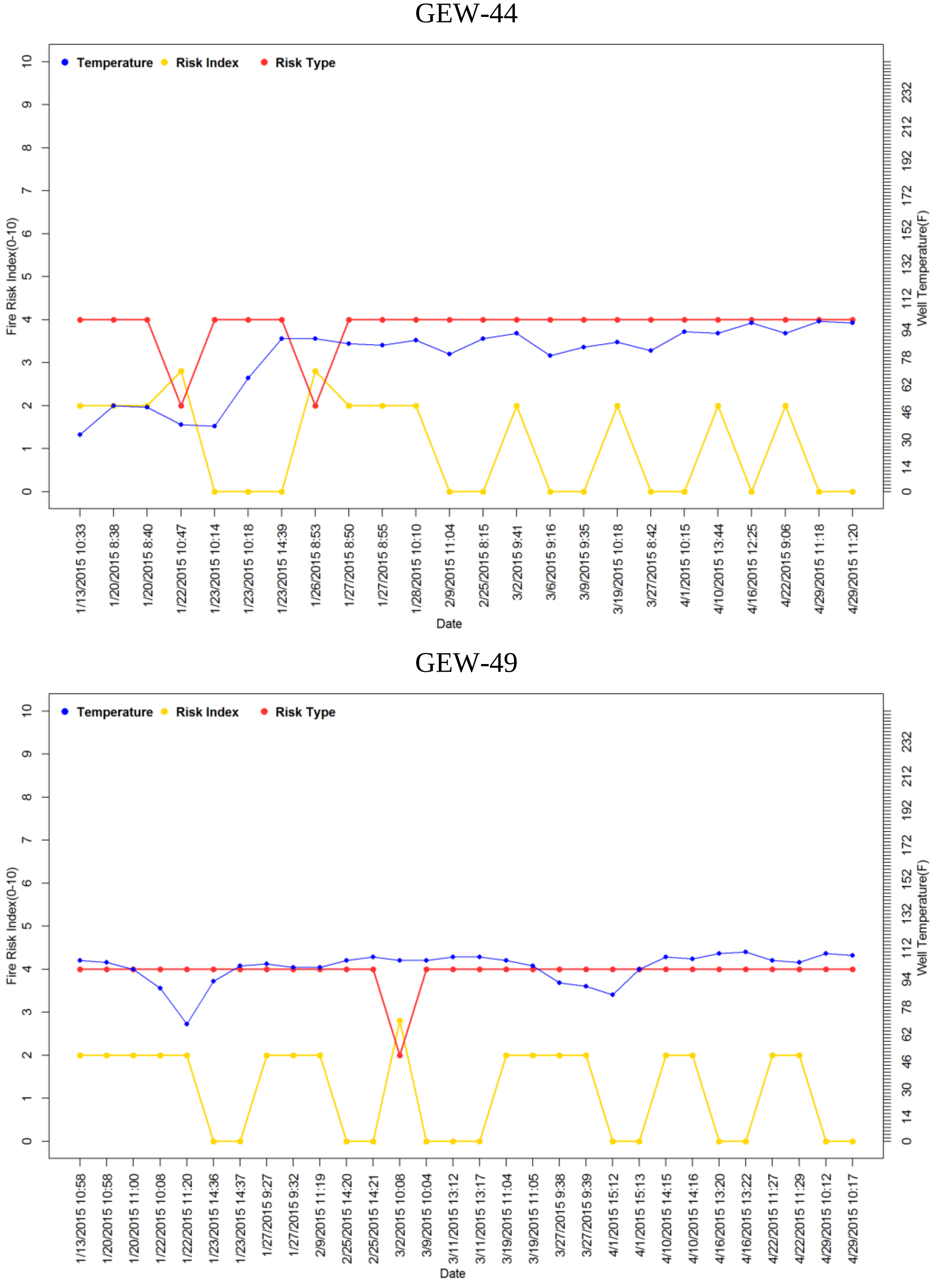
