AN ANALYSIS OF COMBUSTIBLE GAS CONCENTRATIONS IN SOIL NEAR NATURAL GAS EXTRACTION SITES IN NORTH CENTRAL PENNSYLVANIA: BEFORE AND AFTER DRILLING

By
Luke Hershey

A Thesis
Submitted to the Department of
Geography and Earth Science and the Graduate Council
in partial fulfillment of the requirements for the degree of
Master of Science

Shippensburg University
Shippensburg, Pennsylvania
December 2013

DEPARTMENT OF GEOGRAPHY AND EARTH SCIENCE

SHIPPENSBURG UNIVERSITY

Upon the recommendation of the chairperson of the department of Geography and Earth Science this thesis is hereby accepted in partial fulfillment of the requirements for the degree of

Master of Science

Thesis Committee

Committee Chairperson Dr. Scott Drzyzga	Date
Committee Member Dr. Thomas Feeney	Date
Committee Member Dr. Sean Cornell	Date

Table of Contents

List of Figures

List of Tables

List of Equations

GLOSSARY

Combustible Gas – A gas capable of igniting and burning.

Drift Gas – Gases derived from organic material that formed during interglacial periods that were then subsequently buried and sealed by glacial deposits. These gases are known to migrate into formations above and below the glacial-drift source and can also migrate into soils (Meents, 1960).

Dry Gas – Natural gas that primarily contains methane and does not contain much of the other known constituents that are more commonly found in "wet" natural gas (e.g., ethane, butane, propane, etc.).

Hydrocarbon - Organic chemical compounds that are only composed of carbon (C) and hydrogen (H). Different carbon and hydrogen configurations produce different types of hydrocarbons (e.g., methane's chemical formula is CH_4 and propane is C_3H_8 amongst many others). Hydrocarbons are the principal components of petroleum and natural gas.

Light Hydrocarbons - Hydrocarbons that have a low molecular weight such as those found in natural gas. This lesser molecular weight allows light hydrocarbons to migrate through layers of rock more readily than heavier hydrocarbons such as crude oil (Leythaeuser et al., 1982).

Natural Gas – A gas mixture primarily consisting of methane, but also consists of percentages other hydrocarbons such as ethane, butane, and propane. Natural gas is combustible and is commonly used as a fuel source.

Soil gas – Any gas found in the soil. Typically the constituents and concentrations of soil gas are similar (nearly identical) to those found in the atmosphere.

Source Rock – A rock formation rich in organics (typically shales) from which hydrocarbons are generated. Light hydrocarbons are generated from source rocks and migrate into and throughout carrier rocks and reservoir rocks (typically coarser-grained rocks such as sandstones).

Stray Gas – For the purpose of this paper, stray gas is defined as a combustible gas which has migrated from its source. Occurrences of stray gas have natural causes (e.g., migration from near surface glacial-drift or coal deposits) or may be results of human activities (e.g., leaking natural gas pipelines, leakage of active or abandoned oil and gas wells, landfill gas).

Unconventional Drilling Activities – Drilling practices that have only recently come into use and have been shown to increase how much a natural gas well yields. These activities include horizontal drilling, hydraulic fracturing, and drilling at extreme depths.

Wet Gas – Natural gas that contains methane along with comparatively high levels of hydrocarbons other than methane (e.g., ethane, butane, propane, etc.).

ACKNOWLEDGEMENTS

Without the assistance of a number of individuals, this research would not have been possible. First I would like to thank Dr. Scott Drzyzga for his assistance throughout this project. As my advisor for this thesis he provided considerable insight, guidance, and resources. The teachings on Inverse Distance Weighted Interpolation from his GIS III course ultimately led to the inspiration of this project.

Next, I would like to thank Drs. Sean Cornell and Thomas Feeney for their assistance with this project and appreciate their instruction throughout my time at Shippensburg. I would also like to thank the entire Geography and Earth Science department as I have accumulated a wealth of knowledge through the excellent education they have provided during my graduate and undergraduate terms at Shippensburg.

I would like to thank the staff from the Department of Environmental Protection and the Department of Conservation and Natural Resources as their assistance in attaining access to well pads and providing the field house for living arrangements during my weekend trips to Tiadaghton State Forest made this project possible.

Lastly, I would like to thank the students from Penn State who were studying the effects of Marcellus Shale development on wildlife and were also staying at the field house. Their knowledge of the study area and experience studying drilling activity provided me with quick answers to numerous questions I had, which was remarkably helpful. They also provided some much appreciated entertainment on what otherwise would have been rather unexciting nights deep in the Tiadaghton State Forest.

ABSTRACT

Natural gas is a combustible gas. Stray combustible gas can present an asphyxiation or explosion hazard to people when it migrates and pools where people live, work, and play. Natural gas extraction activities disturb soil, aquifers, and rock strata, which can create new pathways for combustible gas to migrate and new destinations for it to pool. In Pennsylvania, the rate and intensity of drilling wells to extract natural gas from the Marcellus Shale Formation has increased rapidly over the last six years. There is, unfortunately, little information available about how drilling activities change pathways for natural gas to migrate or stray. Specifically, little is known about how unconventional drilling of the Marcellus Shale Formation affects levels of combustible gas in soils near well sites, and where people may live, work, or play. This study contributes new knowledge about the relationship of natural gas extraction activities and combustible gas concentrations in soil around 8 sites in the Tiadaghton State Forest region of north central Pennsylvania, where natural gas wells are being drilled with increasing frequency. Elevated levels of combustible gas associated with well drilling were not observed in the study area, but combustible levels of methane were observed over natural gas transmission lines. Also, findings showed that the amount of combustible gas observed in the soil can vary with changes in temperature and barometric pressure, and so, the author recommends that this factor be observed and controlled during future research.

INTRODUCTION

The Marcellus Shale Formation (or Marcellus Formation) is a laterally extensive interval of Middle-Devonian age black, low-density, and organic-rich shale (Engelder and Lash, 2011). It runs from New York to as far south as Virginia. The Marcellus Formation has been a known source of natural gas for decades (Considine, 2009), but was only recently considered suitable for profitable extraction and production. In 2002, the USGS estimated 1.9 trillion cubic feet of economically recoverable gas reserves available in the Marcellus Formation (Milici et al., 2003). Lash and Engelder (2008) challenged the USGS figure and offered a revised estimate of 50 trillion cubic feet of economically recoverable reserves. They credited their markedly higher estimate to recent improvements in technology which included: multidimensional seismology, horizontal drilling, and hydraulic fracturing (Considine, 2009; Lash and Engelder, 2008).

The revision by Lash and Engelder (2008) is substantial, and extracting these resources has created a gas drilling boom which has benefited the economy of Pennsylvania through improved rates of employment and increased wages in regions experiencing drilling development (Hershey, 2013). In addition, gas drilling in Pennsylvania has reduced the price of natural gas throughout the state (United States Energy Administration, 2013). While the economic gain of utilizing this resource is attractive, the potential environmental impacts of natural gas-related drilling activities should also be considered in order to protect the local environment and well-being of people who live near these drilling sites.

Historically, there have been numerous instances where natural gas has migrated through soil and water near natural gas drilling sites (Baldassare and Laughrey, 1997; DEP,

2011). Gas migration from drilling activities has been the cause of a number of different environmental problems that include migration of gas into water wells and homes, well explosions, house explosions, asphyxiation in confined spaces, and other occurrences that are related to stray gas near drilling sites (Baldassare and Laughrey, 1997; DEP, 2011**)**. In the past decade the Pennsylvania Department of Environmental Protection has reported over 50 cases of natural gas migration caused by drilling activities (DEP, 2011). Natural gas companies sometimes claim that these incidents happen due to naturally occurring gases in the soil (Bleichmar and Hollander, 2012). In some areas this appears to be true because of significant levels of "drift gas" that can be found in shallow Devonian bedrock and in soils that contain concentrations of biogenic methane (Howarth, 2011; Martini, 2008).

While there has recently been a boom of research regarding the environmental impacts of drilling into the Marcellus, most of this research has primarily focused on the effects of drilling activities on domestic water supplies, with most of that research being focused on toxic fluids from hydro-fracturing entering local water wells; few studies focus on natural gas migration that may be caused by drilling activity.

Most published studies that focus on natural gas migration (rather than toxic fluid migration) from drilling activities focus on stray gas migrating through water and into water wells. These studies primarily focus on observing the isotopic characteristics of the gas (i.e., geochemical fingerprinting) in order to speculate on the origin of the natural gas sample (Baldassare and Laughrey, 1997; Osborn, 2011; Revesz et al., 2010).

A combustible gas indicator is used in some studies (Pittsburgh, 2009) to measure natural gas concentrations; although it is typically used as a prospecting tool in studies to locate viable sites to collect samples for geochemical fingerprinting. It appears that no

previous studies have primarily employed a spatio-temporal analysis of combustible soil gas concentrations near drilling sites through the use of a combustible gas indicator (Eltschlager et al., 2004).

PURPOSE AND SCOPE

The relationship between natural gas drilling activities and gas migration patterns near these sites is a poorly understood phenomenon. Natural gas production companies and the public appear to be at odds with one another about the relationship. Natural gas companies sometimes report that "methane found in some shale gas areas (e.g., Marcellus) can most likely be traced to natural sources, and likely was present before the onset of shale gas operations" (Bleichmar and Hollander, 2012, pg. 3). Conversely, an Ecology & Environmental Biology professor at Cornell University stated in a written submission to the EPA that "Shale gas development clearly has the potential to contaminate surficial groundwater with methane, as shown by the large number of incidences of explosions and contaminated wells in Pennsylvania, Wyoming, and Ohio in recent years." and that "… shale gas development has clearly contaminated groundwater and drinking water wells with methane" (Groat and Grimshaw, 2012, pg. 8). From statements like these it can be seen that there is disagreement in regards to whether natural gas extraction activities cause conditions of environmentally hazardous methane migration.

Previous studies have investigated drilling sites and focused on known gas migration issues (Revesz et al., 2010, Baldassare and Laughrey, 1997). One recent study states that "often there is insufficient baseline (pre-drilling) sampling or monitoring to establish the impacts of drilling, fracturing, and other operations" (Groat and Grimshaw, 2012, pg. 19).

Determining the origin of observed combustible gas concentrations is not the goal of this study. Unlike previous studies that attempt to identify the source of gas through geochemical fingerprinting, the purpose of this study is to perform an experiment that

observes combustible gas concentrations in the soil at drilling sites before and after drilling. Such observations can indicate whether or not extraction activities are associated with changes in combustible gas concentrations. If gas concentrations change (from before to after drilling) the origin of the gas will remain unknown based on the methods used. What will be identified is whether or not natural gas extraction activities appear to show a relationship to combustible gas concentrations in the soil. An investigation of gas concentrations in soil is important because the primary concern with any combustible gas, no matter what its source may be, is its potential to migrate into homes. Oftentimes, the final pathway into a home is through local soils.

RESEARCH QUESTIONS

As stated in the previous section, the purpose of the study is to perform an experiment that observes combustible gas concentrations in the soil at well sites before and after drilling. To serve this purpose, a series of questions were developed; a primary question, along with ancillary questions. The primary question is as follows:

- Do pre-drilling baseline concentrations of combustible gas (regardless of source) in soils near Pennsylvania Marcellus Shale drilling fracturing sites change after drilling and/or hydraulic fracturing?

Through answering the primary question, answers to other questions may become evident; these questions include:

- If concentrations of combustible gas in the soil are observed to increase after drilling activities begin, are there any spatial trends or patterns in these concentrations that can be observed?

- If concentrations of combustible gas are observed; does the spatial pattern of variation indicate the reason(s) why the gas is migrating?

- If concentrations do not show significant changes, but there are baseline natural gas concentrations, how do these baseline concentrations vary based on: soil type, underlying geology, temperature, barometric pressure, and the time of day that samples were taken.

LITERATURE REVIEW

Recent Drilling Activities in Pennsylvania

Interest in drilling for natural gas in Pennsylvania has increased since Range Resources drilled its first 'Marcellus well' in Pennsylvania in 2004. The reason for this is that in the past few decades there have been great strides in technology to identify natural gas resources underground; but there have also been improvements in the efficiency of extraction technologies (Consodine et al., 2009).

Through the use of multidimensional seismology, recent estimates show that there are more than 50 trillion cubic feet (TCF) of economically recoverable gas reserves in the Marcellus Shale, well above the 2002 USGS estimate of 1.9 TCF (Milici et. al., 2003; Engelder and Lash, 2008). The majority of this resource underlies the Commonwealth of Pennsylvania, but West Virginia, Ohio, and New York also host significant shares of the Marcellus (and its equivalents). These new estimates and improved drilling technology have prompted increases in natural gas drilling and natural gas production in Pennsylvania. For example, the PADEP recently estimated that 1.4 trillion cubic feet of natural gas were produced from Marcellus wells during the first half of 2013 compared to 0.4 trillion cubic feet of production in the first half of 2011 (PADEP, 2013). This is more than a 320% percent increase over two years; a dramatic change in such a short period of time.

Many of the new Marcellus sites are considered to be unconventional because of the extreme depths to which the wells are drilled and the new horizontal drilling and hydraulic fracturing methods that are used to recover gas. This increased use of unconventional

methods has been a public concern when considering environmental impacts at these sites (Osborn, 2011). It is difficult to understand the exact causes of migrating gas near well sites because it is an invisible phenomenon and subsurface processes can alter the composition of gas as it migrates to the surface (Baldassare and Laughrey, 1997). In regards to confirmed migrations in Pennsylvania, faulty well casings, typically from older abandoned wells, appear to be a common cause of gas migration (DEP, 2011).

According to Osborn (2011), it may be possible for gas to migrate through the 1 to 2 kilometer thick geologic formations that are above the Marcellus Shale because these formations are known to have extensive fracture systems and because there are many old, uncased, and abandoned wells in Pennsylvania. Fracture systems can be the result of tectonic deformation, catagenesis, and isostatic rebound following the retreat of glaciers (Warner et al., 2012). Warner et al. (2012) examined brine concentrations in groundwater sampled from wells in various counties in northeastern Pennsylvania. They found that some brine samples have geochemical signatures similar to water from the Marcellus Formation. Some of these geochemically similar brines were sampled prior to any drilling into the Marcellus suggesting that extensive fracturing may have created cross-sectional pathways to the surface allowing brine from the Marcellus to migrate into shallower and fresher aquifers. In contrast to the findings by Warner et al. (2012), Leythaeuser et al. (1982) explained that large swathes of time are required for methane to diffuse through rock formations, likely on the magnitude of hundreds of millions of years. While the findings by Warner et al. (2012) are intriguing, whether fracture systems can actually overcome the extreme depths to the Marcellus (depths of 1,200m to 2,500m in the study by Warner et al.) and cause gas to migrate to the surface is still rather speculative and is unfounded in the scientific community.

Properties of Natural Gas

The properties of natural gas are an important factor when considering natural gas migration. All gas line surveyors in the natural gas industry are required to know the basic combustible properties of natural gas in order to protect themselves and the public from hazardous conditions that may be caused by a natural gas leak. These same concepts are applicable in this study and will be discussed further.

Natural gas is composed of several constituent gas types: methane, ethane, propane, butane, and several others; all of which fall within the alkane series (also known as the paraffin series) of hydrocarbons (Heath, 1993). All members of the alkane series are similar in that they are made of at least one carbon atom bonded with as many as four hydrogen atoms. Other members of the alkane series include octane, which is used in gasoline, and kerosene, which is used in lanterns and as heating oil (Heath, 1993).

Methane (CH_4) is the first and simplest member of the alkane series, for it is composed of only one central carbon atom with four chemically bonded hydrogen atoms. Methane is the primary constituent of natural gas, typically comprising 90% of natural gas by volume. Methane can be liquefied at very low temperatures and/or elevated pressures and is less dense than air (specific gravity = 0.5537 mass of Methane per unit volume/mass of air per unit volume). Ethane (C_2H_6) typically comprises between 3% and 6% of natural gas by volume while butane and propane each typically make up less than 1% by volume (Heath, 1993). All constituents of natural gas are considered light hydrocarbons. Light hydrocarbons are hydrocarbons that have a low molecular weight as compared to heavier hydrocarbons like crude oil (Leythaaeuser et. al., 1982). This lesser molecular weight allows light

hydrocarbons to migrate more readily through layers of rock as compared to heavier hydrocarbons.

Natural gas is also composed of various trace elements. The ratios of elements found in natural gas can vary because different reservoirs of gas have different characteristics that reflect different parent materials or different development processes (Revesz, 2010). Natural gas is colorless and odorless in nature. Natural gas processing facilities mix a sulfur-based odorant called 'mercaptin' with the gas so that people can readily identify gas leaks by smell without special equipment (Heath, 1993).

Natural gas has a critical ignition temperature between 627 and 643 degrees Celsius. Regardless of temperature, however, natural gas will not ignite unless the gas to air volume ratio is between 4.5%, (which is known as the Lower Explosive Limit), and 14.5%, (the Upper Explosive Limit) (Heath, 1993).

Characteristics of Thermogenic and Biogenic Gases

Natural gas can come from many different sources, all derived from organic matter. Biogenic methane, for example, forms through the reduction of CO_2 in marine environments and through the fermentation of acetate in freshwater environments (Schoell, 1988). Thermogenic methane, however, is produced when organic matter is buried in sediments and subjected to high temperatures and pressures. These high temperatures and pressures assist in breaking down the organic matter and its eventual transformation into a range of short and long-chain hydrocarbons and residual byproducts. These long-chain hydrocarbons can then be further decomposed into methane through direct thermal decomposition in a matrix of

sedimentary rocks or by organic decomposition closer to the surface in the presence of bacteria (Baldassare and Laughrey, 1997; Schoell, 1988).

Distinguishing between thermogenic and biogenic gas can lead to a better understanding of the origin of sampled gas and can ultimately improve the credibility of research. When measuring natural gas levels near drilling sites it can be useful to determine whether the gas is thermogenic or biogenic in origin. This can be helpful in eliminating possible methane sources that may not be related to drilling activities.

There are several ways to determine whether natural gas is thermogenic or biogenic in origin, including the analysis of the following: gas composition, stable isotopes, and radioactive C isotopes. Thermogenic gas tends to have higher ratios of ethane, propane, butane, and pentane relative to methane than microbial gas (Revesz, 2010).

Analyzing the ratios of stable isotopes to radioactive isotopes through the use of a mass spectrometer or gas chromatography can often determine whether a gas is thermogenic or biogenic in origin. Biogenic gases have a tendency to have a significantly higher ratio of ^{14}C isotopes in comparison to thermogenic gases; this is attributed to biological uptake of atmospheric CO_2 which has measureable levels of radioactive ^{14}C isotopes (Revesz, 2010). Levels of ^{14}C are even greater in gases and materials created or exposed during and after atomic bomb testing (Revesz, 2010). Therefore recently produced biogenic methane shows exceptionally higher levels of ^{14}C isotopes compared to thermogenic methane. Thermogenic gases were formed over millions of years and should have very low levels of ^{14}C due to radioactive decay, given that the half-life of ^{14}C is 5730 years. Levels of ^{12}C and ^{13}C isotopes should also be present in both thermogenic and biogenic methane (Revesz, 2010).

Determining a definitive thermogenic source can be difficult, especially near well sites. Gas wells are drilled through many layers of rock, some of which are natural reservoirs, or "traps," of natural gas even though they are not the source of natural gas extraction. Drilling through these more shallow layers can provide a pathway for gas to travel to the surface, and sometimes these shallow reservoirs already have pathways to the surface due to imperfect seals in their respective cap rock (Von Der Dick et al., 2002; Kargbo et al., 2010).

As thermogenic gas migrates upwards into soil its composition can sometimes be altered by methanotrophs (Prinzhofer and Pernaton, 1997; Baldassare, 1997). Methanotrophs are oxidizing bacteria that consume hydrocarbons such as methane and convert these hydrocarbons into cell material and produce CO_2 (Baldassare, 1997). This can make significant changes in the chemical makeup of the gas, making it difficult to identify through chemical analysis (Prinzhofer and Pernaton, 1997; Baldassare, 1997).

In contrast to methanotrophs, organisms called methanogens found in the subsurface can actually produce biogenic methane gas in a process known as methanogenesis, where buried organic material found in the soil is used by methanogens to generate methane; this process commonly occurs in swamps and landfill sites (Revesz et al., 2010). Biogenic methane can be produced in the subsurface (including soils) and seasonal variations are known to affect methanogenic processes (Shoell, 1988). In the summertime acetate fermentation is more of a factor than in the winter where CO_2 reduction becomes the more prevalent factor (Schoell, 1988).

Another difficulty in identifying gases near drilling sites over unconventional shale gas reservoirs is that they often contain both thermogenic and microbial gas components (Martini, 2008). When gases diffuse through a porous media, a phenomenon called

"fractionation" often occurs. Fractionation is a fluctuation in the carbon isotope ratios as a result of natural biochemical processes as it relates to their atomic mass. This can make it difficult to identify gases even through isotopic analysis (Prinzhofer and Pernaton, 1997; Revesz et al, 2010).

Gas Migration in Water

Gas migration in water is not uncommon and there have been many documented cases of methane bubbling into streams or accumulating in water wells (DEP, 2011). Natural gas in groundwater can be particularly hazardous because the gas often dissolves into groundwater at depth in a pressurized state. As the gaseous water migrates into areas of lower pressure, the water releases the gas which causes the water in streams and rivers to bubble. This same process can also cause gas to accumulate in a water well (Revesz et al.; 2010, Baldassare, 1997). Natural gas in drinking water is not necessarily hazardous to humans, but once it enters the air in sufficient concentrations (usually in a confined space such as a basement) it can create a hazardous environment conducive to asphyxiation, fire, or an explosion (Osborn, 2011).

A study carried out in Susquehanna County, Pennsylvania, found methane in 51 of 60 sampled water wells (Osborn, 2011). Levels of natural gas were compared based on the distance between water wells and the nearest active natural gas well. The study found that natural gas levels were 17 times higher in water wells within 1000 meters of natural gas extraction sites (Figure 1). The study also found that the lower methane concentrations found at non-active sites had chemistry that was more consistent with a biologically formed gas while the active sites showed higher methane concentrations consistent with a thermogenically formed gas. The data in this study show that levels of dissolved methane in

water wells within 1000 meters of natural gas extraction sites are often significantly higher than methane levels found in wells beyond 1000 meters.

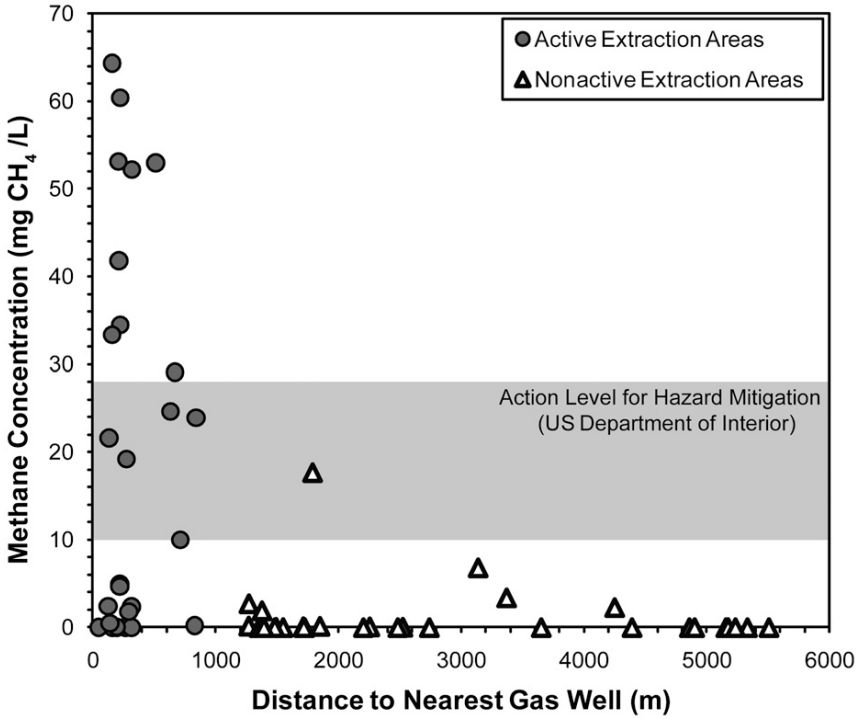


Figure 1: Natural gas levels in water wells in Northeastern Pennsylvania (Osborn, 2011). Wells within 1000 meters from gas wells in the study area had much higher concentrations of natural gas than areas further away. Source: Osborn, 2011.

Gas Migration in Soil

The same hazardous conditions exist for combustible gas in soil as with combustible gas in water (asphyxiation, fire, and explosions). Natural gas migration in the soil is known to occur near drill sites and often occurs when gas is released from water as it enters areas of lower pressure (Revesz et al., 2010; Baldassare, 1997). Once released from groundwater, natural gas rises through the soil, as it is less dense than the atmospheric-like gases found in the soil. Subsurface materials (soil or rock) with highly permeable properties allow gas to flow more readily than less permeable materials. (Rossabi, 2002; Praagman & Rambags, 2008). Natural gas in the subsurface flows in a path of least resistance, and the rate at which gas

flows through the subsurface is dependent on the permeability of the material through which it is being transmitted (Rossabi, 2002; Praagman & Rambags, 2008).

Changes in atmospheric (barometric) pressure can also affect how gas moves through soil and rock. Relatively low atmospheric pressures allow for out-gassing to occur at higher rates with the permeability of the subsurface material being the limiting factor (Rossabi, 2002; Praagman & Rambags, 2008). Diurnal changes and fluctuations in the weather can have significant effects on the rate at which out-gassing occurs. The flow of groundwater can also alter how out-gassing occurs. Areas with lower rates of horizontal water percolation will show higher concentrations of gas, while a faster rate of percolation will cause the gas to diffuse away from its source and show lower gas concentrations (Pirson, 1946).

Impact of Gas Migration resulting from Faulty Well Sites

Gas migration from drill sites is not an uncommon phenomenon and there are many recorded cases in Pennsylvania. Methane migration in soil and water can occur for a number of reasons (Figure 2), including: compromised gas wells, leaking gas-storage fields (if they are located in the region), new pathways created by geologic processes that may have altered the permeability in near surface bedrock, natural biogenic sources that are microbial in origin, from landfills, from underground coal mining activities, and underground pipelines (Revesz et al., 2010; Baldassare, 1997).

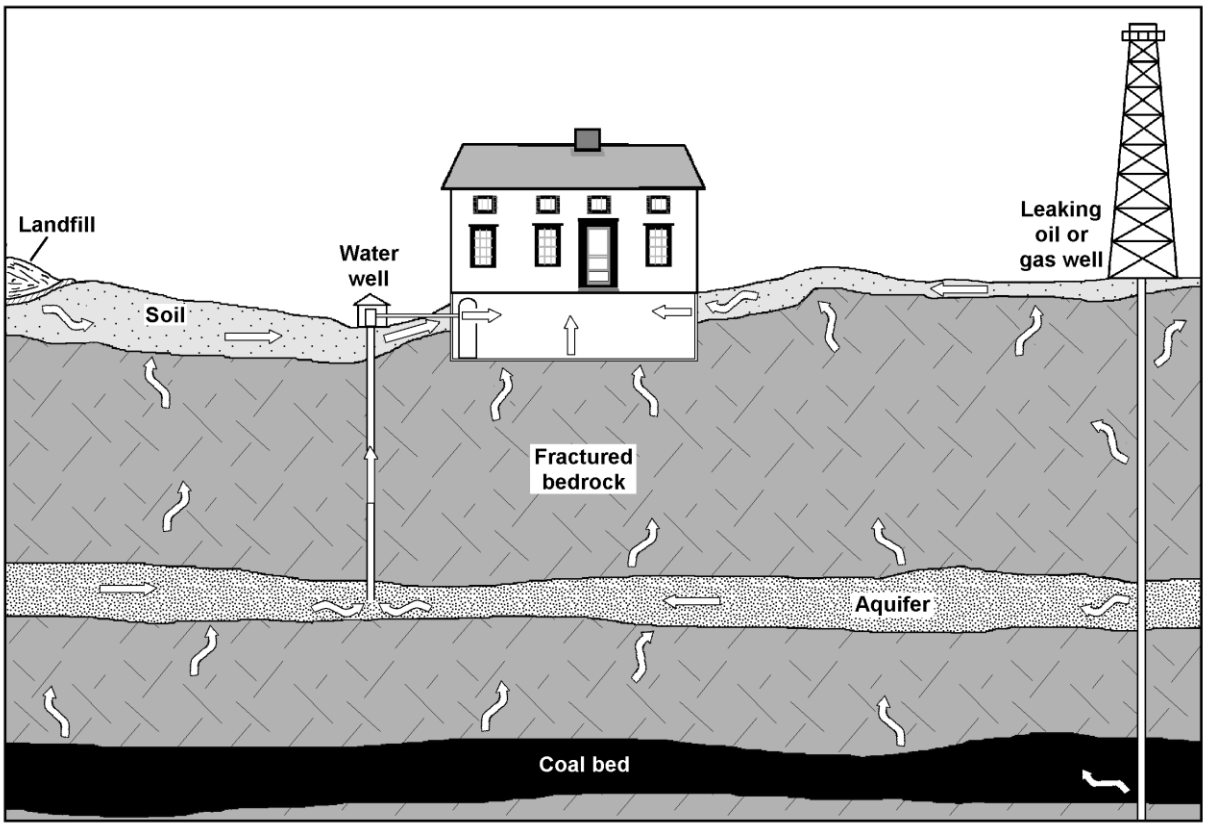


Figure 2: Possible migration pathways that may lead to natural gas leaking into a building. Source: The Pittsburgh Geologic Survey, 2009.

Examples of Stray Gas Migration

A report by the Pennsylvania Department of Environmental Protection includes 65 different examples of gas migration, many of which are related to recent drilling activities (DEP, 2011). Following are examples of specific events that have occurred in Pennsylvania, showing the environmental impacts of stray gas associated with drilling activities (DEP, 2011).

Bradford Township, 2010

A recent example occurred on December 12th, 2010, in Bradford Township, McKean County where a house exploded for reasons that are still under investigation. A month

earlier, there was an explosion nearby at another home where investigators had a "pretty definitive idea that the explosion is from migrating methane (Associated Press, 2011, pg. 7A)." The homeowner did not smell any odor leading up the explosion (Associated Press, 2011). The lack of an odor in this instance implies that the gas was not a processed gas.

Tioga Junction, 2001

In 2001, the Bureau of Gas Management (BOGM) and the PA DEP investigated a set of water wells near Tioga Junction, Tioga County, in north-central Pennsylvania. Investigators noted that water in the wells was bubbling with natural gas. Samples showed elevated levels of dissolved methane and the PADEP thought that the gas could be migrating from "compromised gas wells (improperly plugged, abandoned, or leaking) gas wells, leaking gas-storage fields, or new uncontrolled pathways (such as a seismic event) (Revesz, 2010, pg. 3)." Investigators found both thermogenic and biogenic gases. It was difficult to tell the origin of the thermogenic gases due to possible mixing of gases from various biogenic and thermogenic sources. In this case there was a local natural gas drilling and a natural gas storage field in the area, either of which may have been the source of the thermogenic gases that were sampled based on a later study in this area (Revesz, 2010).

Dimock Township, 2009

The Dimock migration occurred in 2009 and is one of the more publicized examples of gas migration. In this case there was a significant concentration of natural gas that migrated into several homes. Fugitive gas was also found in six water supply wells. This area does not have a past history of drilling other than recent drilling into the Marcellus Shale (DEP, 2011).

McNett Township, Lycoming County, 2009

In this instance natural gas was found migrating into multiple water wells in the area. Gas also migrated into two streams, and one home was evacuated. Roads near the well were closed. Conditions near the well improved once the gas company acted to fix the problem. It is believed that the cause of the migration was due to a failure in the well casing. An investigation of the area continues because concentrations of gas have been detected in wells and in the ground, although to a lesser extent in comparison to the initial findings (DEP, 2011).

Jefferson County, March 2004

This occurrence is one of three examples of a tragic scenario where human lives were lost due to natural gas leaking near a drilling site in Pennsylvania during the past decade. The records from the PADEP (2013) were clear and concise: "An operating gas well. House explosion resulted in three fatalities. Origin/mechanism of migration: Operating gas well. Pressurization of the annulus on one or more operating gas well(s) was the mechanism of stray gas migration that caused the explosion. Status: Final agreement pending. Elements of DEP Compliance Order still outstanding." News reports of the explosion describe the remnants of the house as a pile of rubble, with debris found across the road and insulation hanging from trees (Lustgarten, 2009).

Geospatial Methods Used in Previous Studies

GIS professionals are always concerned about issues of data quality, which include issues pertaining to accuracy, precision, completeness, currency, and logical consistency. Input data collected from various sources or through varying sets of procedures can diminish the quality of any derived output data product and the credibility of the output data provider

(Brus and Grutijer, 1997; Wang et al., 2010). Informally, this is sometimes known as the garbage-in-garbage-out rule. Fortunately, many previous works have used appropriate geospatial methods to sample, collect, and map natural gas migration data. For example, Revesz et al., (2010) collected natural gas samples and location coordinate data from gas production wells, gas storage field wells, gas storage field observation wells and water wells in Tioga County, Pennsylvania (which borders northern Lycoming county, the setting of this study). Resvesz et al. (2010) sent their gas samples to a lab to determine the isotopic composition, and compared the results observed for their gas wells to results obtained from water wells. They then joined their isotopic composition values to their location coordinate data to produce maps of point source gas concentrations in relation to their study area. Their resulting maps show the extent of gas storage reservoirs in the study area overlain with points that represent gas wells and water wells. Next to each well point was data in the form of text expressing isotopic characteristics of the sampled gas. One map showed that dissolved methane concentrations from water wells taken nearer to gas storage reservoirs and gas wells were higher than concentrations found in wells further away. Another map showed that the presence of thermogenic methane was found in many wells overlaying the gas storage reservoir. The mapping techniques are effective at portraying their data, but also show the limitations of their sampling technique. Although many of the samples taken are near or directly above the gas storage reservoirs, most of the gas wells are in the western part of the study area while the majority of water wells are on the eastern side of the study area. This shows that the authors were limited by their methods because they were only able to take samples in locations where there are water wells rather than being able to take samples anywhere in relation to the gas wells.

Very little spatial analysis was performed in any of the gas concentration studies reviewed, with the most complex examples only including inventories of individual spatial locations along with their corresponding combustible gas concentration values (with each location dispersed rather far away from other sample locations). This shows that there is a significant void in the general study of combustible gas concentrations. Granted, these phenomena are not easy (or cost effective) to sample and subsequently measure using gas chromatography, but less complex (and inexpensive) methods are available; allowing for a greater number of samples at a reduced cost and workload. Being able to take a greater number of samples allows for improved comparisons of gas concentrations with other natural phenomena (e.g. time, temperature, barometric pressure, bedrock, soil, etc.), and having a greater number of samples over a small area permits a viable analysis using more complex GIS techniques which will be discussed in the Methods section.

STUDY AREA

The study area is completely contained within the Tiadaghton State Forest, which is located within the PA DCNR Forest District 12. Forest District 12 falls within Lycoming and Clinton counties in North Central Pennsylvania (Figure 3). The study area was chosen because it contains many drilled and proposed well sites, and because it was recommended for study by the PA DCNR. Each well site in this study is located on the plateau above the Pine Creek Gorge, near the village of Waterville.

The study area is almost completely forested with the exception of some small local towns, campgrounds, and well sites that seem to create tiny islands of civilization in the vast expanse of woodland. The Tiadaghton and Pine Creek Riparian Area support a variety of recreational activities such as fishing, swimming and kayaking.

The extent of the project has been limited to a small region of the Tiadaghton State Forest so that each site has similar geologic and climatic characteristics (measured in ArcMap as having an area of 22.3 miles^2). Note that Lycoming County was the location of the McNett Township migration site and is adjacent to the south of Tioga County, where a study on gas migration by Revesz et al., (2010) was performed.

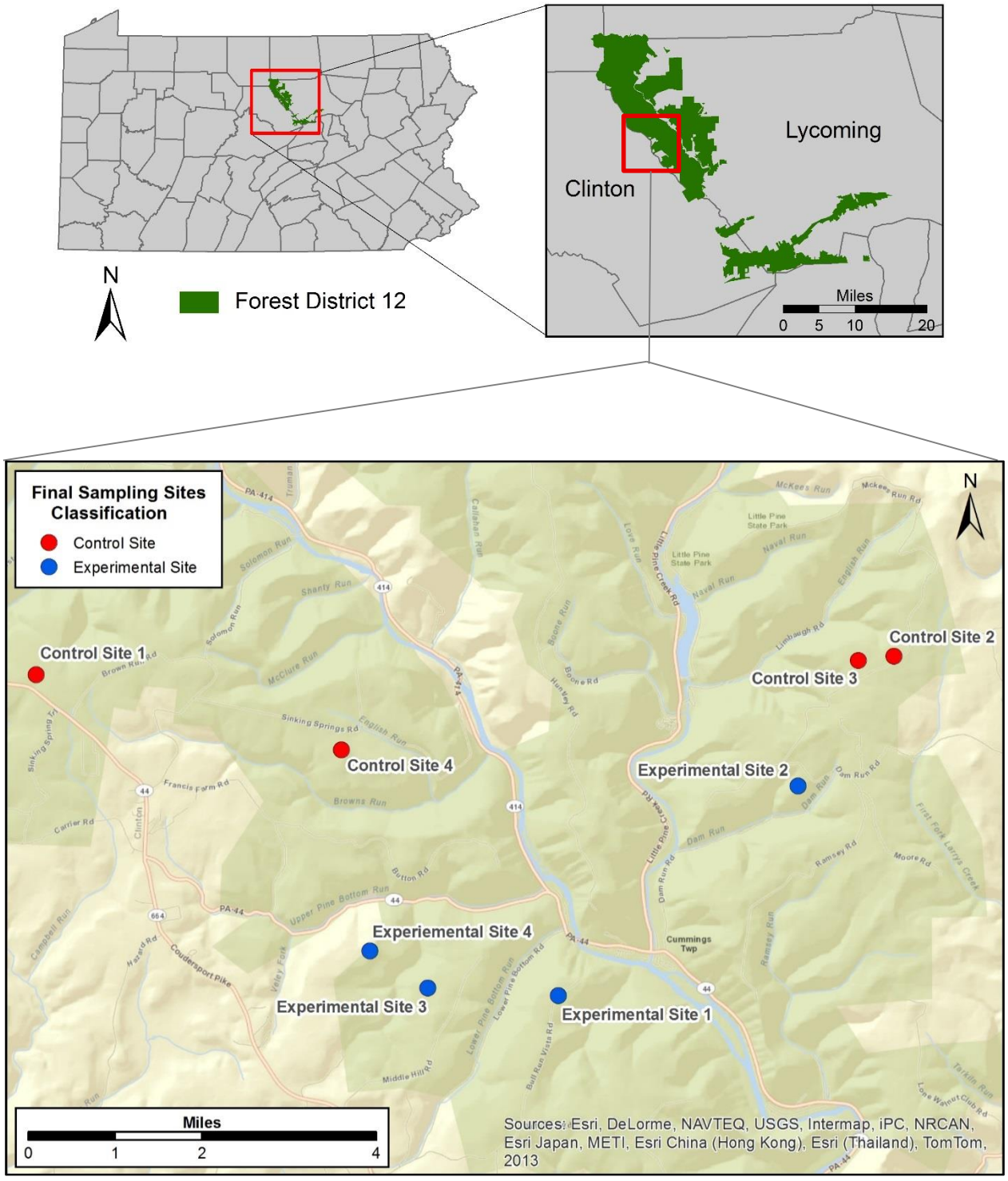


Figure 3: The study area in relation to the state of Pennsylvania and Forest District 12 (shaded in darker green). Each site lies atop a plateau proximate to the Pine Creek Gorge near the border of Clinton and Lycoming Counties.

Soils of the Study Area

Understanding the soils present around the sites in this study is important as the characteristics of these soils differ from one another and these differences could potentially influence how natural gas migrates around well sites (Table 1). There were two primary soil types encountered throughout this study, Dekalb and Clymer soils. Two other soils were also encountered, which are Hazleton and Klinesville soils. Each of these soil types will be discussed based on their parent material, thickness, and permeability.

Table 1: Soils that were encountered in this study.

	Depth to Bedrock	Permeability	Soil Name	Soil Abbr.	Slope in Degrees
Dekalb	36 in.	Rapid	Dekalb Very Stony Sandy Loam	DkB	0 to 8
			Dekalb Channery Loam	DeC	8 to 15
			Dekalb Very Stony Sandy Loam	DkD	9 to 25
			Dekalb and Lehew Very Stony Sandy Loam	DlE	25 to 80
Clymer	44 in.	Moderate	Clymer Very Stoney Loam	CnB	0 to 8
			Clymer Channery Loam	CmB	3 to 8
			Clymer Very Stony Loam	CnD	8 to 25
Klinesville	19 in	Moderately Rapid	Klinesville Shaley Silt Loam	KlC	8 to 15
Hazleton	58 in.	Moderately Rapid	Hazleton Clymer Channery Loam - Extremely Stony	HmD	8 to 25

Dekalb soils were the most commonly encountered soil in this study. They can be moderately level to very steep and are commonly found along mountaintops and in intermountain valleys (Kohler, 1986). Dekalb soils formed from sandstone and shale parent materials under chemical weathering from acid. All Dekalb soils encountered in this study are well drained, and show rapid permeability (Kohler, 1986). Highly permeability soils like Dekalb soils would also be expected to be well aerated allowing for easy outgassing for natural gas (Praagman & Rambags, 2008). The surface layer is a dark gray-brown very channery and sandy loam, approximately 3 inches thick. The subsoil has a thickness of about

23 inches, primarily consisting of brown to yellowish brown very channery loam. The substratum below is approximately 10 inches thick and consists of very channery loamy sand and gray sandstone bedrock can be found below the 36 inch depth of this soil. Slopes of the soils encountered range from 0 – 80° (Kohler, 1986).

Clymer soils were also encountered often in this study. Clymer soils formed from sandstone and shale parent materials under chemical weathering from acid. These soils are typically moderately level to very steep and found on mountaintops or along benchlands (Kohler, 1986). These soils show moderate permeability and should provide average levels of outgassing for natural gas (Praagman & Rambags, 2008). The surface of this soil consists of a dark brown channery loam about 3 inches thick. The subsurface layer below is approximately 23 inches thick consisting of channery loam and sandy clay, darkening from yellowish brown to dark brown from top to bottom. The substratum consists of a very channery sandy loam approximately 18 inches in depth where it meets sandstone bedrock. Total depth to bedrock is about 44 inches (Kohler, 1986).

Klinesville shaley silt loam (KlC) was rarely encountered in this study. This type of soil has a parent material consisting of red shale, sandstone, or siltstone. This is very shallow, well-drained soil that is often found on low hills or ridges. This soil shows moderately rapid permeability which should be well aerated and allow for easy outgassing of natural gas (Praagman & Rambags, 2008). The surface layer is about 4 inches thick and is a reddish brown shaly silt loam (Kohler, 1986). The subsoil is about 8 inches thick and consists of a red shaly silt loam. The substratum is about 7 inches thick consisting of a reddish very shaly silt loam. Total depth to bedrock for this soil is about 19 inches and the permeability is moderately rapid (Kohler, 1986).

Hazleton-Clymer channery loam (HmD) was also rarely encountered in this study. The Hazleton portion of the soil will be described here as the Clymer portion is the same as Clymer soils. This soil shows moderately rapid permeability which should be well aerated and allow for easy outgassing of natural gas (Praagman & Rambags, 2008). This soil is extremely stony, rather deep, and is found on the smooth backslopes of mountain ridges (Eckenrode, 2007). The soil is approximately 58 inches thick with large lithic fragments being rather common throughout. The surface consists of a channery loam about 3 inches thick (Eckenrode, 2007). The subsurface is about 39 inches thick and consists mostly of channery sandy loam. The substratum is about 16 inches thick, consisting of very channery loam (Eckenrode, 2007).

Geology of the Study Area

Understanding the geology of the study area is important because drilling activities could potentially cause gas migration from not only the Marcellus, but more likely the natural gas bearing formations nearer to the surface as they can also be disturbed by drilling activities. It is also possible that these formations naturally produce low levels of combustible gas that migrate to the surface. If this is the case, it would be difficult to identify the origin of any low concentration of combustible gas as either biogenic or thermogenic, as gas migration from either of these sources would appear before and after drilling. Observing temporal and spatial fluctuations (one of the primary methods of this study) in gas migration may provide clues that may assist in determining which of these sources is more likely.

The Marcellus Formation is a black shale containing limestone beds and concentrations of pyrite and siderite (Engelder and Lash, 2011; Roen, 1984). Shales in the Marcellus Formation are considered "black" shales as they show high levels of carbon in

comparison to other shales from the Devonian. The upper sections show a lighter tone and are sometimes referred to as dark grey as carbon levels reduce (Roen, 1984). The darkness of the shales can be attributed to their high organic content and levels of reduced iron and calcium can also contribute to the darkness of the shale (Roen, 1984). Typical mineralogical constituents of black shale include quartz, feldspar, mica, clay minerals, organic matter, phosphate, sulfides, and minor amounts of carbonate. Quartz grains are the most prevalent constituent usually making up 10 to 20% of the shale (Roen, 1984). Organic carbon in the Marcellus is typically around 4%, although that percentage can sometimes be as high as 20% (Roen, 1984).

The Marcellus Formation is found in the northern Appalachian Basin mostly in Pennsylvania with portions of the formation also being in New York, Ohio, West Virginia, Virginia, and Maryland (Ver Straeten et al., 1994). In Pennsylvania, the formation primarily runs through the northern and western parts of the state. Figure 4 shows depth to the base of the Marcellus Formation as compared to the study area, depths exceed 8,000 ft (2743.2 m) at all sample locations. Since the maximum thickness of the Marcellus Formation does not exceed a few hundred feet, the depths drilled within the study area must exceed 7,000 ft (2,133.6 m).

The study area is located in the Deep Valleys section of the Appalachian Plateaus Province that makes up a large share of North Central Pennsylvania. The Pine Creek Valley, also known as the Grand Canyon of Pennsylvania, reaches its deepest point at Waterville which is located near the south-central part of the study area (Reese & Fleeger, 2012).

There are 5 formations that make up the geology of the study area: The Pottsville Formation, Burgoon Sandstone, Catskill Formation, Mauch Chunk Formation, and the

Huntley Mountain Formation (Colton, 1968). Knowing the geology of the study area may help in understanding which geologic formations are likely to play a role if gas migration is found within this area (Figure 5).

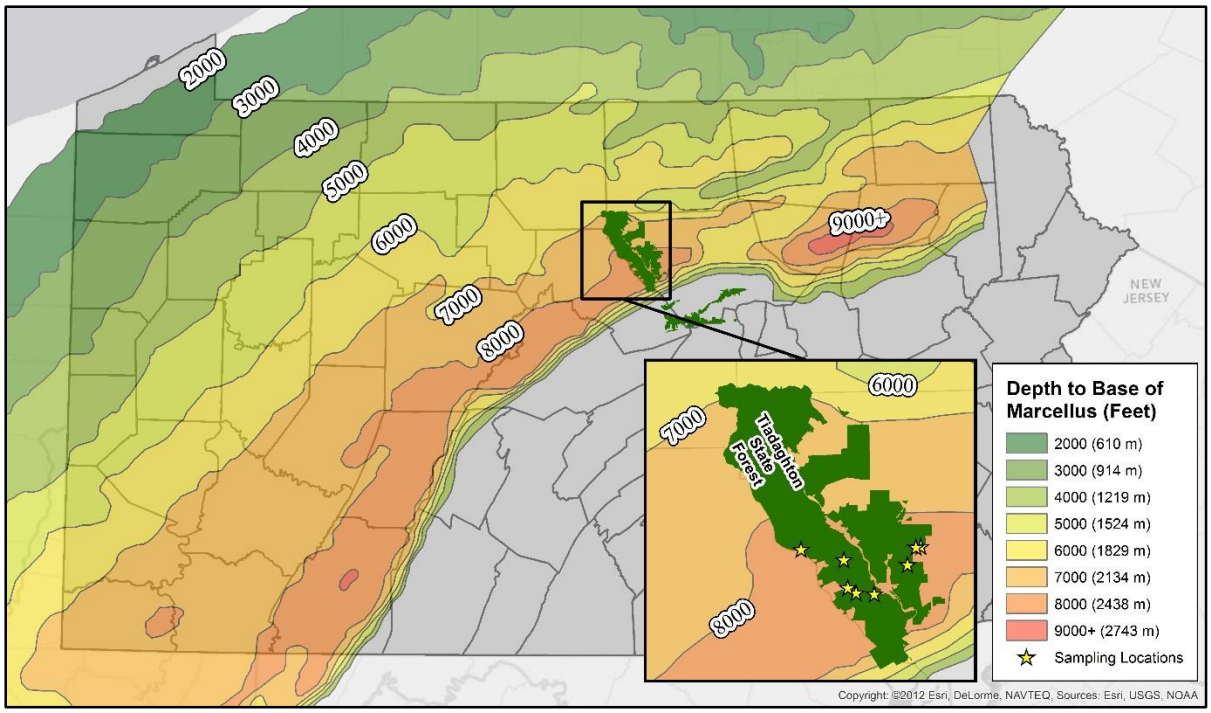
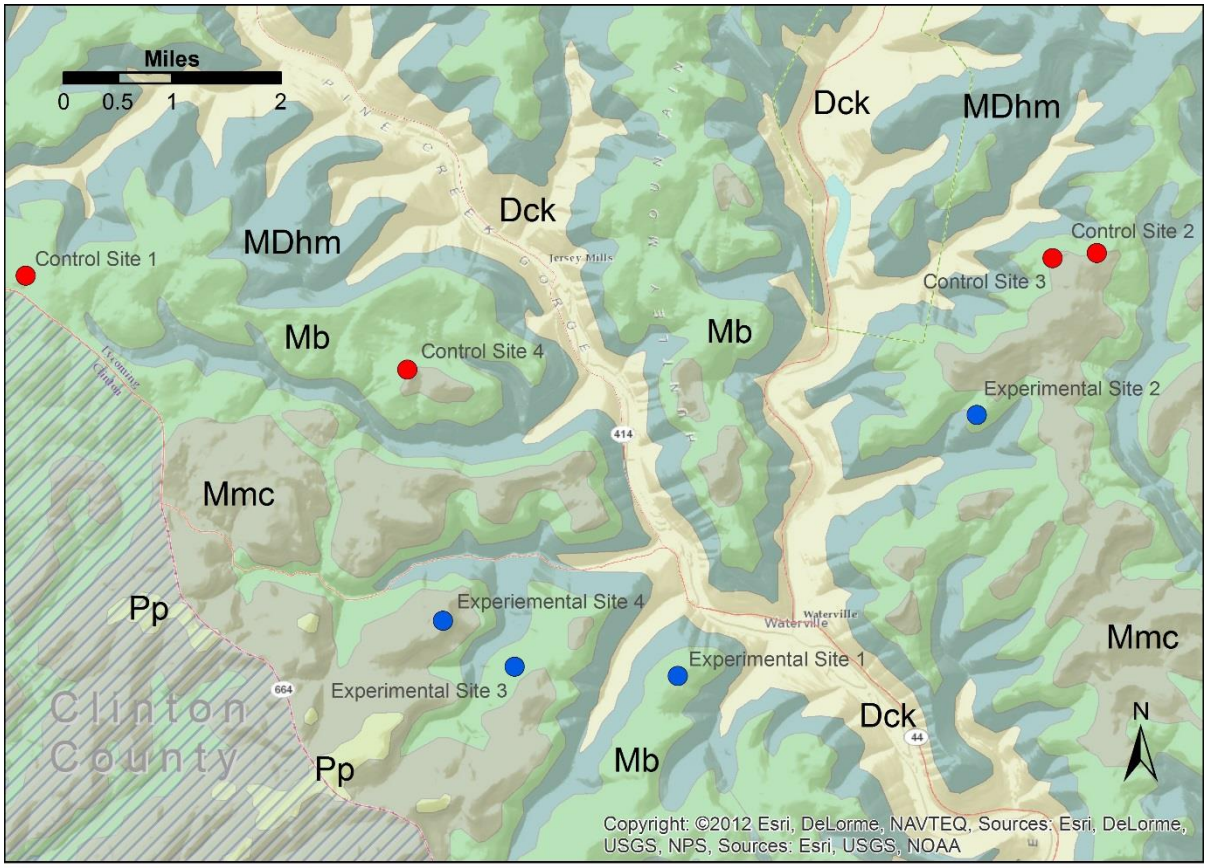


Figure 4: Map showing depth to the base of the Marcellus Formation across Pennsylvania (depth to the gas resources that are economically recoverable). The inset map shows the Tiadaghton State Forest and all of the sample sites indicating the depths at which wells are being drilled in the study area. All of the wells in this study are being drilled to depths exceeding 7,000 ft (2,133.6 m) (Data from: PSU MCOR, 2013).