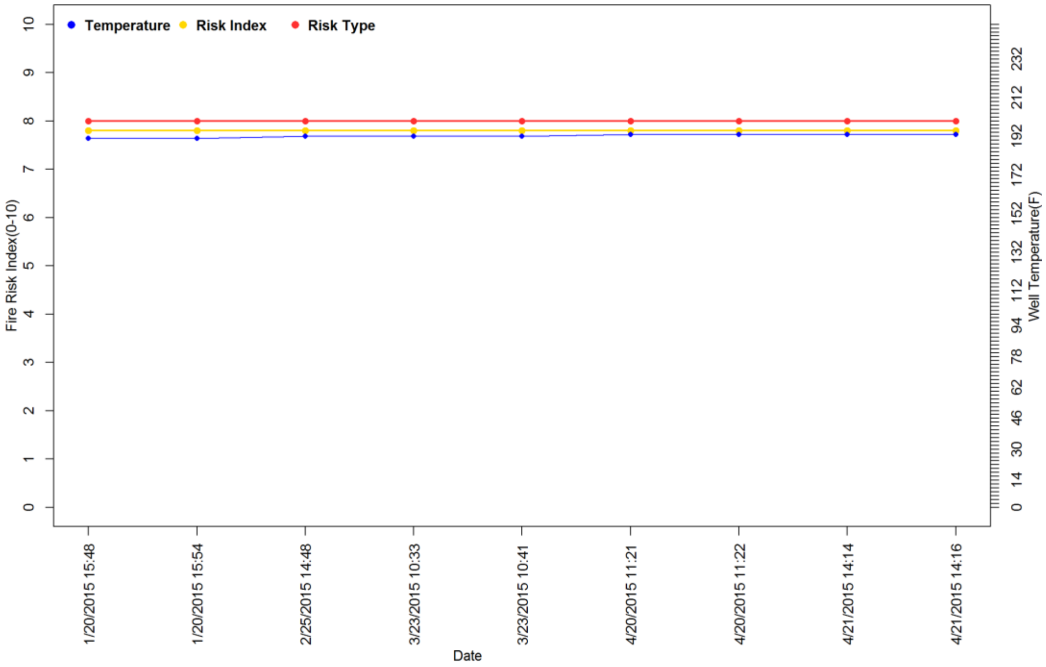