The Pottsville Formation (Pennsylvanian) is the youngest formation in the study area and the oldest division of Pennsylvanian bedrock in the region (Ashley, 1931). The formation is primarily composed of fine to coarse-grained gray sandstone and conglomerate with thin beds of shale, claystone, limestone and coal (USGS, 2012). Although it is found within the region of the study area, the Pottsville Formation lies at elevations above the study area, therefore no sampling was performed on this formation.



Geologic Characteristics of Study Area

Pp - Pottsville Formation (Sandstone & Conglomerate)
MDhm - Huntley Mtn. Formation (Sandstone & Siltstone)
Mmc - Mauch Chunk Formation (Shale & Siltstone)
Dck - Catskill Formation (Sandstone & Siltstone)
Mb - Burgoon Sandstone (Sandstone & Conglomerate)

Figure 5: Characteristics of the geology for the study area. All sites are up on the high plateaus above the Pine Creek Gorge. Formation summaries are presented below in descending order of surface elevation.

The Mauch Chunk Formation (Mississippian) falls below the Pottsville Formation and several sites in this study have soil gas samples taken where this formation makes up the uppermost layer of the underlying bedrock. The Mauch Chunk consists of grayish-red shale, siltstone, sandstone, and conglomerate (USGS, 2012, Colton, 1968). Since the members of this formation are primarily red shales and limestones they will not have a high organic content like a dark gray or black shale (like the Marcellus), and would not be considered a source rock for natural gas. However, if the formation directly underneath is an organically rich and

natural gas bearing source rock, then the Mauch Chunk Formation would be a potential reservoir or carrier rock through which natural gas could migrate (Krooss & Leythaeuser, 1996).

The Burgoon Sandstone (Mississippian) is below the Mauch Chunk, and all but one of the sites had samples taken where this formation made up the uppermost layer of the underlying bedrock. It consists primarily of medium-grained sandstone, but also includes thin beds of shale and coal (USGS, 2012, Colton, 1968). While the shale and coal beds do provide a possible source of natural gas, these thin beds would not likely generate enough gas to measure as it would likely diffuse throughout the system (Leythaeuser et al., 1982).

The Huntley Mountain Formation (late Devonian to early Mississippian) is the transitioning formation between the Burgoon Sandstone and the Lower Catskill Formation. It consists of a greenish-gray and light olive gray flaggy and fine-grained sandstone, siltstone along with occasional thin red shale interbeds (USGS, 2012; Colton, 1968). As with the other formations discussed, this formation is dominantly clastic and lacks the organic matter needed to produce significant levels of light hydrocarbons. This study includes only one site with samples taken where this formation is present.

Beneath the Huntley Mountain Formation is the Catskill Formation (upper Devonian in age), which consists of Grayish-red sandstone, siltstone, shale, and mudstone. While this formation does contain shale, it, like the other formations above it, is dominantly a sandstone formation (USGS, 2012; Colton, 1968). The greenish gray color of the shale component indicates that it is not as organically rich as a typical dark-grey or black shale, therefore the greenish-grey shale is less likely to produce a measurable amount of gas (Leythaeuser et al., 1982; Fertl & Chilingar, 1988).

Interpreting the Geology Study Area in Terms of Gas Migration

Leythaeuser (1985) found that shale does not generate hydrocarbons indefinitely. As pressure gradients decrease over shale formations, light hydrocarbons migrate from the shale to areas of lower pressure (typically towards the surface), which reduces the overall concentration of light hydrocarbons within the shale over time. Shale formations that are thicker will take longer to reduce in overall light hydrocarbon concentrations (Leythaeuser et al., 1982). As light hydrocarbons migrate from the source rock (i.e., shale) into a carrier rock (i.e., sandstone, siltstone) these gases begin to experience a great level of diffusion and this diffusion intensifies exponentially if aquifers exist above and/or below the source rock as water quickly absorbs and carries away any light hydrocarbons (Leythaeuser et al., 1982). If the carrier rock shows great depth/thickness prior to encountering the source rock, light hydrocarbons diffusing through the carrier rock towards the surface will experience a greater level of diffusion (Figure 6), especially if there is a prevalence of migrating water throughout the carrier rock (Leythaeuser et al., 1982).

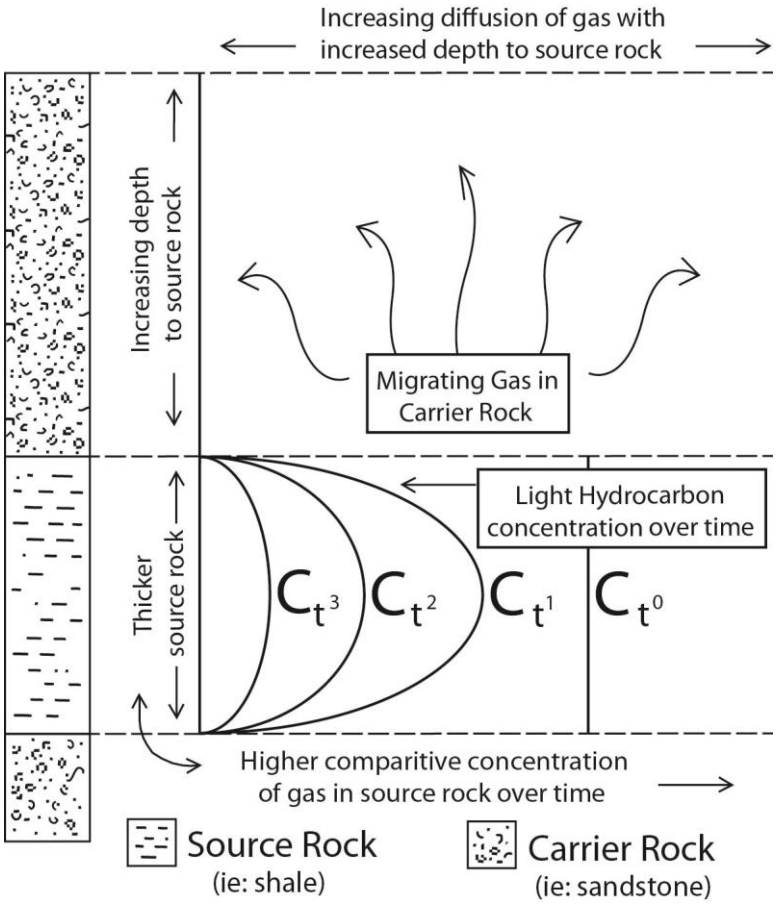


Figure 6: Relationship of shale gas concentrations in relation to the thickness of source rock along with migration of gas through carrier rock as it relates to increasing depth. The concentration of light hydrocarbons depletes quickly with the thinner shale beds like the ones found in this study. Any migrating gas would likely diffuse too much to be measurable as the sandstone formations (carrier rocks) in this study are the predominant rock type and any gas would likely dissolve into the water table and diffuse outward. C_t^0-C_t^3 represents how the concentration of light hydrocarbons in shale decreases over time as they migrate into the carrier rock. (Modified from Leythaeuser et al., 1982)

The geologic formations in this study only contain relatively thin beds of shale; therefore it is unlikely that significant amounts of light hydrocarbons are being generated by them. If drills at natural gas sites are actively penetrating a caprock overlaying one of these shale sources it is still unlikely that a high level of hydrocarbons would make it to the surface as massive beds of sandstone, which likely contain flowing water. This flowing water would likely transport and effectively diffuse migrating gas (Leythaeuser et al., 1982, Pirson, 1946)

from the high plateaus where samples were taken to the lower elevations of the Pine Creek Gorge. Areas at higher elevations typically show lower concentrations of natural gas because water moving down-slope first absorb the gases and then releases them at lower elevations (Figure 7).

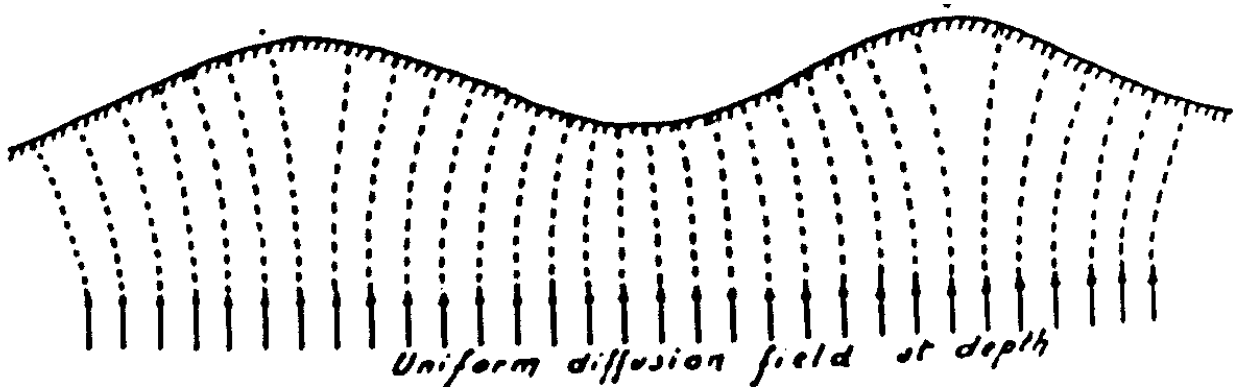


Figure 7: The relationship of elevation change on the diffusion of migrating gas (Leythaeuser et al., 1982, Pirson, 1946). (Figure from Pirson, 1946).

METHODS

The methods employed in this study include spatial and temporal components as data through the use of data collection with a GPS receiver and the subsequent analysis of that data through the use of GIS techniques.

All forms of combustible gas were measured, rather than specifically focusing on natural gas. This is because the process of identifying a gas as natural gas is expensive and determining the gas as being thermogenic or biogenic in origin can never be conclusive due to variations of biogenic gases that can appear to be thermogenic and vice versa. Measuring levels of combustible gas before and after drilling is sufficient as the purpose of the study is to figure out whether drilling activity elevates levels of combustible gas around well sites in general. If measurable amounts of gas are found in locations where they were not found prior to drilling, answering the ancillary questions that were proposed earlier in this paper may provide insights into where combustible gas concentrations may have originated.

The methodology used in this project went through numerous changes throughout the course of sampling and it was not until over halfway through sampling that some of the most significant changes had to be made. The following sections give a general overview the initial methods that were established for this project along with explanations and rationale for how and why some of these methods changed over the course of the study.

Methodology & Timeline

Sampling took place at 8 different sites (4 control sites, and 4 experimental sites). Originally it was expected that there would be three time periods when sampling would take

place: before, during, and after drilling. As the project progressed and well sites were not drilled as expected in the study area, the initial methodology changed. Sampling for this project was performed before drilling at sites that were not drilled (control sites) and after drilling at sites that did experience drilling and hydraulic fracturing (experimental sites). Sampling started in May 2012 and ended six months later in November of 2012.

The control site locations were chosen because they have geologic and environmental characteristics similar to the experimental sites, but these sites were not slated for drilling. Unfortunately, due to a glut in the natural gas market, some of the original sites that were expected to be experimental sites were never drilled during the study period. The purpose of the control sites is to show how gas concentrations at non-drilled sites differ from sites that have been drilled and to reveal possible alternative sources of combustible gas that may occur and vary naturally throughout the study area and throughout the sampling phases.

Datasets

Many different datasets were utilized in this study. Weather data such as barometric pressure and temperature used in the study were gathered online from the National Weather Service. This weather data is based off of the conditions that were recorded for Williamsport, PA.

There were various GIS datasets used in the study. The GPS location for each well site was provided by staff of the Mineral Division of the Pennsylvania Department of Environmental Protection upon request. The digital elevation model used in the slope analysis was obtained using the national map viewer provided online by the United States Geological Survey. Soil and bedrock data for the study area were obtained from the online Soil Data Mart provided by the United States Department of Agriculture Natural Resource

Conservation Service. Aerial Imagery was provided in ESRI's ArcGIS software as one of their base map layers and the various sources for this base map can be found in Table 2.

Table 2: Datasets that were utilized in the analysis of this study. For GPS data collected during this study and the data that was joined to the GPS data (see Appendix III).

Dataset	Source
Site Locations	GPS coordinates provided by representatives of PA DEP
Barometric Pressure	National Weather Service, 2012
Temperature	National Weather Service, 2012
Digital Elevation Model used in ArcGIS to Calculate Slope and Create Contours	USGS, 2011
Soil and Bedrock GIS Data for Lycoming County	USDA NRCS. 2012
Aerial Imagery	ESRI's Source List for World Imagery Layer: ESRI, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, and the GIS User Community

Systematic Sampling Grid

Each site was sampled using a systematic sampling method. This method was chosen because it eliminates any bias in sampling as the sampling pattern stays consistent at each site and because all areas of a site receive the same sampling intensity (Bolstad, 2005). A sampling grid (Figure 6) was created in ArcGIS for each site and centered around the proposed wellbore locations (for control sites these locations were centered based on a GPS location determined through a GIS analysis evaluating viable control sites).

Gas concentrations in the upper 2 feet of soil were sampled in clusters around each drilling and control (non-drilling) site. Within each cluster, 44 observations were distributed systematically using an 83.3-meter sampling interval (Figure 8). The grid covers an area

approximately 500 meters by 500 meters in size. This sampling pattern was considered sufficient to detect stray gas concentrations associated with drilling activities, as Osborn (2011) showed that gas concentrations are often higher in water wells within 1000 meters of gas wells with the highest concentrations being nearest to the gas wells (Figure 1).

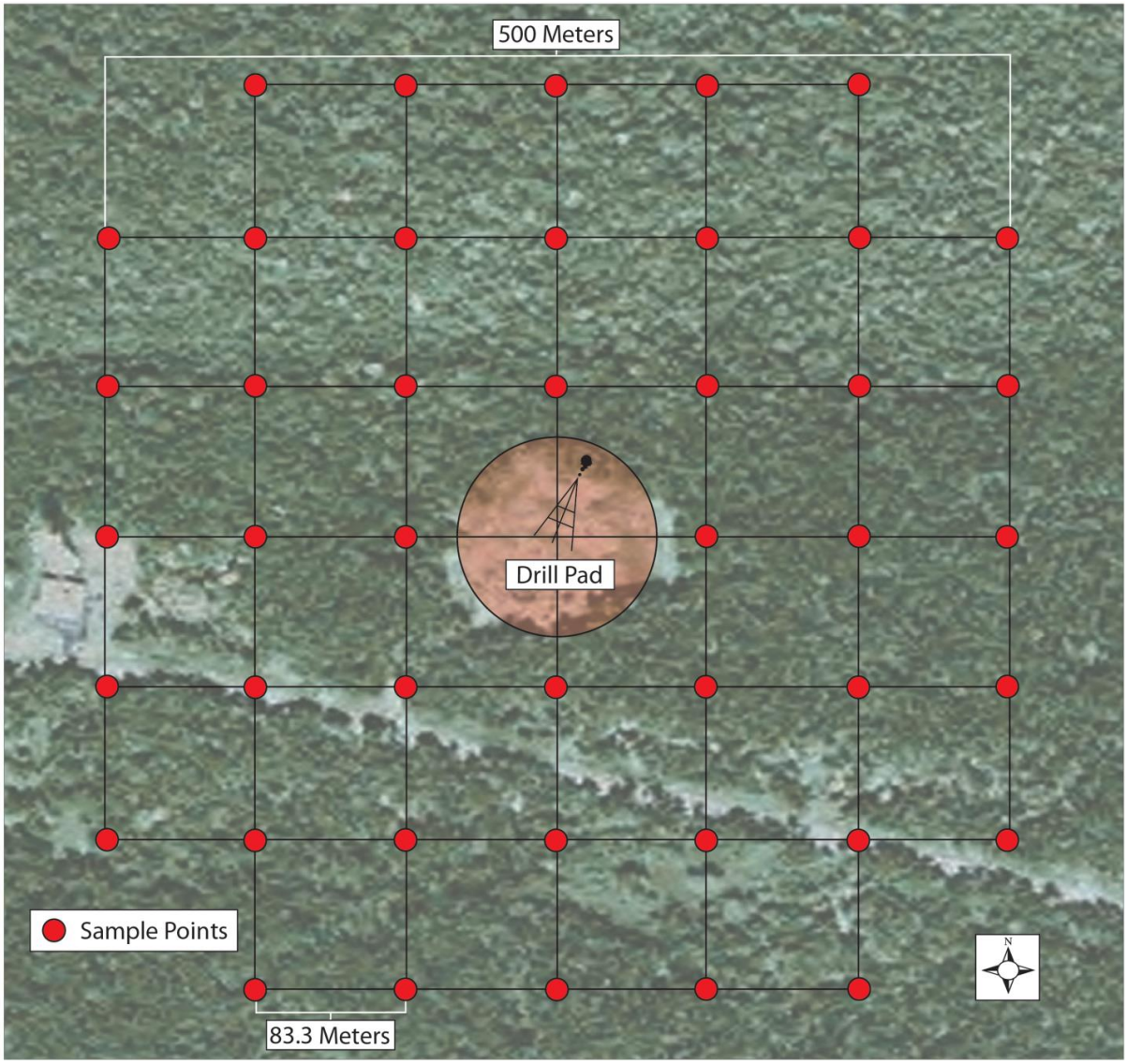


Figure 8: The sampling grid overlain on an aerial image of a drill site. The grid at each site has 44 different sample points in the 500x500 meter sampling grid. The points at the corners of the grid are removed to approximate an annular pattern and to save time in the field.

Evaluating Sites and Determining the Final Sampling Locations

The Pennsylvania Department of Environmental Protection (PA DEP) was the primary source for locating sites that would be drilled in this study. State forest land is being used for drilling in various locations in Pennsylvania where thousands of wells have been, and will continue to be drilled. Information on the drilling activities on state forest land is public information and can be readily accessed through the PA DEP.

In the fall of 2011 representatives from the Mineral Division of the PA DEP were contacted in regards to this thesis research and they confirmed that access to sites could be obtained. DEP staff also had a general idea of when these sites would be drilled. The Mineral Division of the PA DEP provided a list of 19 different sites in the Tiadaghton State Forest that were expected to be drilled during the study period. Before access to the sites could be granted, however, the author and his advisor needed to submit a signed research proposal describing the nature of research along with Pennsylvania Natural Diversity Inventory (PNDI) reports and research conditions. PNDI reports were then created for each of these sites using an online resource called the PNDI Environmental Review Tool (PNHP, 2012). Appendix I includes an example of 1 of the 28 PNDI reports completed for each site (completed for 19 drilling sites and the 9 control sites that could have potentially been sampled). Subsequently, a letter confirming tentative approval of the study was received; this letter was the official documentation indicating approval from DCNR (Appendix II). This letter was used on a couple of occasions in order to gain access from security posts upon entering access roads to the well pads. The process for determining viable sites that would work in the study was a not always an exact science, but rather the results of calculated

observations from a slope analysis and through periodically stopping at the well pads and observing progression towards drilling.

Initial Sampling Locations

In January 2012, DEP provided 19 sites that were considered prime candidates to be drilled in 2012 (Figure 9). Of these, six were removed from consideration because the terrain was considered too steep to traverse safely. These 6 sites have steep slopes in excess of 50^{o} (Appendix V) that would prove very challenging to sample. Four more sites were removed from consideration during reconnaissance trips between March and July because the sites were already in the process of being drilled, which precluded the observation of "before" drilling conditions.

Certain sites were removed from consideration because recent aerial imagery indicated the control sites were occupied by newly constructed well pads. Based off of the findings by Osborn (2011), 1000 meters was set as the minimum threshold distance between any sample site and any other well site that has already been drilled nearby. Proposed sampling sites with drilled wells within this 1000-meter threshold were removed from sampling consideration. Providing this buffer is a precaution that is being taken to reduce the possibility of encountering concentrations of natural gas straying from nearby sites. A few sites were removed from consideration due to this proximity to previously drilled well sites.

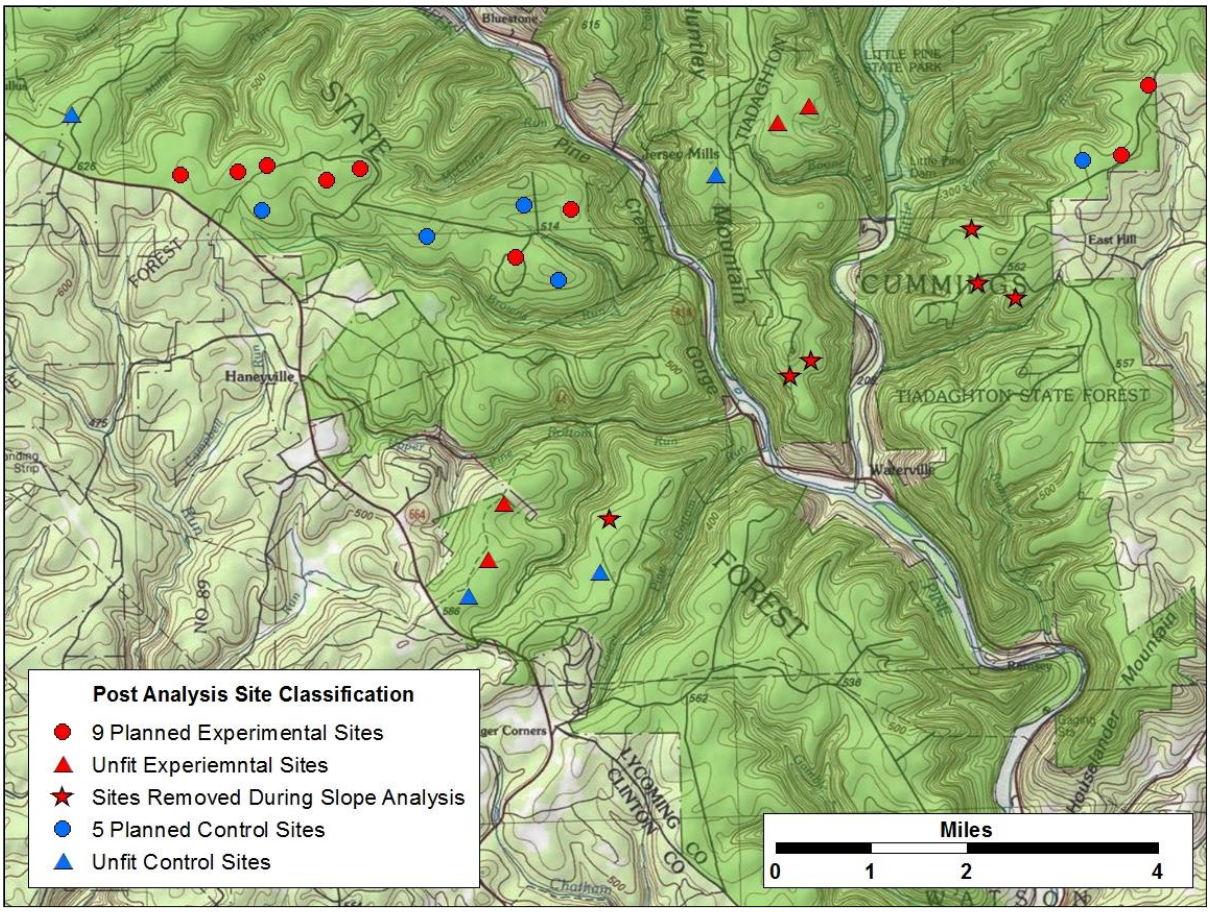


Figure 9: The 19 proposed well sites initially considered for this study. Six sites were deemed unfit for the study after a slope analysis was performed in ArcGIS. Four more experimental sites were determined unfit for the study after 3 reconnaissance trips to the study area.

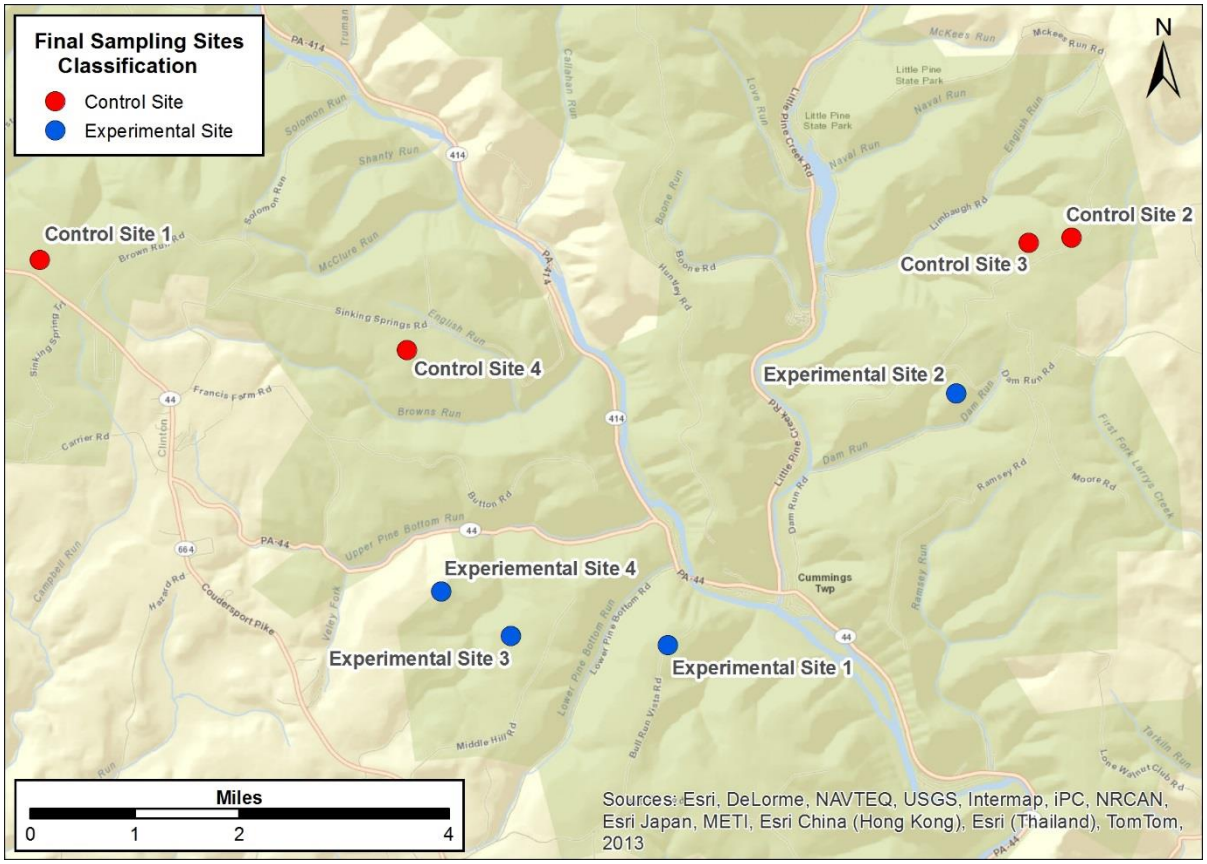


Figure 10: The final 8 sites chosen for sampling combustible gas. The green area represents the Tiadaghton State Forest. (ESRI Topographic Basemap)

The experimental sites were chosen later into the study due to a lack of drilling. Early in September, the PA DEP alerted the author of 4 sites that were to be hydraulically fractured in the months of September and October of 2012. Figure 10 shows the final 8 sites that were chosen for sampling.

Locating Field Sites

The use of a Trimble GeoExplorer 6000 series XH GPS receiver was the primary tool utilized for locating appropriate sample locations. The handheld receiver proved to be remarkably reliable throughout the project as there were very few instances when GPS connectivity could not be attained; having the additional access to the GLONASS satellite

system (an upgrade from the previous version of this receiver) is surely the reason for the excellent GPS connectivity and data quality as the author had issues attaining GPS connectivity using the previous version of this receiver during an internship. Last but not least, a digital reference map of the study area overlain with the sampling grids was loaded onto the GPS receiver to assist way-finding in the field.

A data dictionary was created for data collection and uploaded to GPS handheld. The dictionary contains various different fields that are useful for data collection and understanding the environment at each sampling point. Fields contained in the dictionary include: gas concentration, bar-hole depth, and a comments section to explain any unusual conditions or additional information.

Measuring Combustible Gas in the Soil

A GMI Gasurveyor 522 combustible gas indicator (CGI) was the primary tool for taking measurements of combustible gas in the soil. The CGI is a pump that contains two platinum filaments that sustain an electrical current. When combustible gas passes over the filaments, the filaments heat up which increasing the resistance of the electrical current. The change in resistance is measured by the computer in the CGI which portrays this information on a digital display for the user (Figure 11).

Connected to the CGI is a hose that is approximately 3 feet in length that is connected to a probe that is two feet in length (Figure 12). Prior to sampling on each day, the CGI was checked to make sure it was calibrated properly using two pressurized bottles containing a known concentration of methane. To do this, a hose is run from the bottle into the CGI. Then, as the gas runs through the CGI, the measured readings displayed on the CGI are compared to the known gas concentration in the bottle. Two bottles were used for this to assure proper calibration; the first bottle contains 25,000 ppm methane (2.5% methane gas) which is a relatively low concentration. The second bottle contains the highest possible methane concentration at 1,000,000 ppm (100% methane gas).

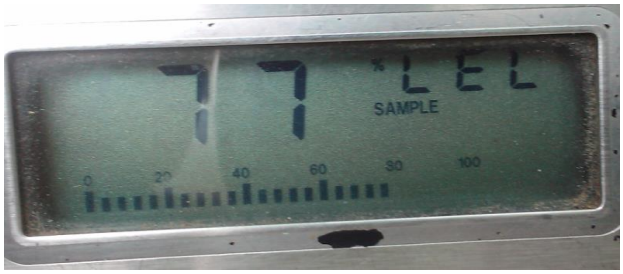


Figure 11: The interface of the CGI shows combustible soil gas readings in terms of the lower explosive limit (LEL) of combustible gas.

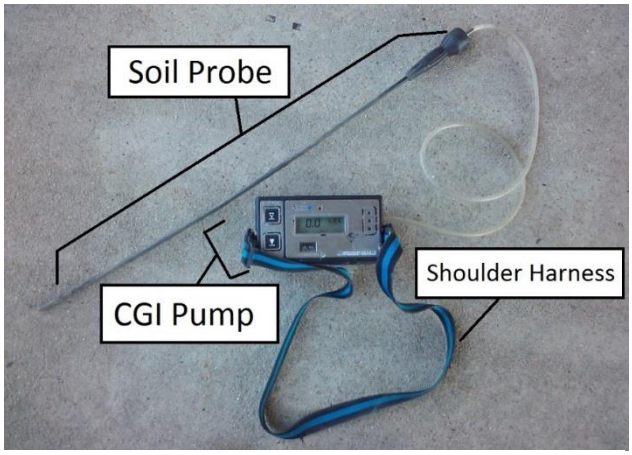


Figure 12: Combustible Gas Indicator (CGI) is the primary tool that was used to take measurements of combustible gas.

Readings on the 25,000 ppm bottle were somewhat high, but consistent with readings ranging from 26,500 to 27,000 ppm, with exceptions on the first two days of sampling where the readings were 28,500 and 29,000 ppm, which may be because 100% methane bottle was used first during these calibrations and left residual gas in the calibration hoses possibly altering the subsequent gas readings. The 100% gas readings were remarkably accurate with readings ranging from 99 to 100% gas (Appendix IV).

To take measurements, a tool called a plunger bar (Figure 13) was used to hammer a three quarter inch diameter hole (bar-hole) into the soil with a depth goal of two feet. If there was difficulty reaching the depth of two feet, a lesser depth was used to take the measurement and this was noted in the comments section on the GPS receiver being used during data collection. The probe was then placed into the bar-hole and the CGI measured the concentration of combustible gas in the soil for 10 seconds. If a non-zero reading was found, the reading was taken until the values started to fall and this peak reading would then recorded into the GPS receiver. The peak reading was recorded because this would be the potential peak reading that could be found in a confined space if the gas migrated into it, as atmospheres of the confined space and the soil want to reach a combustible gas concentration equilibrium.

Figure 13: The plunger bar was used to hammer holes into the soil at a goal depth of two feet. The holes were then probed and gas was pumped from the soil by the combustible gas indicator.

Data Analysis

The primary focus of the analysis was on the distribution of gas around each drill site. If there were no significant differences in combustible gas concentrations at experimental sites as compared to control sites, the focus of the analysis shifted to answering the ancillary research questions:

- If concentrations of combustible gas in the soil are observed to increase after drilling activities begin, are there any spatial trends or patterns in these concentrations that can be observed?

- If concentrations of combustible gas are observed; does the spatial pattern of variation indicate the reason(s) why the gas is migrating?

- If concentrations do not show significant changes, but there are baseline natural gas concentrations, how do these baseline concentrations vary based on: soil type, underlying geology, temperature, barometric pressure, and the time of day that samples were taken.

Data collected using the GPS receiver first underwent post processing using Trimble® GPS Pathfinder Office® software. Post processing of GPS data was completed after the data was transferred from the GPS receiver to a computer. From the computer, post-processing software was run to improve the locational accuracy of the GPS data by comparing the GPS data points collected by the receiver to points that were simultaneously collected by nearby continually operating reference stations. Once post processing was completed, the data was imported into ESRI ArcGIS Desktop 10.1® for analysis. Inverse Distance Weighted (IDW) interpolation was used to reconstruct the field of combustible gas in the soil. In this algorithm, each output cell is given an estimated value based on the values at nearby sampled locations, which are weighted by the (inverse) distances between sampled locations and the cell location (Bolstad, 2005). Sampled values that are closer to the cell will have a greater influence on the value estimated for the cell as compared to more distant samples (Bolstad, 2005). The algorithm can be modified so that cells are only influenced by a specified number of samples or by samples that fall within a specified distance. In this study only the 6 nearest sample points were used to interpolate each cell as the sampling points are dispersed at relatively far distances from one another and therefore the influence of more distant samples will be marginalized. The power feature of the IDW tool in ArcGIS can also be used to influence the significance of surrounding points on the interpolated cell values. For this study the power value was set at 2, which is the default in ArcGIS.

The output cell size used in the IDW tool of ArcGIS is used to determine the cell size of the output raster. Using a cell size finer than the input resolution will not produce more accurate data than the input data, but it can be helpful in avoiding blockiness in the output raster. Since IDW is a gridding algorithm, using a cell size that is too fine can consequently produce visual artifacts (i.e., bulls-eye patterns and sharp edges) in the output raster which should be interpreted as errors as they do not accurately represent the input data. The input resolution in the case of the sampling grids used in this study is approximately 83.3 meters. An output cell size was set to 10 meters, which was coarse enough to avoid most visual artifacts yet fine enough to avoid unpleasant blockiness.

$$Z_j = \frac{\sum_i \frac{Z_i}{d^n_{ij}}}{\sum_i \frac{1}{d^n_{ij}}}$$

Equation 1: Equation for Inverse Distance Weighted Interpolation (Bolstad, 2005).

Bolstad (2005) expresses the Inverse Distance Weighted interpolation equation as seen in Equation 1. Zj is the estimated value for the unknown point; Zi is the value of the known point; n is a user selected exponent representing influence of nearby points; Dij is the distance from the output grid cell to the sampled location. Also, i is a counter that is used to keep track of the 6 sampled values in the interpolation neighborhood around each output cell.

IDW interpolation was used over other methods for a couple of reasons. IDW can effectively represent a gridded field of values without creating ridges which are often created using other interpolation methods. Also, IDW is appropriate because cells that fall within the same geographic location of the sample that they were generated from will hold the same

value as that sample, which is not always the case with other interpolation methods (Bolstad, 2005).

SAMPLING AND RESULTS

The sampling methodology was successfully performed at all sites that were sampled. From time to time a sample location could not be reached; if this was the case, the sample was taken at a location as near as possible to the intended sample location. Instances where this happened were relatively rare and typically occurred along steep slopes, in extremely dense vegetation, or where proposed sampling locations fell within the confines of a water impoundment. Each sampling site will be discussed individually in the following section.

Control Sites

As mentioned earlier in the paper, each of the sites were visited and examined for their viability in this study. Initially it was figured that the best way to determine which sites to sample first would be through visiting each of the sites and look for materials that indicate that they will be drilled soon. What was originally considered to be Phase 1 sampling had been done at three experimental sites that showed evidence that they may be drilled in the near future, unfortunately these sites were never drilled as a glut in the market for natural gas caused a slowdown in drilling throughout the state. These three sites (originally to be called experimental sites 1, 2 and 3) were later reclassified as control sites (control sites 1, 2, and 4).

Control Site #1
(Sampled 05/13/2012)

The first site, sampled on May 13th, is at the end of Browns Run Road and was considered the most ideal site for sampling. Materials on the site indicated that it would be drilled soon (Figure 14). The vegetation was rather sparse which facilitated easy and accurate

sampling. Elevation change at the site was minimal which allowed for all sample points to be taken at their proposed locations.

Figure 14: Photos of dryer station and transmission lines. On the left is a dryer station which typically indicates that a site will be drilled soon (according to a knowledgeable state forest worker who works closely with the drilling activities). Dryer stations are used to reduce the water vapor from extracted gas as this water can cause blockage of compressed natural gas in fueling systems and can contribute to corrosion in storage vessels and piping. On the right is the end of a transmission line which will eventually be connected at the pad.

The Mauch Chunk Formation was the only bedrock type throughout the sampling area. Samples were taken in 3 different soil types (DkB, CnB, and CnD), but there does not appear to be any variation in gas concentrations based on soil type.

Measured concentrations were relatively low with the highest reading being 5150 ppm, which is approximately 1/10th of the concentration that is required for combustion. An isoline map was created to help visualize where the concentrations were higher and lower (Figure 15). Non-zero readings were more prevalent later in the day.

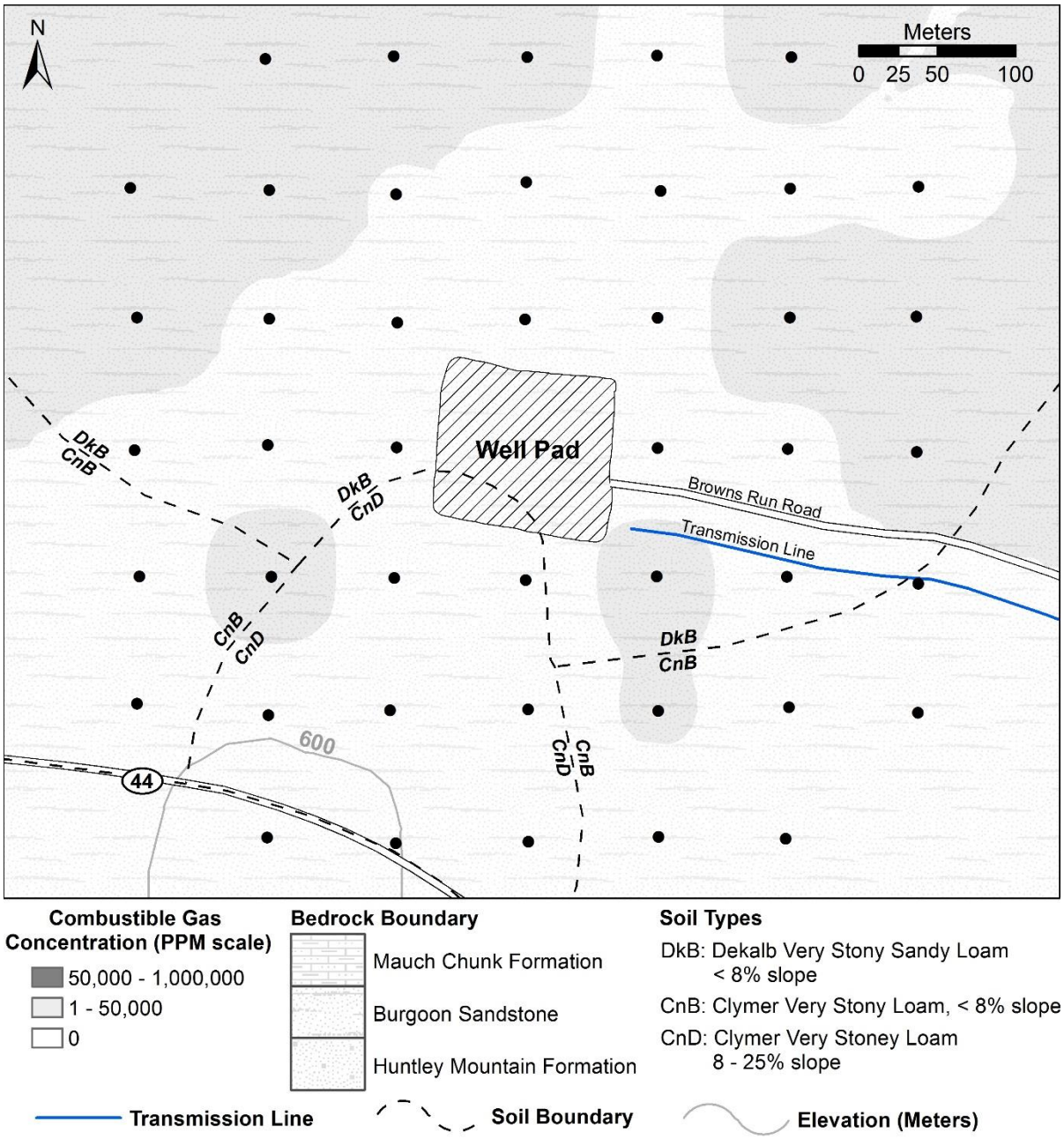


Figure 15: Map of Control Site 1. Combustible gas concentrations at the first sampled site showed low readings, most of which were less than 500 ppm. The highest reading measured was 5150 ppm.

Control Site #2
(Sampled 06/02/2012)

The second site sampled on June 2nd off of Limbaugh Road was sampled with very few issues. There were materials on the site that indicated that it would be drilled soon which included a dryer station and materials that were eventually used to build a natural gas transmission line (Figure 16). The vegetation at this site was denser than the vegetation at Control Site 1 and which slowed sampling progression. The vegetation was remarkably dense in places; pushing and navigating through these sections proved to be far more time consuming than in the sparsely vegetated areas.

Figure 16: Water impoundment and well pad. The water impoundment (left) was quite large at 6 acres and prevented 2 samples from being taken and 2 others from being taken at their proposed sampling location. Samples taken in the disturbed soil next to the perimeter fence showed the highest soil gas levels. The well pad (right) appeared promising for future drilling with a newly painted dryer station along with rolls of plastic piping nearby which were utilized to create a transmission line in the months following.

One sample point could not be collected at the desired GPS coordinate because the mountainous slope prevented access. This was not an unforeseen issue as the slope analysis performed in ArcMap did indicate that slope at this point was in excess of 40°. The sample point was then taken at a different location nearby.

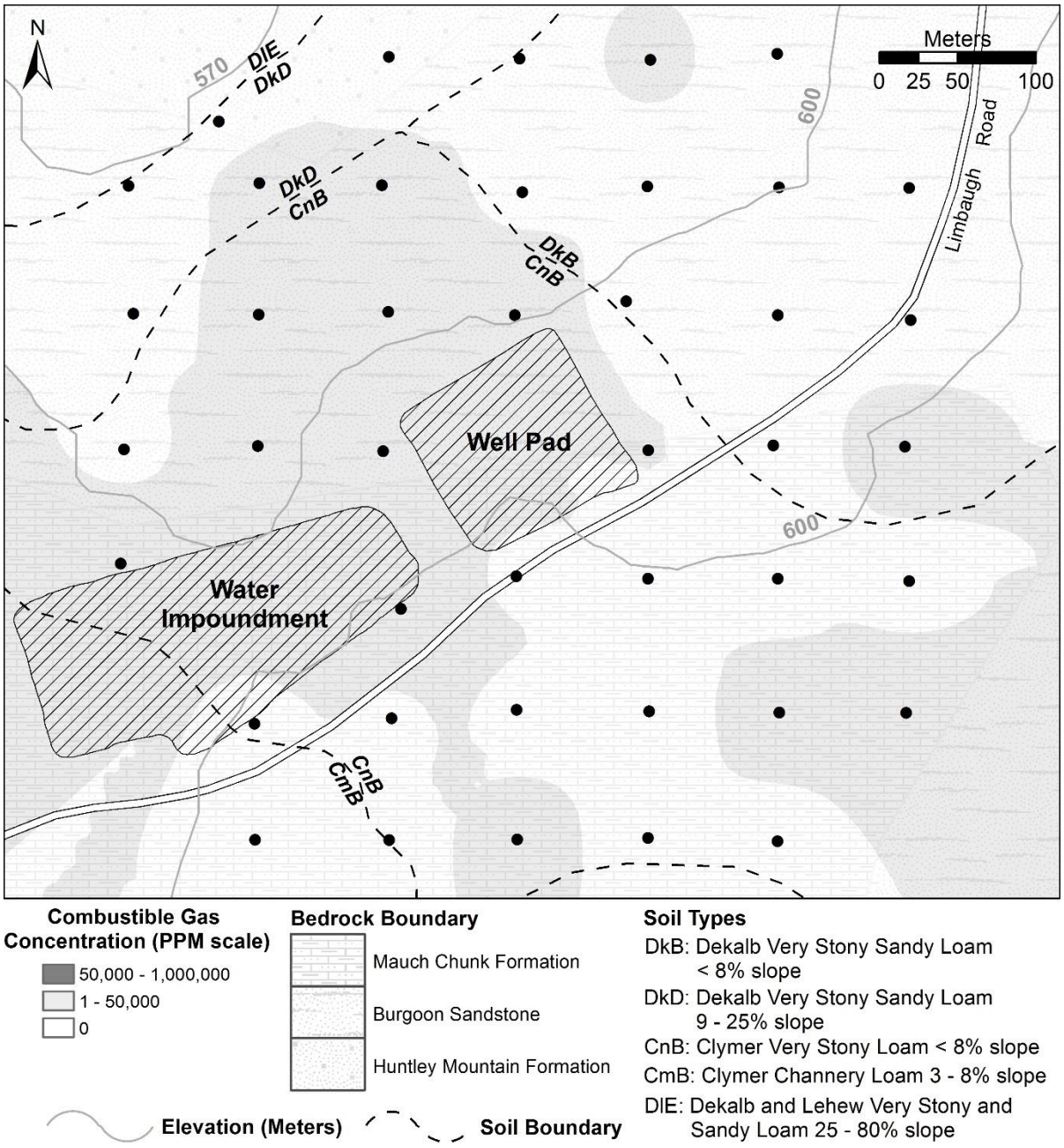


Figure 17: Map of Control Site 2. Combustible gas concentrations at the second sampled site showed low readings, most of which were less than 500 ppm. The highest reading measured was 5500 ppm next to the impoundment.

There were 2 other points that could not be collected because they fell within the area of a water impoundment which is a large artificial lake (GIS analysis shows the impoundment is 6.0 acres and the pad takes up 2.9 acres) used as a source of water for drilling activities

(Figure 17). Two other samples were impacted by the water impoundment; these samples were still taken, rather at locations near to the proposed sample coordinates.

Samples were taken on 3 different rock formations with the majority of the samples taken on the Mauch Chunk and Burgoon Sandstone formations while only 2 samples were taken on the steeper slopes that crossed into the Huntley Mountain Formation. Samples were taken in four different soil types (DkB, CnB, CmB, and DkD). As with Control Site 1, there does not appear to be any variation in combustible gas concentration based on soil or bedrock type.