Figure 14. (GEW-44 and GEW-49) with low temperature less than 131°F.

GEW-29



GEW-65A

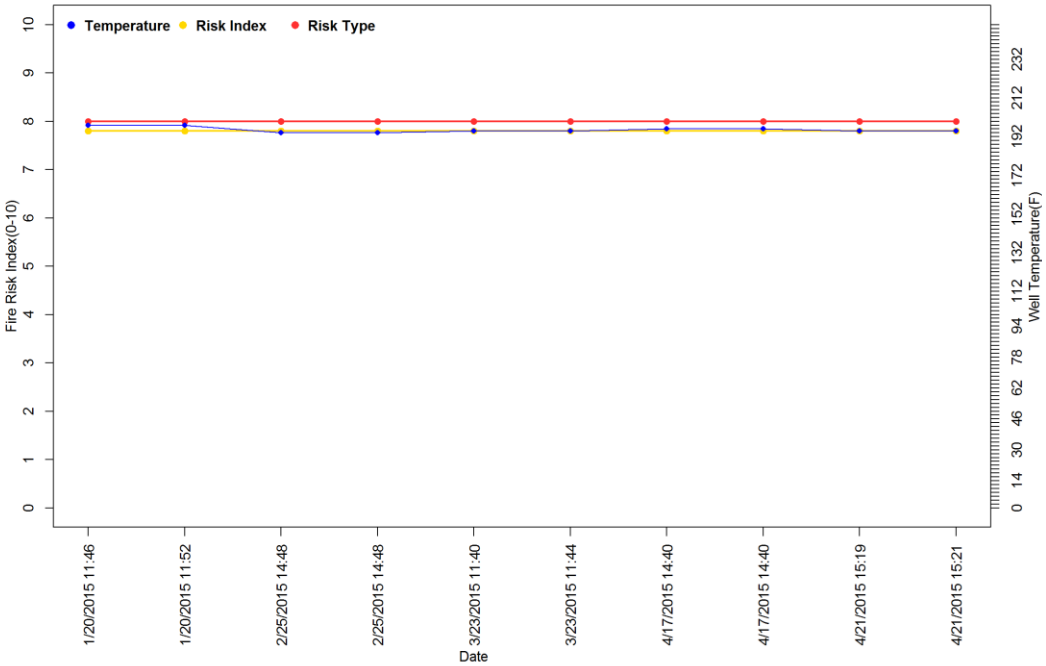
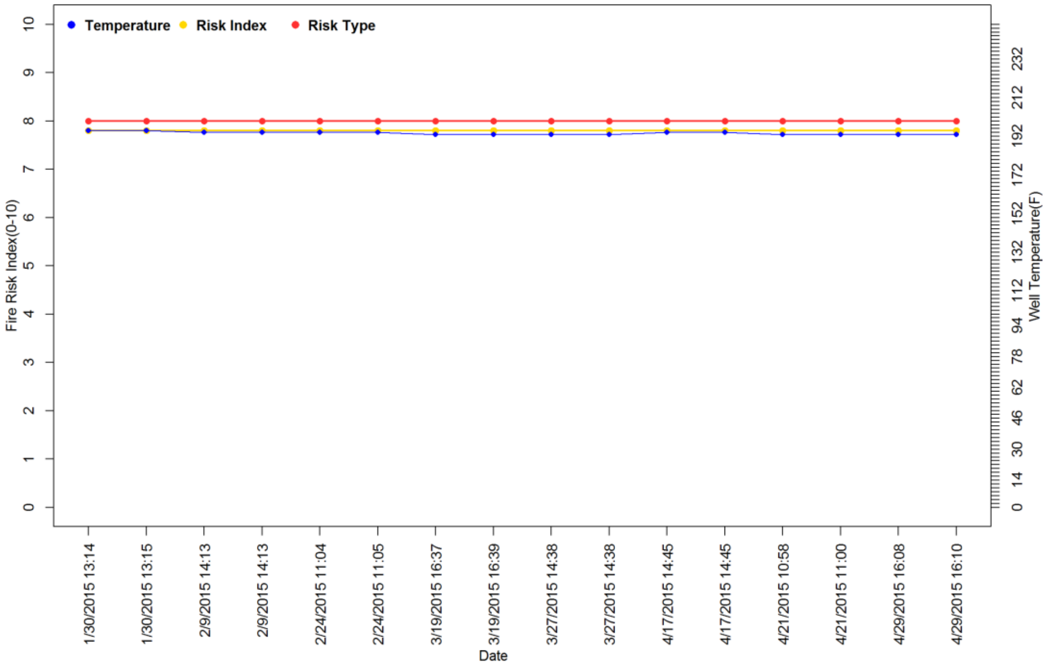


Figure 15. (GEW-29 and GEW-65A) with high temperature (>176°F).