Measurable concentrations of combustible gas were found at the site. Concentrations were relatively low with the highest reading being 5500 ppm in soil that was recently disturbed during the construction of the water impoundment.

Control Site #3
(Sampled 06/23/2012)

The third site, sampled on June 23rd is the only site sampled that was initially intended to be a control site as the other control sites were relabeled from experimental sites that were never drilled. Since there are no plans for drilling on this site, it was the only site in this study with no well pad.

The vegetation at this site was comparable to that at Control Site 2. The vegetation was dense in places and a couple sample points could not be measured at the proposed sample locations; these were sampled nearby due to vegetation density. That said, the overall accuracy of the samples taken at this site were likely the best of all of the sites due to the lack of steep slopes and because there were no water impoundments. There was very little elevation change at this site (Figure 18).

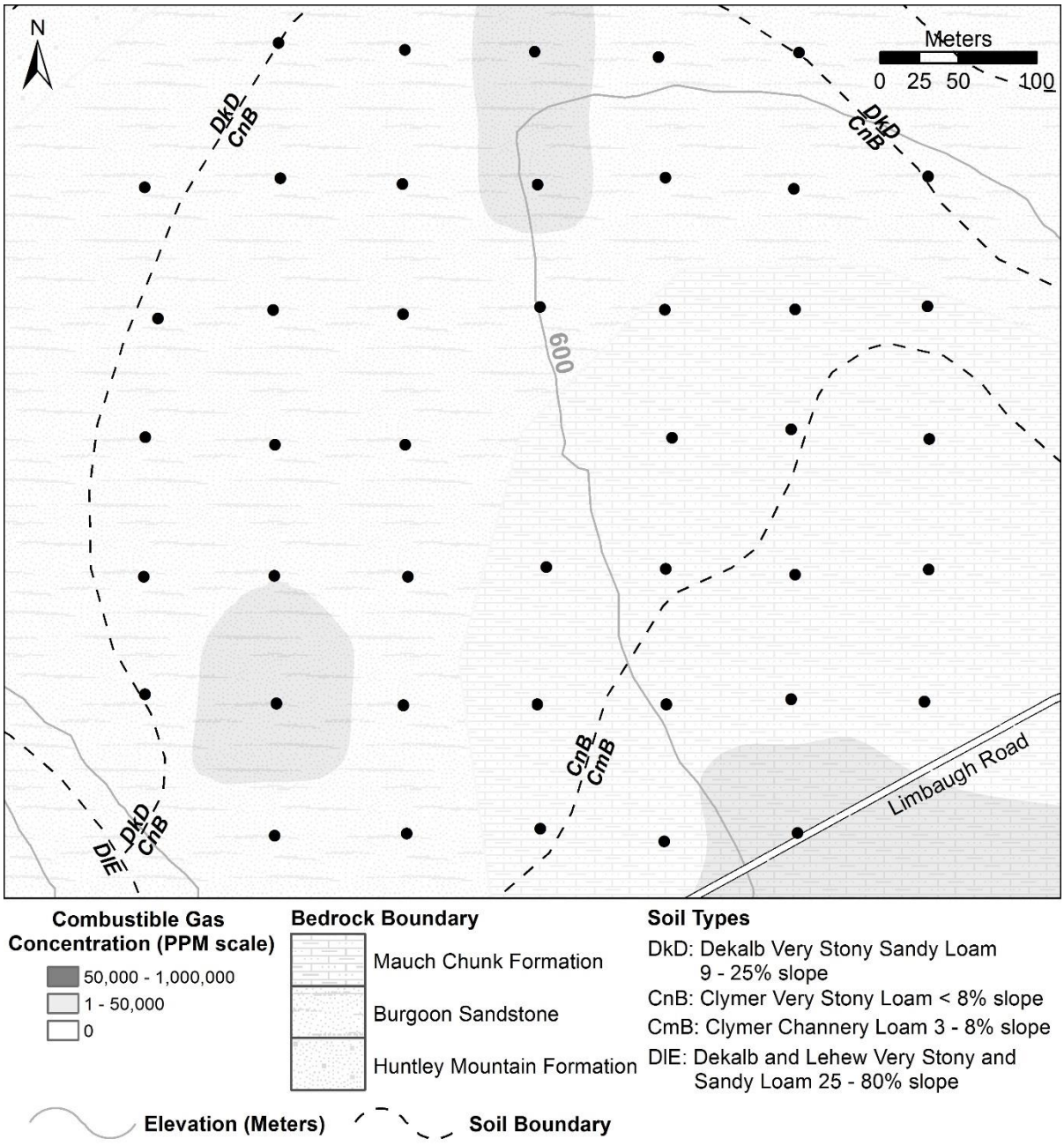


Figure 18: Map of Control Site 3. This site showed very few non-zero combustible gas readings with the highest reading taken along Limbaugh Road being 3200 ppm. There does not appear to be any spatial pattern or trend in the non-zero gas readings.

Samples were taken on the Mauch Chunk and Burgoon Sandstone formations. Samples were taken in 3 different soil types (CnB, CmB, and DkD). Overall, there were very few non-zero readings and amongst these readings there does not appear to be any variation

in combustible gas concentration based on soil or bedrock type. Of the measurable readings the highest was 3200 ppm, which is not a particularly high reading. This reading was taken alongside the road in soil that had been recently disturbed in the construction of the road.

Control Site #4
(Sampled 08/11/2012)

The final control site, off of Sinking Springs Run Road, proved to be one of the more interesting sites. There was equipment at this site which included rolls of transmission piping along with a couple trucks and a compact track loader which is why this site was initially considered as an experimental site. In the months prior to sampling, a right-of-way was cleared and a transmission line was buried along the access road leading to the well pad. As with Control Site 2, this site also has a water impoundment. The impoundment could not be digitized as it had not yet been created when the most recent aerial imagery was taken (Figure 19). The impoundment prevented one sample from being taken and another sample had to be taken alongside the perimeter fence as the proposed location could not be reached.

Figure 19: Image of the Control Site 4 water impoundment. This does not appear in the map of the site (Figure 20) as it falls to the northeast of the well pad.

While vegetation was rather sparse throughout much of the site, there were sections that proved difficult to sample due to vegetation. Elevation at the site does not show significant change as is seen in Figure 20, although it was surprisingly hilly in places, which

is not evident when viewing the map. Two samples in the southeastern part of the study area were sampled, but the data was lost during post processing and were never recovered, those samples did not show non-zero soil gas readings.

The final sample taken on this day could not be taken in its proposed location because it would need to be taken in the middle of the access road. Therefore, the sample was taken a few feet west of the access road as a gravel lot leading to the water impoundment was east of the road and also prevented sampling. The sample was taken where a right-of-way was cleared for a natural gas transmission line and the soil was rather hard-packed making it difficult to punch bar holes. The initial sample was measured a 150,000 ppm sustained reading (this is the upper explosive limit of methane, 15% gas) which was completely unexpected. Upon reviewing the surroundings, the reason for this high reading became apparent as the blue pylons following alongside the road indicated the natural gas transmission line ran directly below where the sample had been taken. A second bar hole was arduously created and probed a few feet to the north of the initial one with a sustained reading of 100,000 ppm.

There was a strong desire to continue sampling, but the current methodology was not developed for a scenario involving point source gas concentrations. Mapping concentrations over a gas line leak would require many additional samples to be taken in a much tighter grid and would not help in developing answers to the questions proposed in this paper.

A gas leak over a transmission line is not uncommon and in this case a gas line inspector would not consider this to be a serious issue as there were no confined spaces nearby that could become saturated with gas and become a potential explosion hazard and

imminent danger to anyone. See Appendix VIII for the author's note on the significance of a leak such as this one.

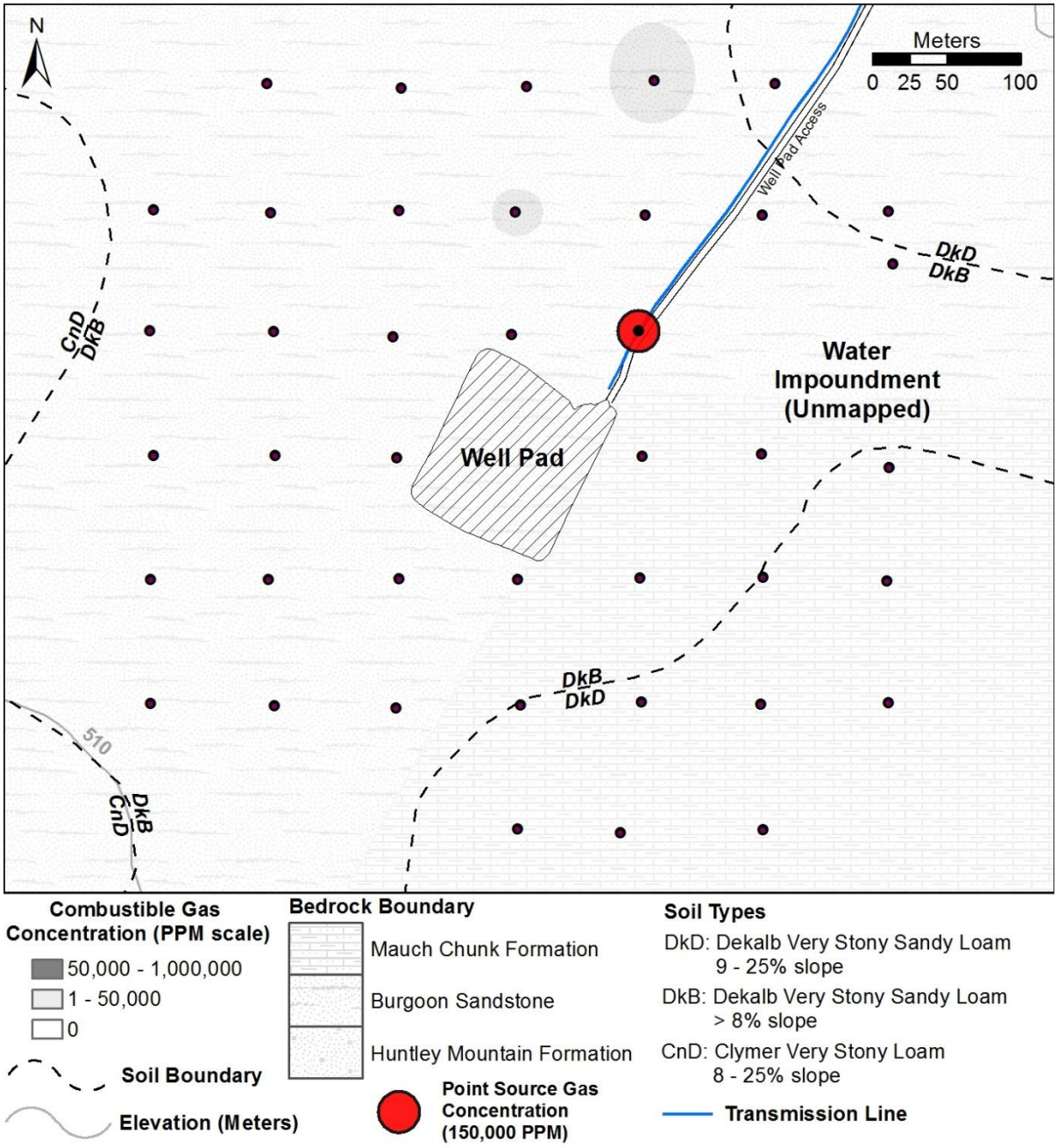


Figure 20: Map of Control Site 4. One of the sampled gas readings taken at Control Site 4 was taken over a transmission line that runs parallel to the access road; this sample showed a combustible gas reading of 150,000 ppm.

Samples were taken on the Mauch Chunk and Burgoon Sandstone formations. Samples were taken in 3 different soil types (CnC, DkB, and DkD). Overall, there were only 4 non-zero readings and amongst these readings there does not appear to be any variation in combustible gas concentration based on soil or bedrock type.

The extremely high point source gas readings found over the transmission line did not produce the desired result when the value was interpolated in ArcMap using the methodology designed for this study. The interpolation method is most accurate when samples nearby have relatively similar values; in this case the extremely high value recorded over the transmission line dwarfs the lower surrounding readings and effectively surrounds them with elevated non-zero values when using IDW interpolation.

Control Site #1
(Resampled 09/30/2012)

Control Site 1 was resampled in late September to observe any differences or changes in soil gas concentrations from the time it was initially sampled 3 months earlier in May 2012. No observable progression towards drilling was made at the site as it was essentially the same as when it was initially sampled. This was the only site that experienced rain during the sampling process where rain persisted for ~45 minutes and sampling was postponed during this period. Sampling restarted at 12:45 pm, and the rain did not appear to affect sampling or readings. The samples were taken in a different order than during the first sampling period as samples were initially taken along the outside of the site rather than the inside. This was because the access road was gated off about a mile back from the site (according to a state forest ranger, this is done to prevent vandalism); therefore the site was accessed from Route 44 to the south.

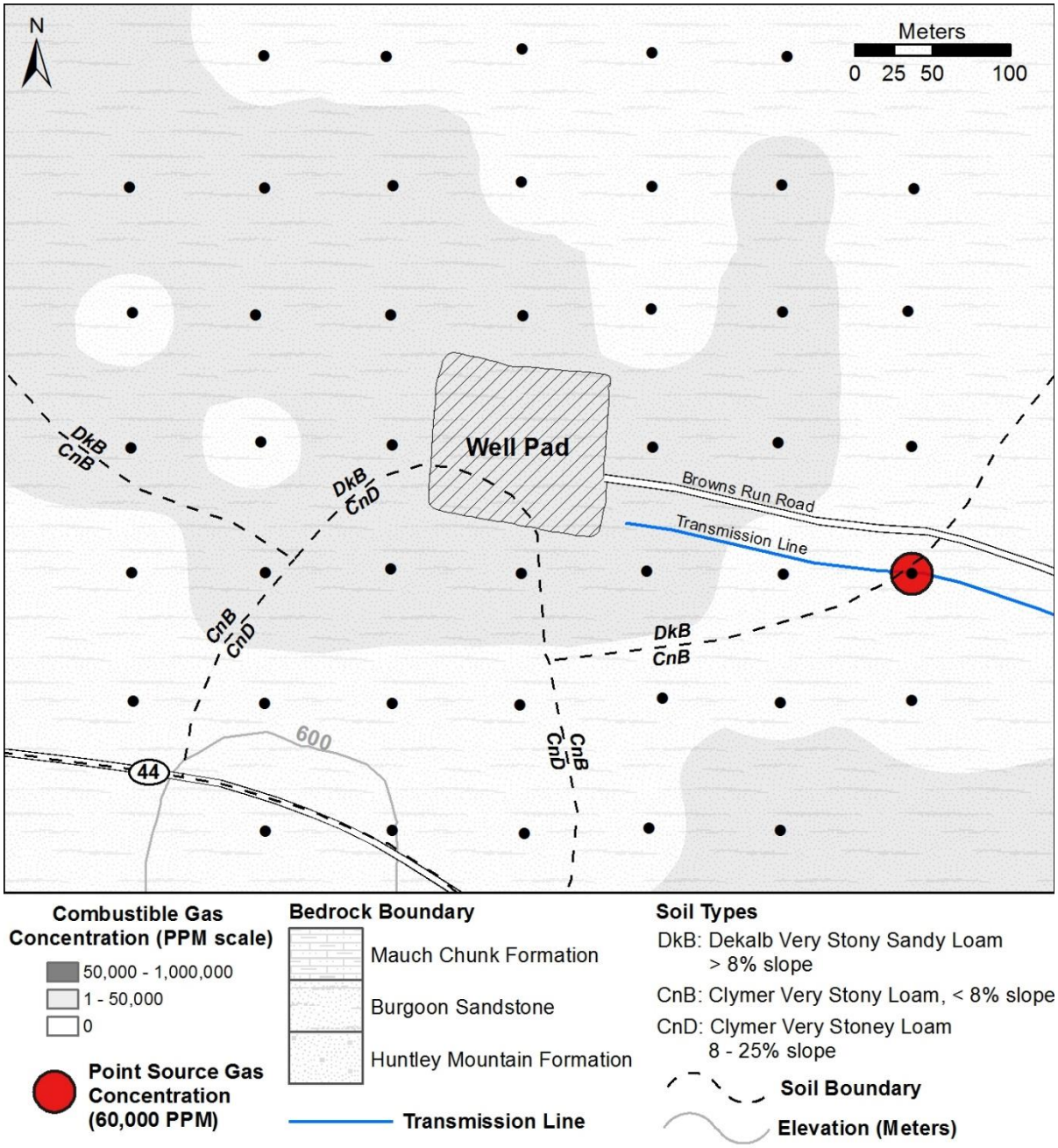


Figure 21: Map of Control Site 1, resampled on September 30th, 2012. A sample was taken at the proposed location over a transmission line (during the initial sampling on May, 13th this sample was taken further south due to recent construction activity). This sample was taken directly over the transmission line and showed a value of 60,000 ppm.

When this site was initially sampled, there was a sample that was not measured at the proposed GPS location due to excavation activities near the transmission line. For this second

sampling phase, the sample was taken over the gas line and showed a reading of 60,000 ppm (Figure 21).

It was at this site that a sampling trend became apparent. It was found that samples taken later in the day showed a greater frequency of non-zero readings. This trend was apparent at other sites too, as non-zero values sampled later in the day at most sites showed very similar readings to one another. This site strengthened the earlier evidence of the sampling trend seen at other sites by showing a prevalence of concentrations that were measured at 1150 ppm. This site was the first to implement a method to confirm the viability of the sampling method used in this study, as will be discussed in the following section.

Test to Examine Viability of Sampling Method

During the defense of the proposal of this thesis (on 09/16/2012) the viability of the sampling method was questioned. The problem that arose was that all non-zero readings may be from an unknown point source (e.g., decaying plant matter or a point source methanogen producing combustible gas at the sampling point) rather than an area source (e.g., a methane producing shale formation, a continuous field of methanogens, or readings from the widespread diffusion of fugitive gas from a gas well). A test was developed to examine whether or not the sampling method being used in this study is viable.

To perform the test, first a non-zero value had to be encountered. Next, additional samples were taken approximately 3 feet to the north, south, east, and west of the original sample. If non-zero values were found around the initial sample, the sample was considered an area source gas concentration.

A point source gas concentration should not migrate far from its source, especially if the measured value of the concentration is low. If combustible gas readings are found that

show a low value, that gas should not migrate a very far (distances less than a foot or two depending on the reading) if it is point source concentration. Conversely, an area source concentration will likely show similar non-zero readings at distances beyond a few feet from the originally sampled location.

During this test, the samples were specifically selected if they showed low readings. Therefore, if similar non-zero values are found even a few feet away they are not likely from a point source (stumps and other large decaying plant matter was avoided in all cases to avoid possible readings from these large point sources). This test was performed at various sites, but 4 of the 8 tests completed were done during the sampling of this site. Table 2 below shows the findings of this test.

Table 3: Results from the sampling viability test. Samples are ordered by time of day the sample was taken, albeit many of the samples taken in the table were sampled on different days.

Time	Date	Initial Sample ppm	North Sample ppm	South Sample ppm	East Sample ppm	West Sample ppm
11:53 AM	9/29/2012	4250.00	2050.0	0.0	750.0	1400.0
12:14 PM	9/30/2012	4200.00	0.0	0.0	200.0	100.0
1:33 PM	9/30/2012	1700.00	1350.0	150.0	3150.0	350.0
2:09 PM	10/13/2012	100.00	100.0	100.0	100.0	100.0
2:28 PM	9/30/2012	1150.00	1150.0	1150.0	1150.0	1150.0
2:39 PM	9/30/2012	2950.00	2800.0	2300.0	1150.0	950.0
3:16 PM	10/13/2012	1200.00	1150.0	1200.0	1200.0	1200.0
3:38 PM	10/14/2012	1250.00	1250.0	1250.0	1250.0	1250.0

Three of the four viability test samples taken at 2:39 pm on 9/30 showed readings higher than 1150 ppm, but those values dropped and sustained themselves at 1500 ppm, the lower reading (950 ppm) was likely lower because sufficient depth was not attainable at that location due to the rocky soil.

Samples taken earlier in the day seem to show less consistency when running the test than samples taken later in the day. This is particularly interesting since, among all samples, most non-zero samples seem to be taken later in the day. Also, among all samples, those taken later in the day appear to most often show similar values to one another and this will be discussed later.

Experimental Sites

The final experimental sites were chosen later into the study after it was determined that the proposed well pads were not going to be drilled as originally anticipated. An alternative methodology was developed in which the sites would not be sampled twice (once before drilling and once after drilling), rather different sites would be sampled that had already been drilled and underwent the hydraulic fracturing process; these sites would then be compared to the control sites.

DEP and DCNR representatives were contacted again, in early September, to determine if there were any sites that were recently drilled, or would undergo hydraulic fracturing soon. A staff member from DCNR responded with coordinates to 5 sites; one that would be actively drilled in August 2012, and the others were to undergo hydraulic fracturing at specified times from August through November. It was found that the sites undergoing hydraulic fracturing had viable characteristics and all were chosen to be part of the study. The site that was undergoing drilling was found to have slopes too steep for sampling.

Experimental Site #1
(09/29/2012)

According to DCNR this site experienced hydraulic fracturing in August 2012 and this was apparent on site as there was a 'christmas tree' (e.g., Figure 22) over the well head which indicates the completion of drilling. Elevation change was not found to be an issue at this site.

Figure 22: A 'christmas tree' seen at one of the well sites in the area. Seeing this indicates that a well has been drilled and is considered important for this project for determining viable phase one sampling sites.

The Burgoon Sandstone was the primary bedrock type found throughout the site. Samples were taken in 4 different soil types (DkB, DkD, DlE, and CmB). Figure 23 seems to show an interesting trend, as non-zero value samples appear to be present more often in two specific soils (DkB and CmB) and zero value samples appear to wrap around the other two soils (DlE and DkD). While these trends are interesting, the original trend of seeing more non-zero samples later in the day held true at this site as well with 17 of the last 18 samples showing a non-zero value. Of these 17 non-zero samples, 8 of them show almost the exact same reading (4 had readings of 1200 ppm and the other 4 had readings of 1150 ppm). These findings are quite interesting and based on findings at previous sites, these trends appear to be caused by a diurnal phenomenon.

Lastly, the highest reading was 6500 ppm; this sample was taken in close proximity to a natural gas transmission line. The sampling viability test was run on this sample with readings of 2400, 2800, 10000, and 5500 ppm, with the southernmost sample showing the

highest reading (10,000 ppm) being the nearest to the transmission line at about 10 feet away (Note: this was not included in the sampling viability test results in the previous section due to this apparent influence from a gas leak).

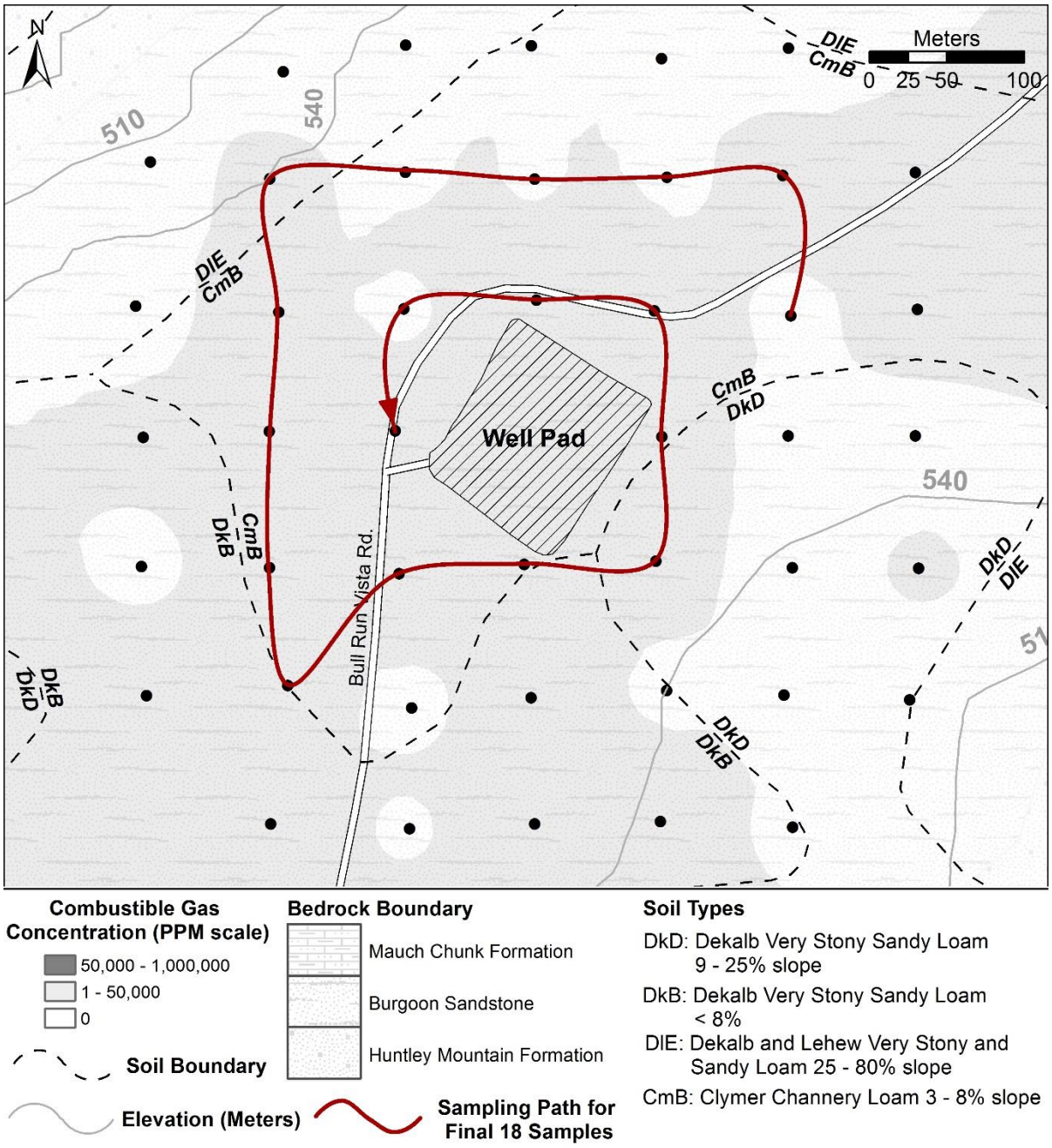


Figure 23: Map of Experimental Site 1. This shows the sampling path taken for the final 18 samples, 17 of these showed combustible gas readings. These findings along with findings at other sites appear to indicate that there may be a phenomenon that is causing combustible gas to emanate from the soil in the afternoon rather than earlier in the day.

Experimental Site #2
(10/13/2012)

According to DCNR this site experienced hydraulic fracturing in early-September 2012 and this was apparent on site as there was a 'christmas tree' over the wellhead and there was also equipment on site. Vegetation at the site was dense at times, especially along the western portion of the site. Elevation change was most difficult at this site, as compared to any of the others, which made it one of the more challenging sites to sample. This site was initially removed from sampling consideration due to steep slopes, and in hindsight, would have been the one site which could have been sampled before and after hydraulic fracturing and/or drilling. Unfortunately, the author had never been contacted by DCNR in regards to this site being drilled and/or hydraulically fractured early in the study, also, the site was not monitored for drilling activity throughout the entire period of the study unlike the other sites due to its elimination during the slope analysis. The site was only reconsidered for sampling when, on September 5th, DCNR indicated that hydraulic fracturing would occur in early-September 2012, by this time the sampling methodology for the project had changed, and there was no time to perform sampling prior to hydraulic fracturing.

The Burgoon Sandstone was the primary bedrock type found throughout the site although the Huntley Mountain Formation was also present in some areas. Samples were taken on 3 different soil types (DkD, DlE, and CmB). There does not appear to be any specific trend associated with the soil or bedrock type, but it is interesting how the non-zero samples appear close to the well pad (Figure 24). While there were non-zero readings sampled throughout the day, it is interesting that the final 9 samples all showed a non-zero reading and 5 of those samples had the same reading of 1200 ppm.

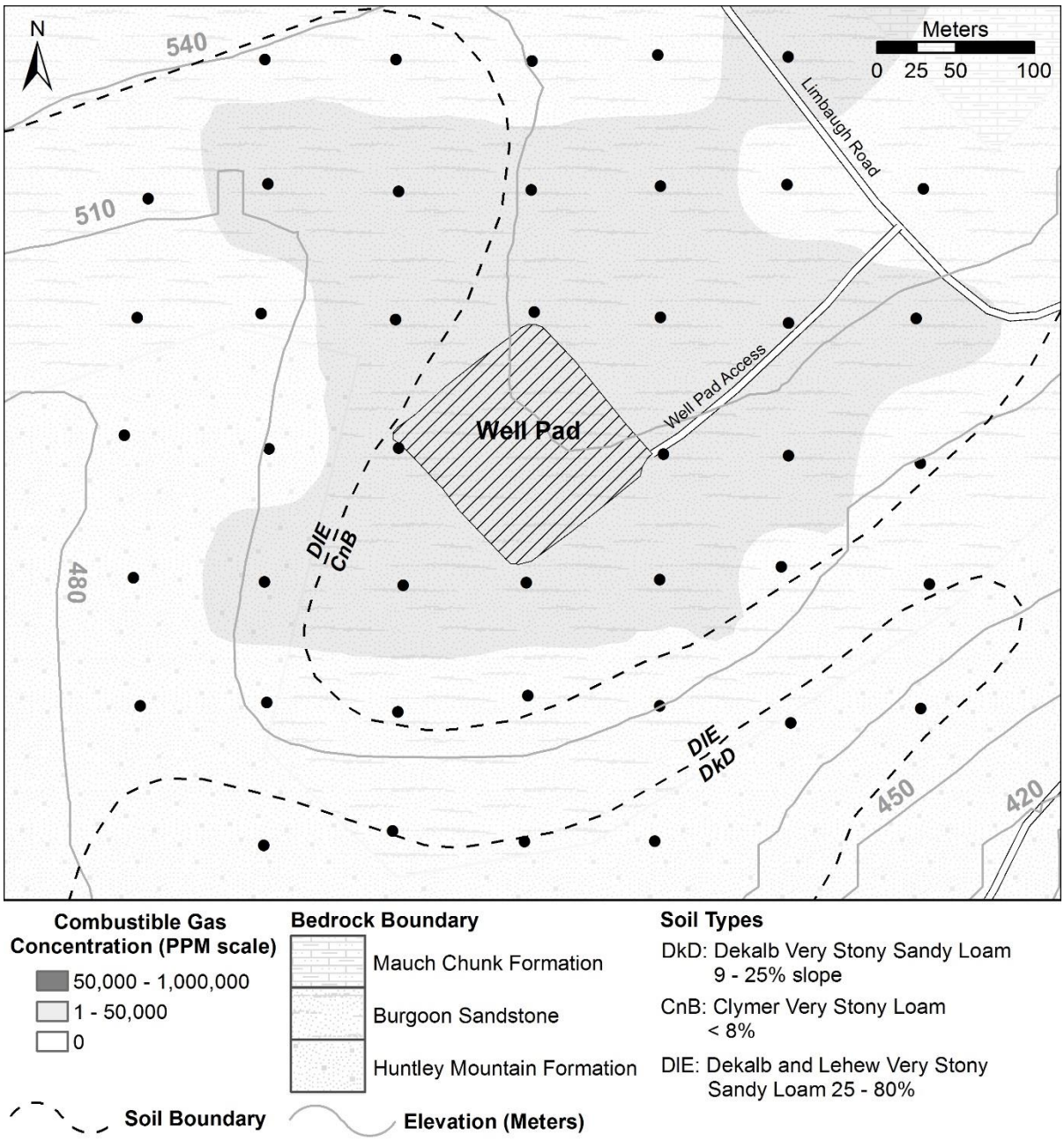


Figure 24: Map of Experimental Site 2. This was the only site that could have been sampled before and after hydraulic fracturing and/or drilling, but was removed during the slope analysis early in the study.

Experimental Site #3
(10/14/2012)

According to DCNR this site experienced hydraulic fracturing in mid-September 2012 and this was apparent on site as there was a 'christmas tree' over the wellhead and there was also a large truck on site used for transport of water used for hydraulic fracturing. There is no aerial imagery available for this site therefore pads or roads are not digitized on the map of results (Figure 25).

Typically, sampling at sites was completed in a very efficient manner, starting either from the inner part a site outward or vice versa. The sampling order for this site was quite random in comparison to how the other sites were sampled as there was a long perimeter fence surrounding much of the southern and western parts of the site, which altered the most efficient sampling path. Access inside the fence could only be attained through special gates at three spots along its perimeter (which is approximately 1.3 miles). Three samples could not be taken due to extremely steep slopes along the northwestern part of the site, and 3 other samples had to be taken at locations away from their proposed sampling location due to these steep slopes.

The Burgoon Sandstone was the primary bedrock type found throughout the site although the Mauch Chunk Formation was present in the southeastern part of the site. Samples were taken on 3 different soil types (DeC, CmB, and KlC). There does not appear to be any specific trend associated with the soils or bedrock type. As with most other sites, a diurnal change in combustible soil gas seemed to be apparent as 22 of the final 25 samples showed a non-zero reading and, of these, 12 showed readings of 1200-1250 ppm. Only 4 of the first 16 samples taken earlier in the day showed a non-zero reading.

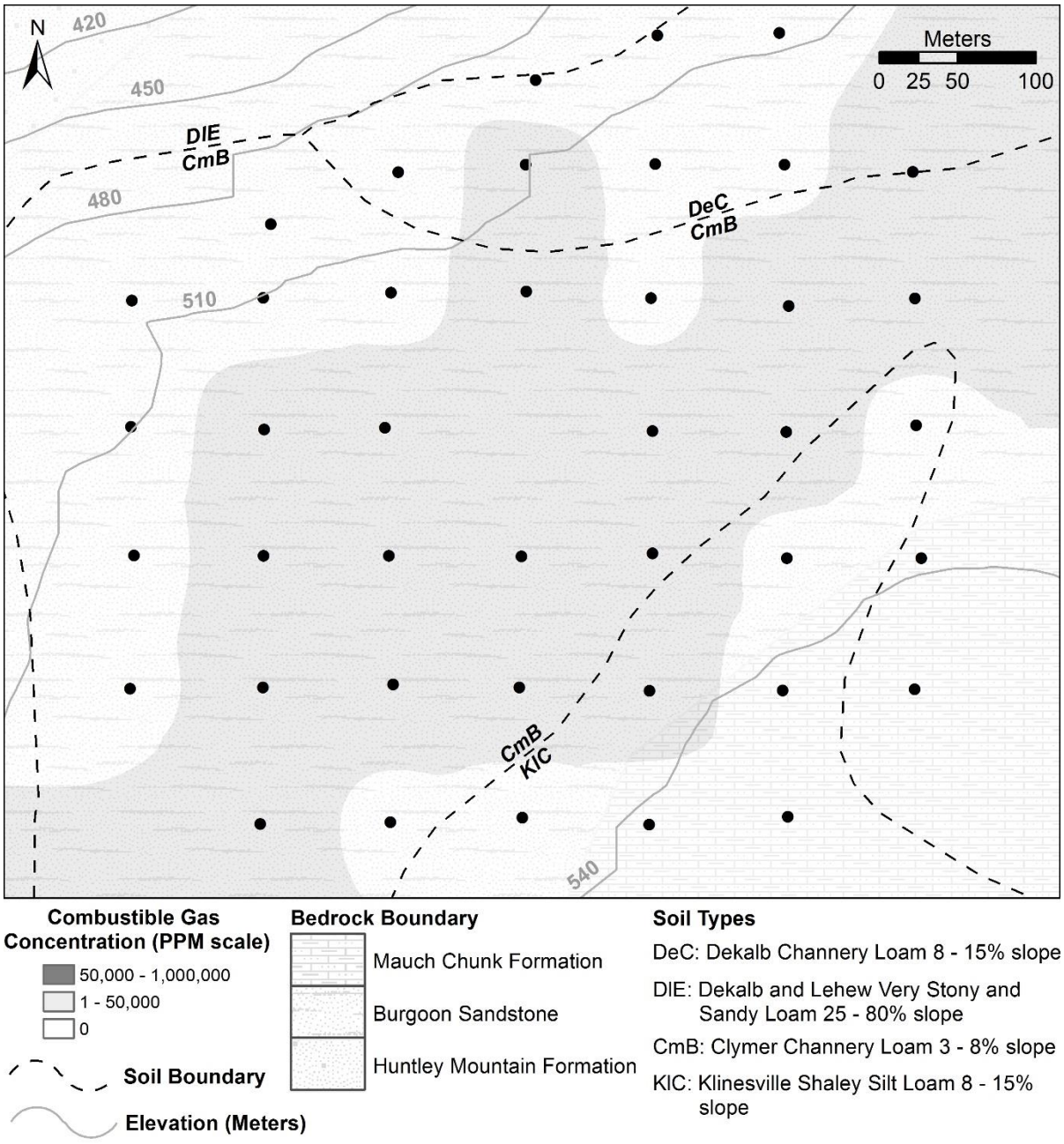


Figure 25: Map of Experimental Site 3 which was hydraulically fractured in mid-September and sampled on October 14th. Samples taken later in the day appeared showed a higher ratio of non-zero measurements as compared to samples taken earlier in the day.

Experimental Site #4
(11/10/2012)

According to DCNR this site started hydraulic fracturing in early October 2012. This site showed the greatest evidence of recent hydraulic fracturing of all sites sampled and there still appeared to be some activity related to the hydraulic fracturing process taking place. This was most apparent due to the fact that there was a crane holding a large piece of equipment over the wellhead along with many trucks and workers on site throughout the duration of sampling (Figure 26). A conversation with one of the well workers confirmed that hydraulic fracturing had recently occurred at this site.

Figure 26: Image showing the general level of activity on the well pad during sampling for the Experimental Site 4.

The site seemed to be the most physically challenging to sample as most of the samples were on a slope and areas that were flat all seemed to be heavily vegetated (Figure 27). The Mauch Chunk Formation was the primary bedrock type found throughout the site. Samples were taken on 3 different soil types (DlE, DkB, and HmD). There does not appear to be any specific trend associated with the soils or bedrock type. The southeast side of the site shows many non-zero readings and the northwest side of the site does not which may be indicative of heating of the soil due as the southeast side of the site surely receives more daily sunlight than the northwest side. As with the other sites, this site also shows a higher ratio of non-zero samples later in the day as compared to samples taken earlier in the day. Also notable was the fact that the temperature throughout the day ranged from 5.5°C to 10°C.

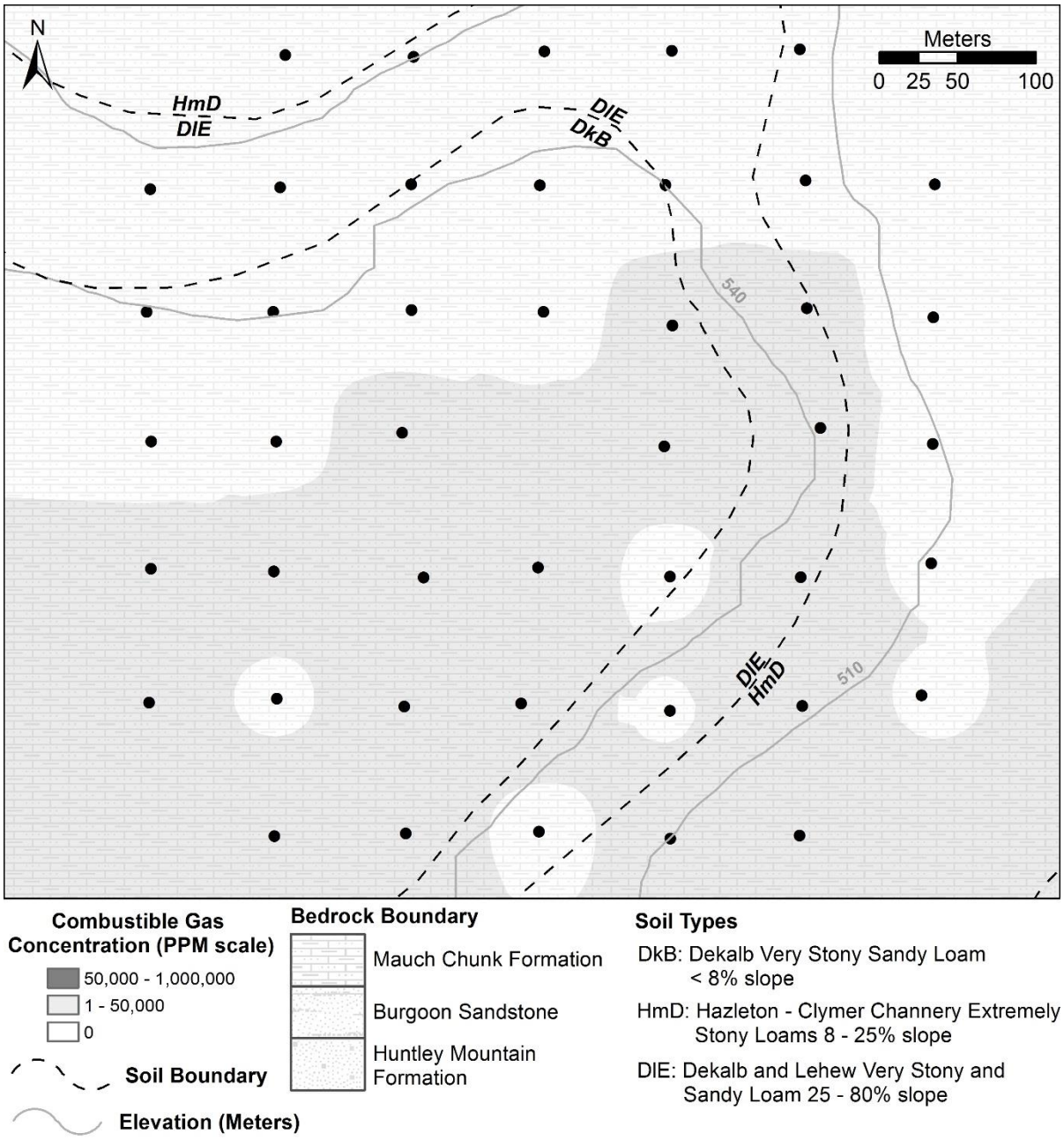


Figure 27: Map of Experimental Site 4. This was the last site sampled and showed a higher ratio of samples with non-zero readings in the southeast part of the study area as compared to samples taken in the northwestern part. The higher ratio of non-zero samples were measured later in the sampling period.

FURTHER ANALYSIS

Levels of combustible gas found at each of the sites were markedly low with no samples showing values near the Lower Explosive Limit of any type of combustible gas (with exception of those influenced by fugitive gas from transmission lines). That said, there were a significant number of non-zero readings, albeit low readings. While these data do not specifically relate to the primary question of this study in regards to hazardous levels of combustible gas in the soil around well pads, the data can still be analyzed to reveal general trends of these low-level combustible gas readings as per the final ancillary question which is as follows:

- If concentrations do not show significant changes, but there are baseline natural gas concentrations, how do these baseline concentrations vary based on: soil type, underlying geology, temperature, barometric pressure, and the time of day that samples were taken.

The point source samples measured in this study were excluded completely from the analysis as these samples have no correlation to the area source samples examined and should not represent a zero or non-zero reading.

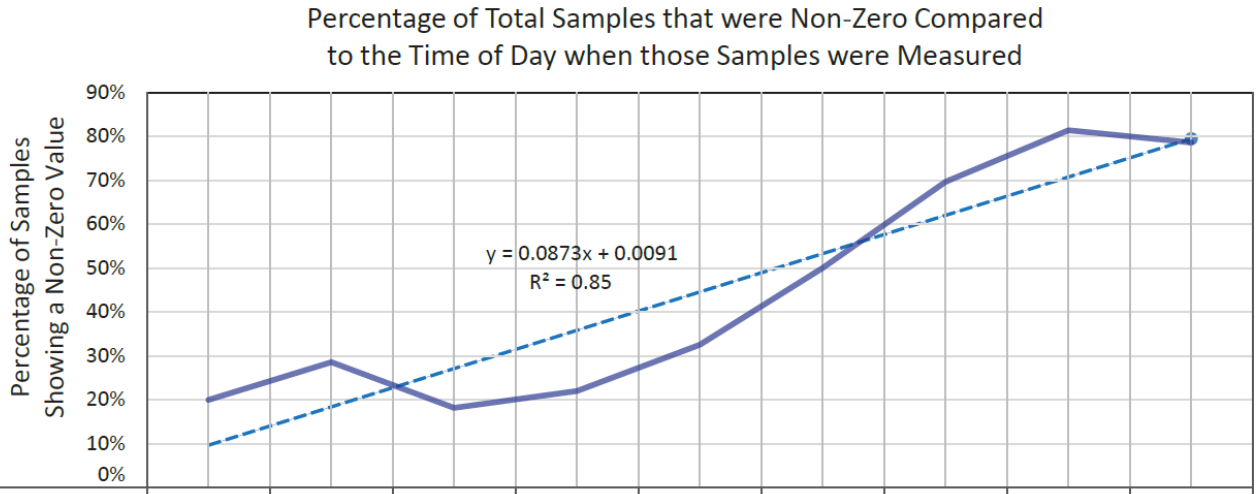
Time of Day

Observations during sampling seemed to show that time of day was surely a factor as there seemed to be a higher ratio of non-zero samples later in the day than earlier in the day. This variable will be analyzed first and if the apparent trend holds true, the findings may be used when analyzing subsequent variables.

The number of samples showing a non-zero value was examined over nine different 1-hour intervals (Figure 28), which accounts for all area-source samples taken during the

study. These intervals ranged from the 8:00 AM hour through samples taken after 4:00 PM (there was one sample taken at 5:09 PM which was included in the after 4:00 PM interval). These 1-hour intervals were chosen because choosing a smaller interval would compromise the statistical significance of each interval due to the reduced the number of samples examined over each interval. An interval larger than 1 hour would increase the statistical significance of the data for each interval, but there would be a reduction in the number of intervals examined, eliminating the possibility of finding trends within shorter spans of time.

Other variables in Figure 28 include: total number of samples, total non-zero samples, and the percentage of samples with non-zero values. When observing this figure it can be seen that the percentage of samples showing non-zero readings appear to increase throughout the day.



Time of Day of Sampling	8:00 AM	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM
Total Samples Taken	10	28	44	59	83	50	56	43	14
Total Non-Zero Samples	2	8	8	13	27	25	39	35	11
Percent Non-Zero Values	20%	29%	18%	22%	33%	50%	70%	81%	79%

Figure 28: Graph showing the number of samples taken over the course of the study and the times when non-zero samples were measured most and least often.

Fewer samples were taken during certain time periods. If periods with fewer than 30 samples are removed from consideration (as sample sizes greater than 30 typically yield

statistics with normal distribution characteristics) it can be seen that the percentage of non-zero samples does continue to increase unabated throughout the afternoon. The R^2 value measured .85, showing a strong positive correlation between the percentage of non-zero samples and time of day.

Next, control sites and experimental sites were directly compared by time of day in which samples were taken (Table 4). It can be seen that the percentage of non-zero samples taken at experimental sites is much higher (59%) than at control sites (31%). With no further analysis, based on these results, one could potentially conclude that the drilling and hydraulic fracturing at experimental sites results in a larger field (or a greater sampling percentage) of non-zero combustible gas concentrations. That said, further analysis is required.

When reviewing the data in Table 4 it is apparent that, in general, samples were taken earlier in the day at control sites and later in the day at experimental sites. Notice that no samples were taken prior to 11:00 AM at experimental sites and no samples were taken after 3:00 PM at control sites. When averaging the aggregate of samples taken at control sites based on time, the average sampling time at Control Sites is 11:30 AM, whereas the average

Table 4: Comparison of Control Sites to Experimental Sites based on time samples were taken. Samples were generally taken earlier in the day at Control Sites and later in the day at Experimental Sites. The percentage of non-zero samples taken at control sites is markedly lower than the percentage of non-zero samples taken at Experimental Sites.

	Control Sites			**Experimental Sites**		
Time of Sampling	# Samples Taken	# Non-zero Samples Taken	Percent Non-Zero Samples	# Samples Taken	# Non-zero Samples Taken	Percent Non-Zero Samples
8:00 AM	10	2	0.20	0	0	N/A
9:00 AM	28	8	0.29	0	0	N/A
10:00 AM	44	8	0.18	0	0	N/A
11:00 AM	52	11	0.21	7	2	0.29
12:00 PM	50	15	0.30	33	12	0.36
1:00 PM	14	12	0.86	36	13	0.36
2:00 PM	17	10	0.59	39	29	0.74
3:00 PM	0	0	N/A	43	35	0.81
4:00 PM	0	0	N/A	14	11	0.79
Total	**215**	**66**	**31%**	**172**	**102**	**59%**

sampling time at experimental sites is 2:13 PM. This is a rather significant time difference. The reason for this difference in sampling average times was primarily to avoid rattlesnakes, which are most active during the afternoons in July and August, when the control sites were sampled. Avoiding the late afternoon heat during the summer (which is why no sampling took place during the extreme heat over the weekends in July) months and avoiding the chilly mornings during the fall are also accountable for these differences in sampling times.

When observing Table 4, it can be seen there are four time periods that overlap between the control sites and the experimental sites where sampling occurred at both (11:00 AM through 2:00 PM). Rather than summing the number of non-zero samples taken and dividing by the total number of samples taken for each control sites and experimental sites, a weighted average was used to eliminate bias associated with the number of samples taken during each time period (although bias still exists, due to the lack of reliability of data from periods with smaller sample sizes). To do this, the percentage of samples showing a non-zero value during the four sample periods for each control sites and experimental sites were averaged. Therefore if an even number of samples were taken during each of these four overlapping sampling periods at both control sites and experimental sites, the result is 49% of samples at control sites being non-zero and 44% of samples at experimental sites being non-zero. These percentages are rather similar and effectively marginalize the validity of comparing the total amount of non-zero samples taken at control sites (31%) to experimental sites (59%).