GEW-139



GEW-140

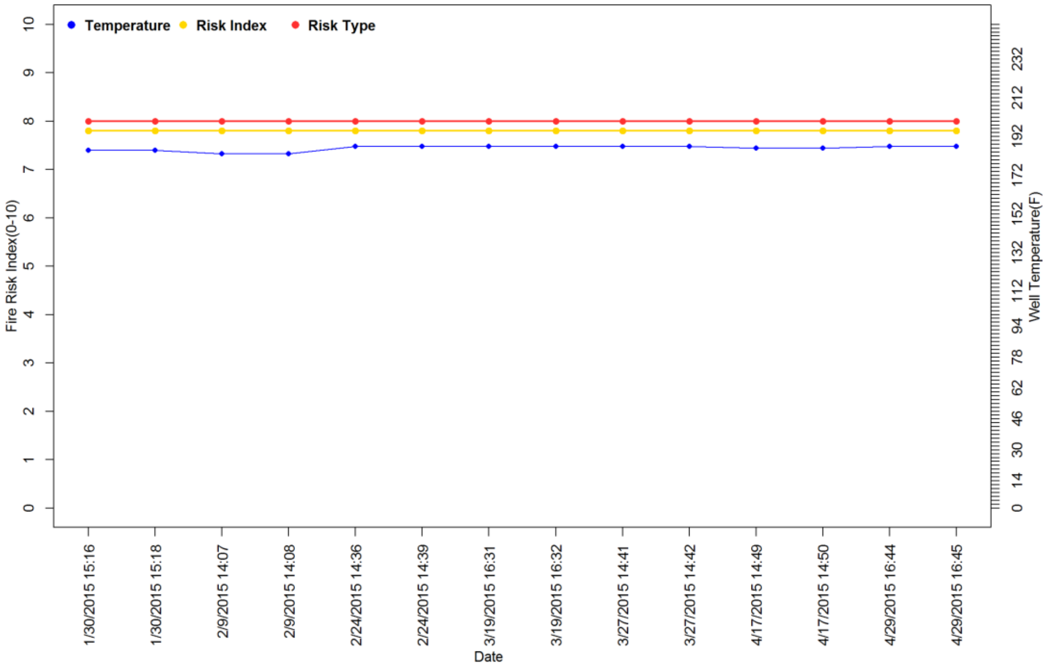
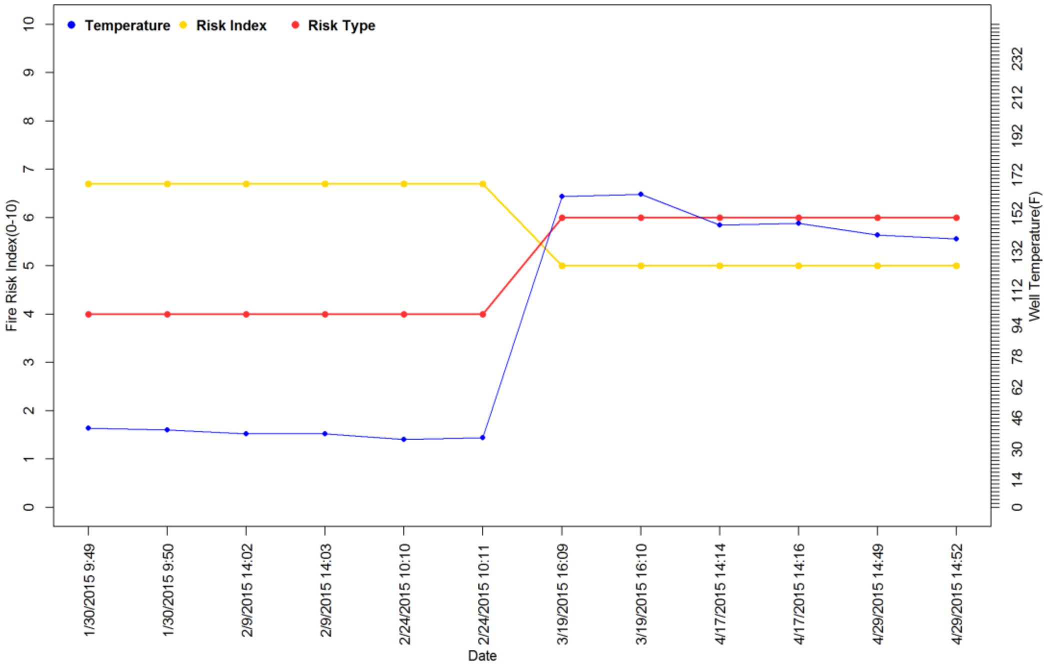


Figure 16. (GEW-139 and GEW-140) with high temperature (>176°F).