Samples taken after 1:00 PM at both Control Sites and Experimental Sites showed a markedly higher percentage non-zero values as compared to samples taken prior to 1:00 PM (Table 5). Also, it can be seen that the average combustible gas value at control sites (1252 ppm) is higher, albeit very similar to the average value found at experimental sites (1116

ppm). The percentage of non-zero samples taken after 1:00 PM was 65% at control sites and 67% at experimental sites. The percentage of non-zero samples taken before 1:00 PM was 24% at control sites and 35% at experimental sites. Counter to the results in Table 4 showing dissimilarity in the percentage of non-zero values found at control sites as compared to experimental sites, the results seen here (Table 5) show that the two are rather similar.

Table 5: Comparison of samples taken prior to 1:00 PM and after 1:00 PM at Control Sites and Experimental Sites.

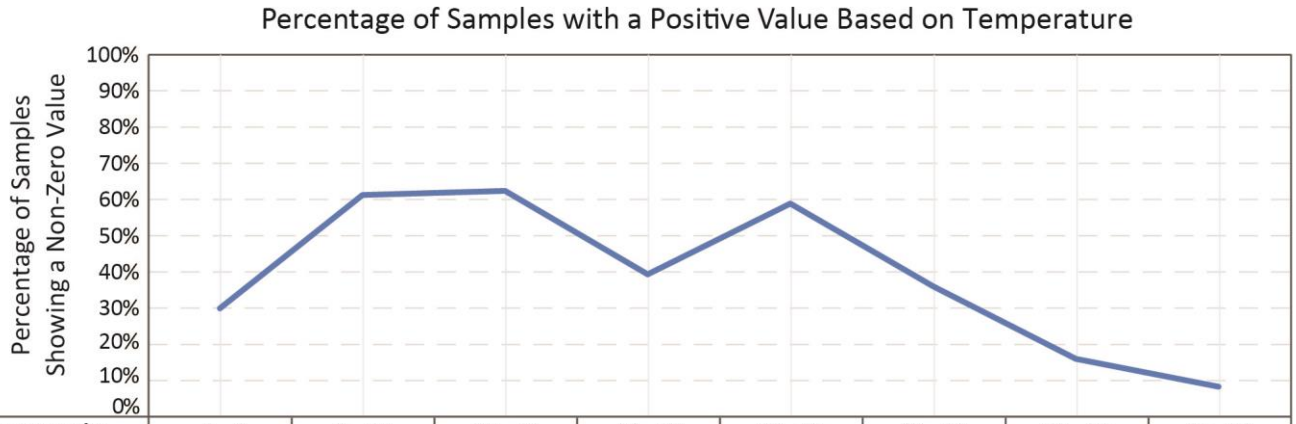
		Control Sites	Experimental Sites
Samples Taken Prior to 1:00 PM	# Samples taken	184	40
	# Non-Zero Samples taken	44	14
	Percent Non-Zero Samples	**24%**	**35%**
Samples Taken After 1:00 PM	# Samples taken	46	132
	# Non-Zero Samples taken	30	88
	Percent Non-Zero Samples	**65%**	**67%**
	Avg. Combustible Gas Concentration of Non-Zero Samples	**1252 ppm**	**1116 ppm**

Both tables show that samples measured later in the day returned a larger share of non-zero values than those taken earlier in the day. The cause of this drift over time is unknown, but it could be associated with increasing daytime temperature. Previous studies have also mentioned emissions of natural gas from soil can be effected by changes in barometric pressure. Therefore, temperature and changes in barometric pressure will be examined further.

Temperature

A possible association between the percent of non-zero readings and air temperature was examined (Figure 29). Unlike the time-of-day results that suggested temperatures might moderate gas readings, the temperature results do not confirm the association. The graph

shows that the ratio of non-zero value gas readings are lowest at the highest and lowest ends of the temperature range (5 – 8°C and 23 – 29°C).



Temperature °C	5 - 8	8 - 11	11 - 14	14 - 17	17 - 20	20 - 23	23 - 26	26 - 29
Total Samples Taken	20	31	48	71	95	61	25	36
Total Non-Zero Samples	6	19	30	28	56	22	4	3
Percent Non-Zero Values	30%	61%	63%	39%	58%	36%	16%	8%

Figure 29: Graph showing the number of samples taken throughout the study and shows the temperatures at which non-zero samples were measured most and least often.

The number of non-zero gas readings drop as temperatures rise above 20°C. This correlates well with previous studies (Mikkela, C., et. al, 1995; Börjesson, G. & Svensson B, 1997) which show that methane emissions are negatively correlated with soil temperature. Findings in these studies show that a rise in temperature typically correlates with an increase in biological methane oxidation by methanotrophs while methane production by methanogens remains unchanged. The drop in non-zero gas readings at the lowest temperatures in this study may be due to a lack of samples (and sample periods) at those low temperatures as there were only 10 samples taken in the lowest temperature regime.

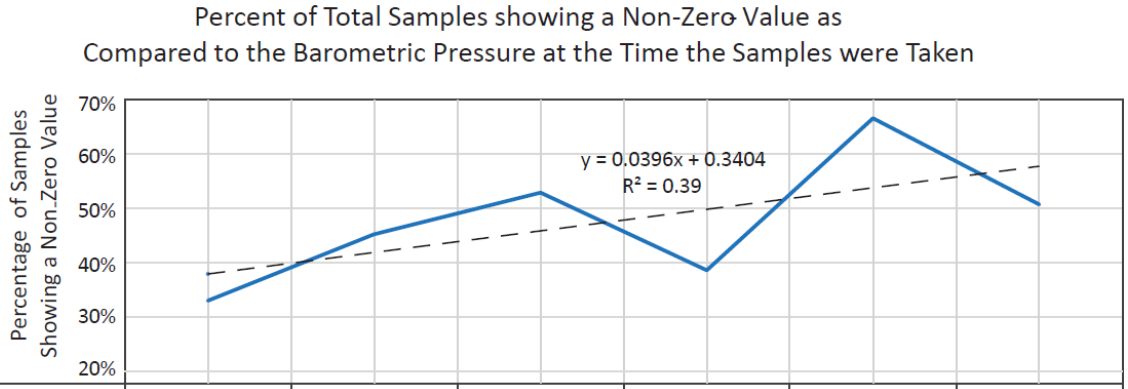
Barometric Pressure

Barometric pressure is a factor that is known to have an effect on the outgassing of natural gas from bedrock and soil into the atmosphere. Various studies have shown that lower air pressures promote outgassing and higher air pressures inhibit outgassing

(Baldassare and Laughrey, 1997; Pirson, 1946; Rossabi, 2002). Therefore, if gas is migrating from bedrock rather than being produced by methanogens in soil, barometric pressure changes could be a cause of any changes in soil gas concentration that are observed.

When observing the data for barometric pressure (Appendix III), it can be seen that barometric pressure actually rises throughout the morning hours and drops throughout the afternoon, which is a normal diurnal pattern that occurs as air temperatures increase, air molecules move further away from each other and rise higher into the atmosphere, which is why barometric pressure typically drops in the afternoon.

Figure 30 suggests, however, that the share of non-zero values tends to increase with increasing barometric pressure. The calculated R^2 value, 0.39, also suggests there is a weak positive correlation between barometric pressure and the number of non-zero samples measured. These results are contradictory to what is found in the literature as non-zero samples should be more prevalent when barometric pressure is dropping.

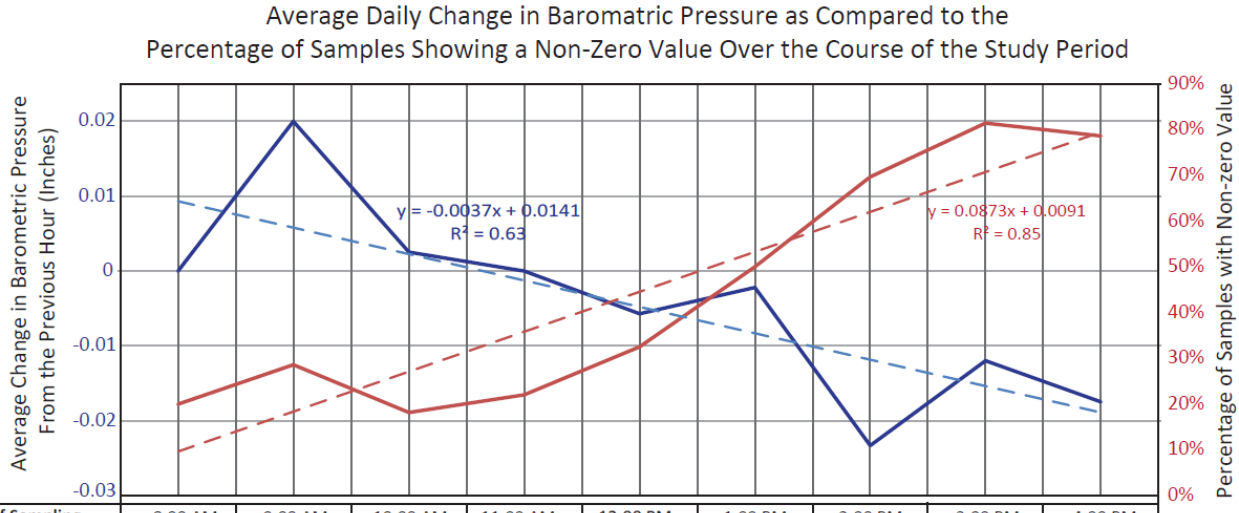


Barometric Pressure Range (In.)	29.76 - 29.86	29.87 - 29.97	29.98 - 30.08	30.09 - 30.19	30.20 - 30.30	30.31 - 30.42
Total Samples Taken	127	95	34	44	24	63
Total Non-Zero Samples	42	43	18	17	16	32
Percent Non-Zero Values	33%	45%	53%	39%	67%	51%

Figure 30: Graph showing the percentage of samples showing a non-zero value in the study as compared to barometric pressure. Frequency of total samples and non-zero samples taken in 6 barometric pressure ranges are also illustrated.

Upon further examination, an explanation became apparent. Sampling periods did not all overlap perfectly and barometric pressures differed from one day of sampling to another. Coincidentally, on days where sampling occurred earlier in the day, overall daily barometric pressures were significantly lower than on days where sampling occurred later in the day, which caused the unexpected results seen in Figure 30. The barometric pressure at a specific point in time does not necessarily have an effect on outgassing. The current trend in barometric pressure change is what should have the greatest effect on outgassing. If barometric pressure is falling, the literature states that outgassing should occur, whereas rising barometric pressure should inhibit outgassing. Therefore, the data needed to be analyzed using an alternative method that accounts for change in barometric pressure.

Another graph (Figure 31) was developed showing the average change in barometric pressure for all of the sites during all hours when sampling took place. Examining average change in barometric pressure throughout the day (rather than just comparing the number of



Time of Sampling	8:00 AM	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM
Chg. in Baro Pressure	0	0.02	0.0025	0	-0.0057	-0.0022	-0.0233	-0.012	-0.0175
Total Samples Taken	10	28	44	59	83	50	56	43	14
Percent Non-Zero Values	20%	29%	18%	22%	33%	50%	70%	81%	79%

Figure 31: Graph showing the number of samples taken throughout the study and shows how changes in barometric pressure relate to the percentage of samples with a non-zero value.

samples taken at certain barometric pressures) effectively overcomes the issue of some sampling days a having higher or lower overall barometric pressure than other sampling days, and how certain times of day when sampling took place did not overlap from one sampling period to another.

Average change in barometric pressure over all sampling periods shows an R^2 value of .63 which is an improvement over the original dataset. A 1-hour period where change in barometric pressure is above 0 on this graph indicates that the barometric pressure has risen as compared to the previous 1-hour period, and vice versa for samples with a barometric pressure below 0. The more that barometric pressure increases from the previous hour, the more that outgassing should be more inhibited; resulting in fewer non-zero combustible gas values. Where barometric pressure drops, the more that outgassing should occur; resulting in a greater number of non-zero combustible gas values. For example, even though the average change in barometric pressure increased from 2:00 PM to 3:00 PM, the average barometric pressure at 3:00 PM still dropped as compared to 2:00 PM, as average change in barometric pressure is -0.012 at 3:00 PM. Therefore it would still be expected that that percentage of samples showing a non-zero combustible gas reading would continue to rise. This is the expected negative correlation that is referred to in the literature (Baldassare and Laughrey, 1997; Pirson, 1946; Rossabi, 2002).

Differences in barometric pressure are also apparent when comparing control sites to experimental sites. Sites in Figure 32 are ordered from high to low total barometric pressure change from the start until the end of sampling the site. The total change in barometric pressure experienced at each site during sampling, was inverted on the graph, as drops in barometric pressure should correlate with increased outgassing in soil. When examining

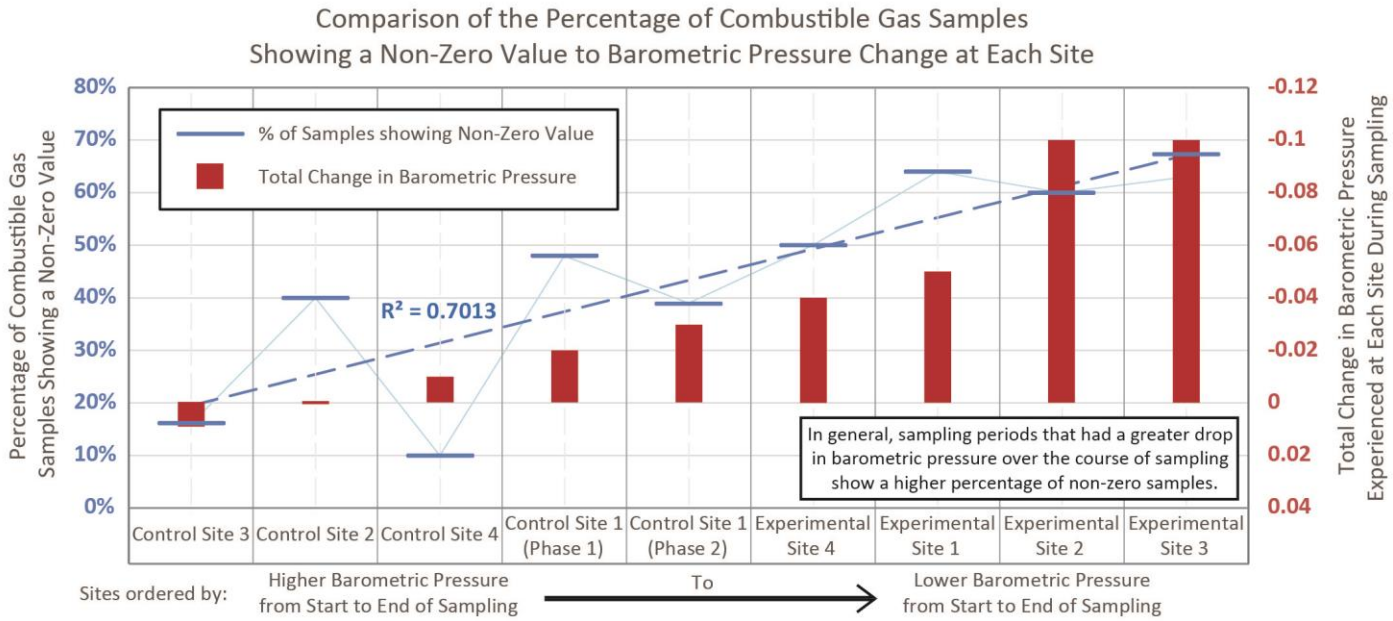


Figure 32: Graph showing the percentage of combustible gas samples showing a non-zero value at each site as compared to the total change in barometric pressure at each site from the start of sampling until the end of sampling.

change in barometric pressure from the start until the end of sampling at each site, it was found that sites that had greater drops in barometric pressure over the course of sampling also, in general, showed a greater percentage of non-zero value samples. The 4 sites showing the highest barometric pressures were, coincidentally, all of the experimental sites. The greater drops in barometric pressure experienced at the experimental sites likely resulted in outgassing of combustible gas from the soil, leading to the higher percentage of non-zero combustible gas readings that were also observed at those sites.

Only 10% of samples measured at Control Site 4 showed non-zero readings, which makes this site stand out in Figure 32. Since barometric pressure dropped slightly throughout the day it would be expected that a higher percentage of non-zero soil gas readings would have been observed. A reason for this may be that the high temperatures (average temperature of 25°C during sampling) provided an environment where methanotrophs were more active, reducing methane concentrations in soil. Interestingly, high average

temperatures may also have resulted in reduced methane concentrations in soil at Control Site 3 (avg. temp: 23.9°C; percent non-zero samples: 16%) and Control Site 1 (avg temp: 21.1°C; percent non-zero samples: 39%). These sites have the second and third highest average temperatures during sampling, and the second and third lowest percent of non-zero combustible soil gas values.

Soil and Bedrock Type

An analysis of soils and bedrock are important for this analysis as each soil/bedrock type has its own distinct characteristics (i.e., total organic content, porosity, etc.) which can effect soil gas migration. The soils were compared to one another and the bedrock types were compared to one another by cumulative frequency and also by the percentage of samples that showed non-zero combustible gas readings.

There were 3 different bedrock types used in the cumulative frequency analysis (Figure 33). The Mauch Chunk Formation (Mmc) showed the highest frequency of zero value samples (64%) followed by the Burgoon Sandstone (54.6%) and the Huntley Mountain Formation (41.7%). Only 12 samples were taken over the Huntley Mountain Formation (MDhm); this low sample size likely reduces the statistical significance of the data for this formation. The other bedrock types, which have sample pools of 100 samples (Mauch Chunk Formation - Mmc) and 275 samples (Burgoon Sandstone - Mb) are likely to have greater statistical significance because of their larger sample sizes.

The trend in the cumulative frequency of the Mauch Chunk and Burgoon Sandstone were relatively similar. The Burgoon Sandstone shows a higher percentage of non-zero combustible gas concentrations than the Mauch Chunk Formation, which would be expected based on the geologic characteristics of these formations. The Burgoon Sandstone primarily

contains medium-grained sandstone with thin beds of shale and coal which would be a more likely source of natural gas than the grayish-red shales and sandstones of the Mauch Chunk Formation. The cumulative frequency trend for the Huntley Mountain Formation was more sporadic and jumped ahead of the other formations for concentrations greater than 100 PPM, which is likely be due to the low number of samples taken over this formation.

The Burgoon Sandstone was the only formation having samples with combustible gas concentrations greater than 10,000 ppm and 100,000 ppm as samples taken over the gas lines were 50,000 and 150,000 ppm. The other formations showed a cumulative frequency of 100% for sample concentrations beyond 10,000 ppm.

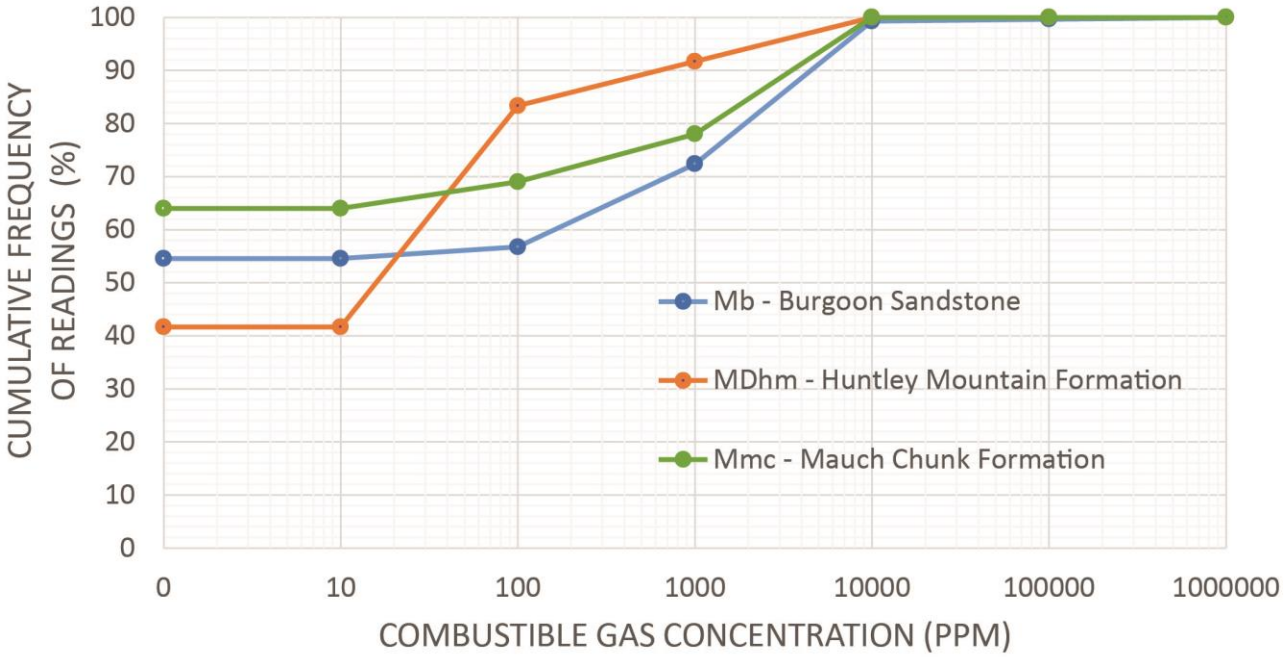
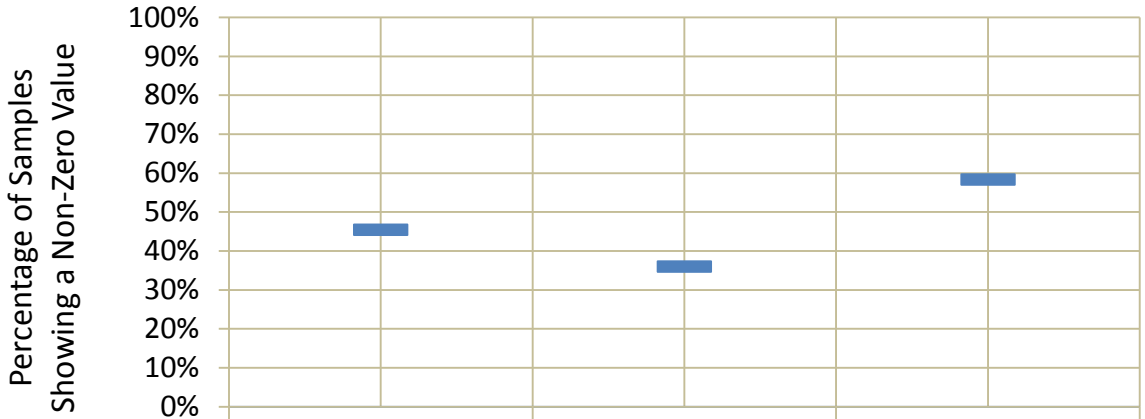


Figure 33: Cumulative frequency plot showing the percentage of combustible gas readings over each bedrock type based on combustible gas concentration.

The percentage of samples showing non-zero values taken over each bedrock type can be seen in Figure 34; this figure also shows the number of samples taken over each of these

bedrock types. When comparing the Burgoon Sandstone and the Mauch Chunk Formation, it can be seen that the Burgoon Sandstone has a greater percentage of non-zero concentrations (greater by 9.5%). This difference may have resulted from the coal beds and darker shales seen in the Burgoon Sandstone that are not seen in the Mauch Chunk.

The lack of samples taken over the Huntley Mountain Formation (only 12 samples) reduces its statistical significance when comparing it to the other formations. The Mauch Chunk and Huntley Mountain Formations do not contain bedrock types that are known to produce high levels of natural gas; therefore, it would be expected that the Huntley Mountain Formation would have a lower percentage of non-zero gas concentrations than the Burgoon Sandstone, which is not evident in Figure 34.



	Burgoon Sandstone	Mauch Chunk	Huntley Mountain
% Non-Zero Values	45.5%	36.0%	58.3%
# of Samples Taken	275	100	12

Figure 34: The percentage of samples taken over bedrock showing non-zero sample values. Notice the number of samples taken over each bedrock type as well.

Next, the cumulative frequency of samples by combustible gas concentration for soil types were analyzed (Figure 35). Characteristics of each member of these soil groups (Clymer and Dekalb) are similar to one another with the primary difference only being the slope they

are found on. Grouping soils that have similar characteristics seems logical as making comparisons within these soil groups may reveal trends.