GEW-137



GEW-124

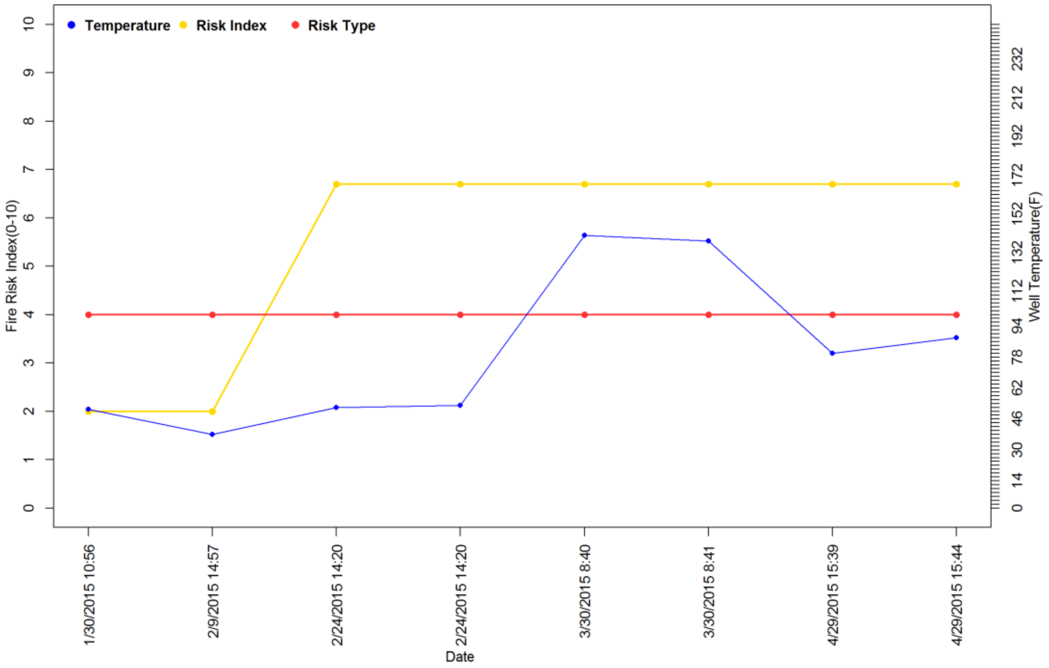
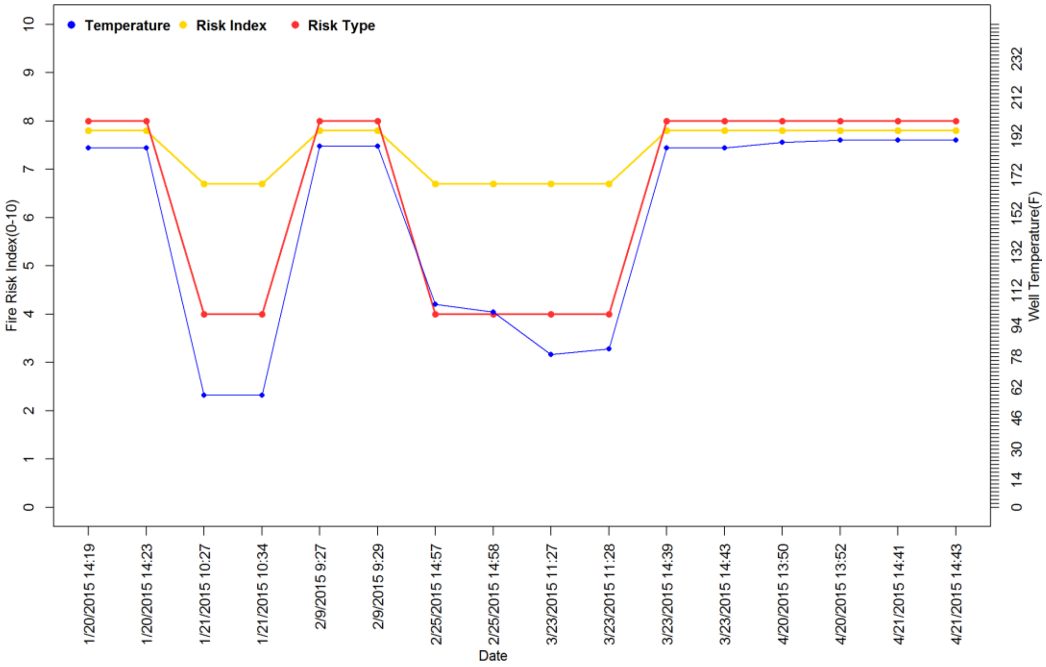


Figure 17. (GEW-137 and GEW-124) with fluctuating temperature.

GEW-11



GEW-120

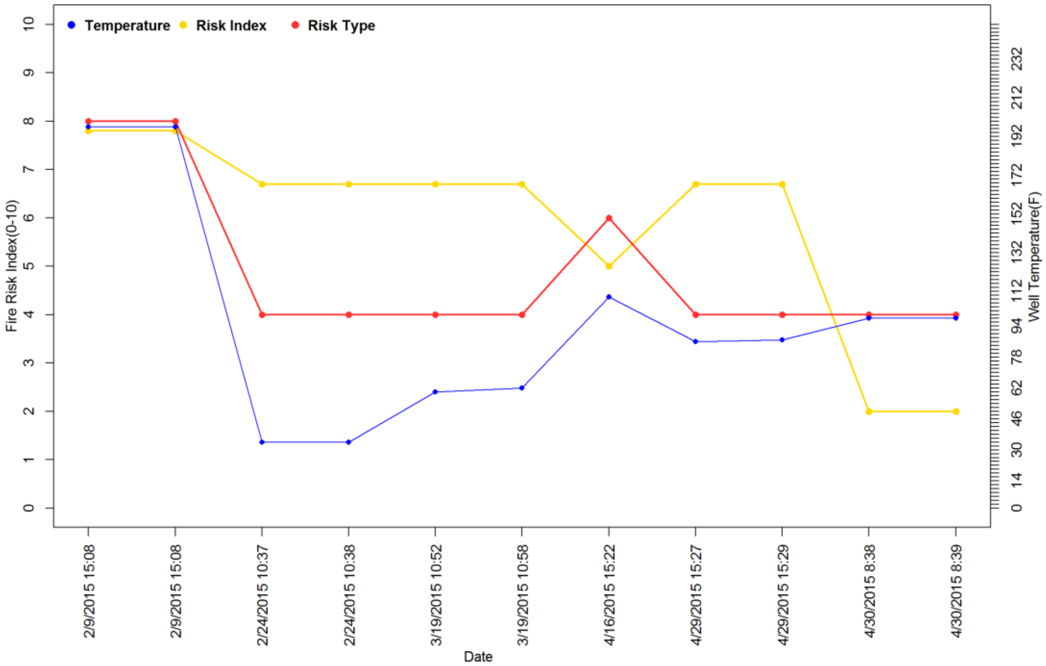


Figure 18. (GEW-11 and GEW-120) with fluctuating temperature.

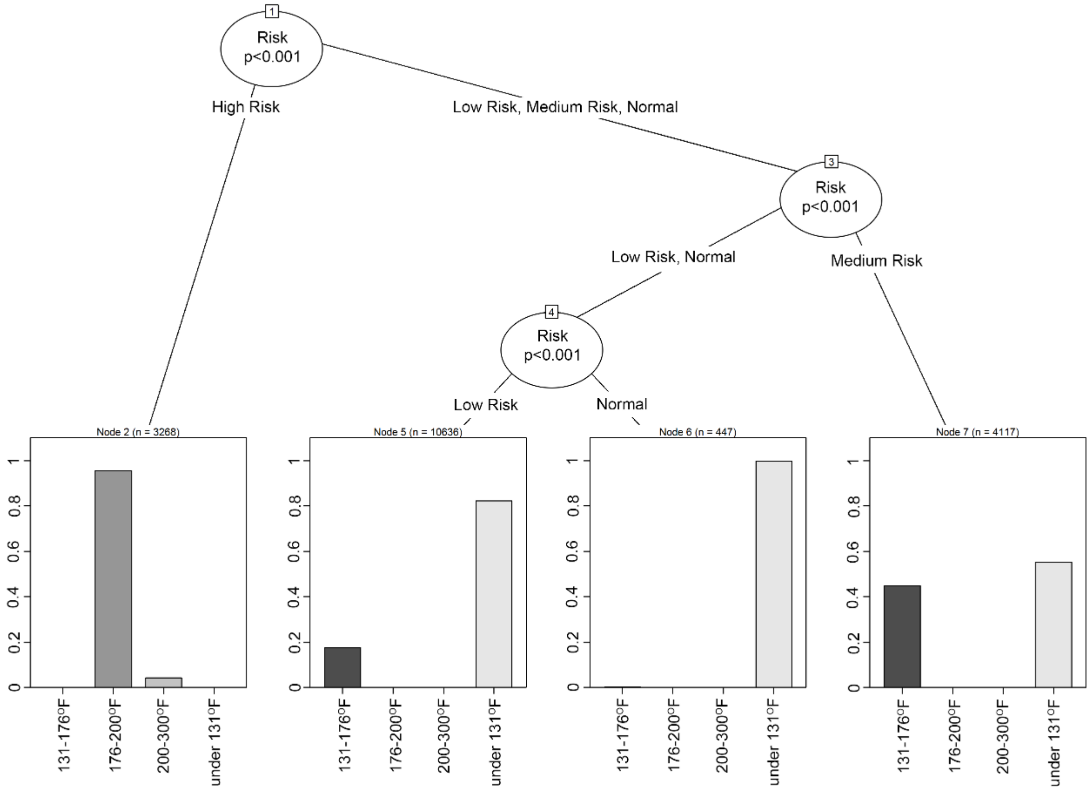


Figure 19. Conditional inference tree on risk types and temperature ranges.

2.7 Conclusion

Safety is an important component to the health and well-being of individuals in all types of settings. In order to safeguard safety, risk assessments are implemented wherever possible, especially in environments such as landfills where different threatening scenarios may occur. Due to their importance, landfills require a risk assessment process that is practical, sustainable, and easy to understand. The proposed landfill fire risk index is derived from collected data set of a case-study landfill with several incidents with subsurface elevated temperature. During the completion of the risk assessment, the primary characteristics that increase a landfill's susceptibility to subsurface fire were identified and their unsafe ranges were analyzed in chapter 1. The results of the statistical analyses in this thesis indicate that high subsurface temperatures are best related to combinations of gas parameters, rather than considering one parameter. Each combination has certain levels of association with temperature which can be used as weighting values in order to generate a risk index model.

The index can be considered as a useful and sustainable tool for decision-making. Although the risk index scale does not predict temperature sequentially, identifying risk categories associated with possible combinations may assist landfill authorities to estimate landfill fire risk and to focus management attention on possible fire outbreaks. The completed Risk Assessment can be used by landfill personnel during their weekly monitoring well checks and can become a monthly landfill protocol to avoid possible fire catastrophes and direct preliminary measures that reduce economic and environmental costs. The risk assessment can be improved by including some important parameters such as carbon monoxide, subsurface pressure, leachate collection, etc. and setting thresholds for them.

The possibility of further research includes developing a method for forecasting future temperature considering several uncertainties in subsurface environment of landfills and predicting temperature using the neural network algorithm. It is also possible to design a software program incorporating the proposed methodology for the purpose of preventing subsurface smoldering events in landfills.

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