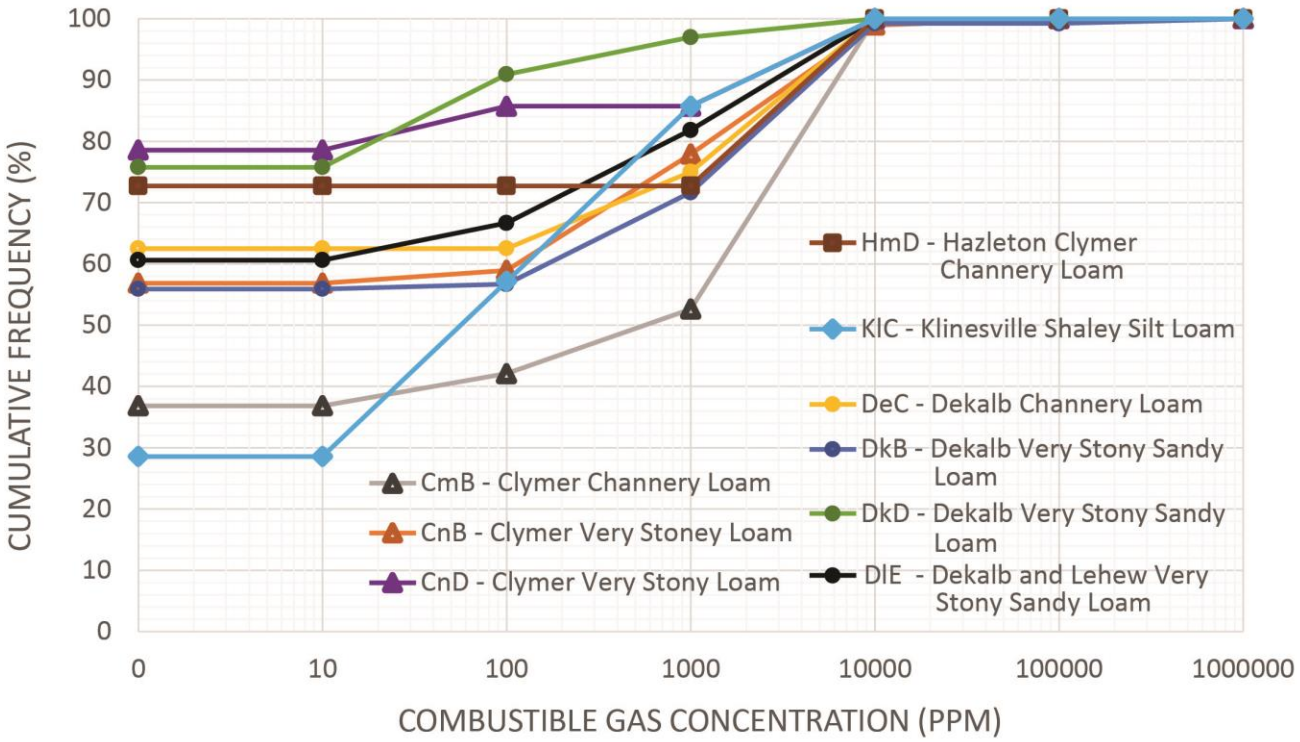
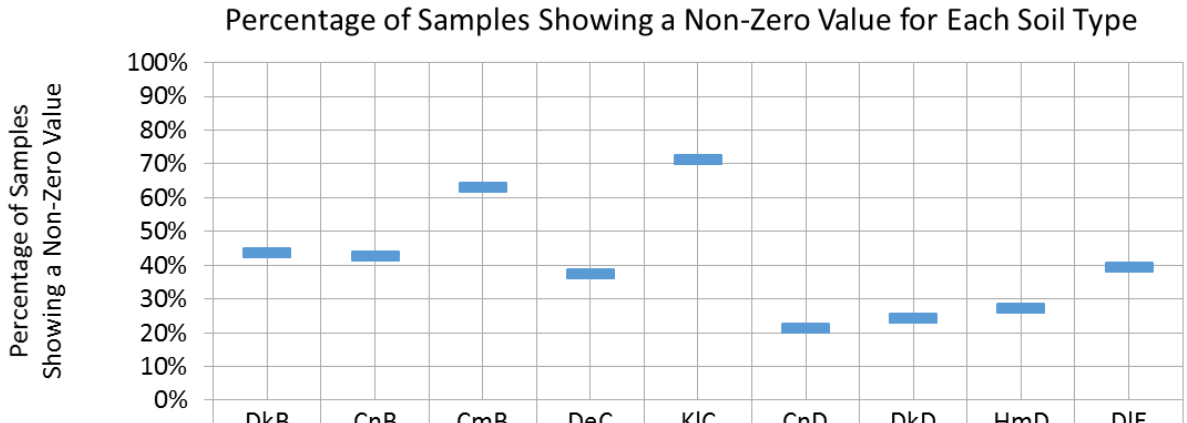


Figure 35: Cumulative frequency plot showing the frequency of combustible gas readings over each soil type based on combustible gas concentration.

Dekalb soils show the most similarity in regards to non-zero values. It can be seen that these soils are grouped much more closely together at 1 ppm than Clymer soils. What is quite interesting, and difficult to explain, is that the Clymer soils CnB (Clymer Very Stoney Loam) and CmB (Clymer Channery Loam) show markedly different trends in their cumulative frequencies. These two Clymer soils both have a moderate permeability and are found on similar slopes (CnB is found on 0-8% slopes while CmB is found on 3-8% slopes). The primary difference between these soils is that CnB is stonier than CmB. Also note that both soil types have over 50 samples taken from them (CmB had 57 samples and CnB had 94 samples).

Also interesting, but expected, is that the two soil types with the highest number of samples taken (DkB at 126 samples and CnB at 94 samples) showed very similar cumulative frequencies. This may indicate that the high number of samples taken over these soils allowed for the needed sampling diversity (diversity in location and time) to show that soil type does not make a significant difference in combustible gas concentration.

Also notable, is the similarity in slope and cumulative frequency trends of combustible gas in soil types CnB and DkB (both 0-8% slopes), also between CnD and DkD (both 8-25% slope). In Figure 36, CnD and DkD show a high frequency of samples in the 1 ppm tier, which indicates that soils on steeper slopes in general are less likely to show non-zero soil gas concentrations. Note that the permeability of these soils are different, as Clymer soils all have moderate permeability and the Dekalb soils all have rapid permeability, which indicates that soil permeability does not likely influence soil.



	DkB	CnB	CmB	DeC	KlC	CnD	DkD	HmD	DlE
% Non-Zero Values	44%	43%	63%	38%	71%	21%	24%	27%	39%
# of Samples Taken	126	94	57	8	7	14	33	11	33
Max Slope in Degrees	8	8	8	15	15	25	25	25	80

Figure 36: The percentage of samples taken over soils showing non-zero sample values. These soils are primarily ordered by increasing slope and where slope is equal they are further ordered by increasing permeability.

Frequency of non-zero soil gas concentrations are further compared by slope in Figure 36. Soils on the left of the graph have slopes that are less steep, slopes get steeper towards the right of the graph. Soils with equal slopes are then further organized by permeability with more permeable soils being found on the right side of their slope class. The author expects that a more permeable soil may show higher combustible gas concentrations as these soils would provide a path of lesser resistance for gas to transmit through as compared to a less permeable soil. This graph does not appear to show any definitive relationship between slope and non-zero combustible gas readings, even when omitting the soils that had very few samples taken from them.

DISCUSSION OF THE RESULTS

The data collected through sampling combustible gas concentrations in soil around natural gas well sites and the subsequent GIS and statistical analysis of this data provided answers to the primary and ancillary research questions proposed in this study. The following sections provide a discussion of these questions.

Discussion of the Primary Question

- Do pre-drilling baseline concentrations of combustible gas (regardless of source) in soils near Pennsylvania Marcellus Shale natural gas drilling sites change after drilling and/or hydraulic fracturing?

Findings showed that combustible gas concentrations in soil at control and experimental sites did not indicate that drilling had any effect on soil gas concentrations. The observed soil gas levels were quite low with the highest reading being 5500 ppm, which is only 11% of the lower explosive limit of natural gas. High-level soil gas concentrations (concentrations exceeding the lower explosive limit of natural gas) were only observed over leaking natural gas transmission lines, and therefore were deemed as outliers and removed from the analysis. Based on the results, it would be unusual to find elevated levels of combustible gas in the soil after drilling in this particular region and/or geology type. This said, soil and geology characteristics do change throughout the state and therefore many additional sites would need to be sampled in other regions to more thoroughly answer this question.

Discussion of Ancillary Questions

- If concentrations of combustible gas in the soil are observed to increase significantly after drilling activities begin, are there any spatial trends or patterns in these concentrations that can be observed?

Soil gas concentrations before drilling and after drilling were characterized as being very low. The highest before drilling readings (not associated with pipeline leaks) did not exceed 5500 ppm. The highest post-drilling readings (not associated with pipeline leaks) did not exceed 5000 ppm. Consequently, the concentrations of combustible gas in soil were not observed to increase, let alone increase significantly, after drilling occurred.

- If concentrations of combustible gas are observed; does the spatial pattern and variation of these concentrations indicate the reason why the gas is migrating?

The only common spatial trend that could be observed is that samples taken near disturbed soil do typically show non-zero readings and these readings are usually somewhat higher than baseline readings around sites. This trend was often seen around where soil was disturbed by the construction of well pads, water impoundments, and roads. It appears that samples taken closer to the wellbore show more non-zero readings, but this is most likely because samples near the wellbore were usually taken later in the day when barometric pressures dropped and outgassing was more likely to occur, along with the fact that the soil was often disturbed at samples nearest to well pads. While at some sites a spatial pattern does seem to appear in relation to soil and geology, the pattern is not always definitive and those patterns do not appear to hold up amongst all other sites with similar geology and soil types.

- If concentrations do not show significant changes, but there are baseline natural gas concentrations, how do these baseline concentrations vary based on: soil type, underlying geology, temperature, barometric pressure, and the time of day that samples were taken.

While the statistical analysis of soil and bedrock type did not appear to show a clear effect on soil gas concentrations, other variables did appear to influence gas concentrations.

It appeared that the time of day that samples were taken had the most influence on the gas readings found. Variables that change throughout the day where then analyzed (temperature and barometric pressure) and it was found that barometric pressure typically dropped throughout most of the study periods. The decrease in barometric pressure most likely led to the observed outgassing as other sources confirm that barometric pressure has a strong influence on the outgassing of natural gas (Baldassare and Laughrey, 1997; Pirson, 1946; Rossabi, 2002). The results of this study agree with earlier studies as it was found that falling barometric pressure lead to an increase in outgassing of low-level combustible gas concentrations. It was also found that sampling periods that showed greater drops in barometric pressure, also showed a higher number of non-zero combustible gas readings than sampling periods where barometric pressure dropped very little or rose. While it cannot be confirmed that the observed gas was methane, it would be rather unusual to find other combustible gases in soil. It is known that methane can be produced by sources such as methanogens and from natural gas source rocks such as shale and coal.

Limitations

This study had numerous limitations along with some unexpected difficulties (Appendix VI). The most significant limitation was the lack of a set drilling schedule for the well sites in the study area. Unexpectedly, drilling activity in Pennsylvania dropped off in 2012 from 2011 before ramping back up in during the first half of 2013 (PADEP, 2013). The timing of this drop was, therefore, unfortunate because it limited viable sampling locations, thusly requiring substantial changes in methodology.

Communication between drillers and PA DEP representatives and the author was also a limitation as the author was never given information on upcoming drilling and/or

hydraulic fracturing unless requesting it, which was not the expectation based on initial interactions with PA DEP.

Another limitation was the number of samples that could reasonably be taken at each site. Sampling at each site took between 3.5 and 4.5 hours of work that proved to be rather physically demanding. Originally a grid with 100 samples was proposed for each site; this would have provided higher resolution digital surfaces of the combustible gas concentrations, but such a grid would be quite challenging to sample without additional assistance.

The number of sites that could be sampled during the study period was another limitation. At most, two sites were sampled on any given weekend. Only 4 of the sites sampled experienced hydraulic fracturing. Therefore, it is difficult to tell whether the result seen here is the norm around well sites throughout the state or even amongst other sites in the study region.

Amongst these limitations various things went very well. Attaining access to well sites was not very challenging and security personnel at the sites as well as all DEP and DCNR representatives and rangers were very kind and accommodating. GPS connectivity was also initially a concern, but the new Trimble Geoexplorer XH receivers never dropped connectivity which greatly helped in the efficiency of sampling and produced high quality results in terms of sampling accuracy. Lastly, the fact that the PA DEP provided unrestricted access to a field house throughout the course of the study was rather liberating as the initial expectation was camping outdoors.

CONCLUSION

The results of the study indicate that natural gas drilling within the limits of the study area does not result in higher combustible gas concentrations in soil. To determine this, a method of sampling and analysis was developed primarily involving the use of a combustible gas indicator, GPS receiver, and ArcGIS to examine combustible gas concentrations in soil around well sites to determine if hazardous levels of combustible gas appear after drilling. A gridded sampling pattern was developed and used in order to take a large number of samples (as compared to similar studies) at distances as far as 300 meters away from the well bore at well sites. Combustible gas concentrations in soil were measured at 4 wells sites that have been drilled and hydraulically fractured (experimental sites) and also at 4 sites that did not experience any drilling activity (control sites). Maps were developed in ArcGIS and a statistical analysis was performed to analyze the gas concentrations and determine whether trends exist.

Hazardous levels of combustible gas were found, but only over natural gas transmission lines that were leaking gas. Very low levels of combustible gas were also observed at well sites and control sites. These sampled values were processed in ArcMap using Inverse Distance Weighted interpolation to create digital surfaces revealing the spatial distribution of combustible gas concentrations at all sites. The results of this analysis were helpful in revealing how samples taken later in the afternoon at both control sites and experimental sites experience a higher level of outgassing of combustible gas.

A statistical analysis examining additional variables was also conducted. Control sites and experimental sites were first compared by their percentage of total non-zero samples. It

was found that 31% of samples taken at control sites, and 59% of samples at experimental sites, showed non-zero combustible gas readings. Sampling primarily occurred during the morning at control sites and during the afternoon at experimental sites. To account for these differences in sampling times the control sites and experimental sites were further compared based on the weighted percentage of non-zero samples taken during four different overlapping 1 hour time periods (as some hours didn't experience sampling for both control sites and experimental sites). The weighted percentages showed that 49% of samples taken at control sites, and 44% of samples taken at experimental sites, showed non-zero combustible gas readings. This indicates that the differences in combustible gas concentrations at control sites and experimental sites were negligible.

Further analysis indicated that barometric pressure was the primary factor influencing the outgassing of combustible gas. There were greater drops in barometric pressure at all experimental sites than at all control sites which likely accounts for the greater overall percentage of non-zero combustible gas readings measured at experimental sites. Samples taken at temperatures over 20°C showed an unusually low number non-zero combustible gas readings, possibly caused by oxidizing bacteria in the soil called methanotrophs, which consume methane and thrive at higher temperatures (Börjesson, G. and Svensson, B, 1997).

When observing combustible gas concentrations in bedrock, interesting differences were seen when comparing the percentage of samples showing non-zero combustible gas readings in the Mauch Chunk Formation and the Burgoon Sandstone. Figure 34 shows that samples taken over the Burgoon Sandstone showed a 9.5% higher incidence of non-zero combustible gas readings than were observed over then Mauch Chunk Formation. This may be the result of the coal beds and darker shales seen in the Burgoon Sandstone that are not

seen in the Mauch Chunk. It is also a possibility that the Mauch Chunk, due to the amount of shale and siltstone interbeds, is acting as a trap rock overtop of the Burgoon Sandstone, preventing gas from migrating upward, resulting in the excess gas seen in the Burgoon Sandstone.

There was no conclusive evidence that soils or bedrock are primary factors influencing the outgassing of combustible gas in this study. While there are differences in how many non-zero measurements were observed in each soil/bedrock type, there does not appear to be any specific characteristic(s) that definitively explain why one soil/bedrock type would show a greater number of non-zero measurements than another. Further sampling would likely be required to determine the influence of each soil/bedrock type on combustible gas concentrations found in soil.

While most measurements at the sites were relatively low and did not indicate an environmental hazard, some concentrations found over the natural gas transmission lines were significantly elevated and above the lower explosive limit of methane. While elevated levels of gas were not found around the well sites after drilling, the sampling methodology appears to be effective as lower concentrations were measured and analyzed without any issues. If elevated combustible gas concentrations caused by drilling activity existed around well sites, the methodology used in this study would surely find the elevated concentrations unless the gas migrated laterally over distances in excess of 300 meters beyond the wellbore, where samples were not collected. This scenario is unlikely based on findings by Osborn (2011) showing that elevated combustible gas concentrations in water wells were highest when located in close proximity to gas wells and dropped significantly at distances further than 1000 meters away.

The primary issue with this study was that a larger number of sites could not be examined as only 4 experimental sites were surveyed. Further studies comparing the spatial and temporal relationship of drilling activity and changes in soil gas concentrations would surely prove to be valuable. Identifying sites as having elevated concentrations after drilling would be a rather unique finding, as there does not appear to be any research completed examining gas concentrations before and after drilling where elevated concentrations were observed after drilling. The lack of findings is good. Hopefully future research is completed showing similar findings as it would indicate that current drilling and hydraulic fracturing techniques are suitable and should bring an improved sense of security to those living nearby. The methodology used in this study could be performed on a larger scale examining a greater number of sites as the methods used here are rather inexpensive to perform as compared to using other common methods such as a mass spectrometer or gas chromatography.

REFERENCES

Ashley, H. G. 1931. A Syllabus of Pennsylvania Geology and Mineral Resources. Department of internal affairs, Topographic and geologic survey.

Associated Press. 2011. Attorney: Methane Probed in NW Pa. House Explosion. Chambersburg Public Opinion. 7A.

Baldassare, F.J., and Laughrey, C.D. 1997. Identifying the Sources of Stray Methane by Using Geochemical and Isotopic Fingerprinting. Environmental Geosciences 4(2): 85-94.

Bleichmar, F.M., Hollander, L.J. 2012. Energy Institute Study Confirms Fracturing's Safety Record. Atlas Resources. Energy Newsline 14(1): 3

Bolstad, P., 2005. GIS Fundamentals: A First Text on Geographic Information Systems. 2nd Edition. Elder Press, White Bear Lake, MN, USA.

Börjesson, G., Svensson, B. 1997. Seasonal and diurnal methane emissions from a landfill and their regulation by methane oxidation. Waste Management and Research, 15, 33–54.

Brus, D.J., Gruijter, J.J. 1997. Random Sampling or Geostatistical Modelling? Choosing Between Design-Based and Model-Based Sampling Strategies for Soil. Geoderma 80(1-2): 1-44.

Cobbold, P.R., Rodrigues, N. 2007. Seepage Forces, Important Factors in the Formation of Horizontal Hydraulic Fractures and Bedding-Parallel Fibrous Veins ("Beef" and "Cone-in-Cone"). Geofluids 7(3): 313-322.

Colton, J.W. 1968. Geologic map of the Waterville quadrangle, Pennsylvania. Atlas (Pennsylvania Bureau of Topographic and Geologic Survey); PR 174, plate 1

Considine, T., Watson, R., Entler, R., Sparks, J., 2009. An Emerging Giant: Prospects and Economic Impacts of Developing the Marcellus Shale Natural Gas Play. Penn State University.

Eckenrode, J. J. 2007. Soil Survey of Clinton County, Pennsylvania. United States. Soil Conservation Service, Pennsylvania State University. College of Agriculture, Pennsylvania. State Conservation Commission.

Eltschlager, K.K., Harris, M., Baldassare, F.J., 2004. Fugitive Carbon Based Gases Blasting Related or Not. Proceedings of the Annual Conference on Explosives and Blasting Technique 30(1): 409-418.shle

Eltschlager, K. K., Hawkins, J. W., Ehler, W. C., Baldassare, F.J. 2001. Technical Measures for the Investigation and Mitigation of Fugitive Methane Hazards in Areas of Coal Mining. US Department of Interior - Office of Surface Mining Reclamation and Enforcement. Pittsburgh, PA. Setembro.

Engelder, T., Lash, G.G. 2008. Marcellus Shale Play's Vast Resource Potential Creating Stir in Appalachia. The American Oil and Gas Reporter.

Engelder, T., Lash, G.G. 2011. Thickness trends and sequence stratigraphy of the Middle Devonian Marcellus Formation, Appalachian Basin: Implications for Acadian foreland basin evolution. AAPG Bull 95(1): 61-103.

Fertl, W., Chilingar, V., 1988. Total Organic Content Determined from Well Logs. Society of Petroleum Engineers. SPE Formation Evaluation, 3(2): 407-419

Praagman, F., Rambags, F. 2008. Migration of natural gas through the shallow subsurface. M.Sc. Thesis. University of Utrecht: Netherlands

Groat, G. C., Grimshaw, W. T., 2012. Fact-Based Regulation for Environmental Protection in Shale Gas Development. The Energy Institute, The University of Texas at Austin.

Heath Consultants Incorporated. 1993. Gas Leakage Control Seminar. Field Operations Manual.

Hershey, L. 2013. An Analysis of the Economic and Demographic Effects of the Development of Unconventional Natural Gas Drilling Activities in Northeastern Pennsylvania. Shippensburg University Geography Earth Science Dept. M.S. Practical Exam

Howarth R., Ingraffea A., Engelder T. 2011. Natural gas: Should Fracking Stop? Nature 477(7364): 271-275.

Kargbo, D., Wilhelm R., Campbell, D. 2010. Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities. Environmental Science & Technology 44(15): 5679-5684

Kohler, C. 1986. Soil Survey of Lycoming County, Pennsylvania. United States. Soil Conservation Service, Pennsylvania State University. College of Agriculture, Pennsylvania. State Conservation Commission.

Krooss, B. M., & Leythaeuser, D. 1996. Molecular diffusion of light hydrocarbons in sedimentary rocks and its role in migration and dissipation of natural gas. AAPG Memoir, 66, 173-183.

Leythaeuser, D., Schaefer, R. G., & Yukler, A. (1982). Role of diffusion in primary migration of hydrocarbons. AAPG Bulletin, 66(4), 408-429.

Lustgarten, A. 2009. Water Problems From Drilling Are More Frequent Than PA Officials Said. ProPublica. http://www.propublica.org/article/water-problems-from-drilling-are-more-frequent-than-officials-said-731

Penn State Marcellus Center for Outreach and Research (PSU MCOR). 2013. Depth to Marcellus Shale Base. Digitized and georeferenced by Karen Edelstein from presentation by Penn State Marcellus Center for Outreach and Research. Presentation found at: http://www.marcellus.psu.edu/images/Marcellus_Depth.gif
Data accessed from:
http://www.arcgis.com/home/item.html?id=04d1ad755628457ab01ec7341086d214

Martini, A.M., Walter, L.M., McIntosh J.C. 2008. Identification of Microbial and Thermogenic Gas Components from Upper Devonian Black Shale Cores, Illinois and Michigan basins. AAPG Bull 92(3): 327-339.

Meents, W. F. 1960. Glacial-drift gas in Illinois. Illiniois State Geological Survey, Dept. of Natural Resources. Circular 292.

Mikkela, C., Sungh, I., Svensson, B. H., & Nilsson, M. 1995. Diurnal Variation in Methane Emission in Relation to the Water Table, Soil Temperature, Climate and Vegetation Cover in a Swedish Acid Mire. Biogeochemistry (Dordrecht), 28(2), 93-114.

Milici, R.C., Ryder, R.T., Swezey, C.S., Charpentier, R.R., Cook, T.A., Crovelli, R.A., Klett, T.R., Pollastro, R.M., Schenk, C.J. 2003. "Assessment of undiscovered oil and gas resources of the Appalachian Basin Province, 2002." United State Geological Survey.

National Weather Service. 2012. Weather History for Williamsport, PA. National Weather Service data provided through Weather Underground. Weather data for all well sites retrieved December, 2012. www.wunderground.com.

Osborn, S.G., Avner, V., Warner N.R., Jackson R.B. 2011. Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing. Proceedings of the National Academy of Sciences of the United States of America 108, no. 20: 8172-8176.

Pennsylvania Department of Environmental Protection Bureau of Oil and Gas Management (DEP). 2011. Stray Natural Gas Migration Associated with Oil and Gas Wells. http://www.dep.state.pa.us/dep/subject/advcoun/oil_gas/2009/Stray%20Gas%20Migration%20Cases.pdf

Pennsylvania Department of Environmental Protection (PADEP). 2013. Statewide Data Downloads By Reporting Period. PA DEP Oil & Gas Reporting Website. https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/DataExports/DataExports.aspx

Pennsylvania Natural Heritage Program (PNHP). 2012. PNDI Environmental Review Tool. Department of Conservation of Natural Resources. Accessed February 2012. http://www.gis.dcnr.state.pa.us/hgis-er/Login.aspx

Pirson, S.J. 1946. Disturbing Factors in Geochemical Prospecting. Geophysics 11(3): 312-320.

Reese S., Fleeger, G. 2012. Outstanding Geologic Features of Pennsylvania, Pine Creek Gorge – PA Grand Canyon Tioga and Lycoming Counties. DCNR. http://www.gis.dcnr.state.pa.us/topo/ogf/OGF_PineCreek.pdf

Roen, J. B. 1984. Geology of the Devonian Black Shales of the Appalachian Basin. Org. Geochem 5(4): 241-54.

Prinzhofer, A., Pernaton, E., 1997. Isotopically Light Methane in Natural Gas: Bacterial Imprint or Diffusive Fractionation? Chemical Geology 142: 193–200.

Revesz K.M., Breen K.J., Baldassare A.J., Burruss R.C. 2010. Carbon and Hydrogen Isotopic Evidence for the Origin of Combustible Gases in Water Supply Wells in North-Central Pennsylvania. Applied Geochemistry 25(12): 1845-1859.

Rossabi, J., and Falta, R.W. 2002. Analytical Solution for Subsurface Gas Flow to a Well Induced By Surface Pressure Fluctuations. Ground Water 40(1): 67-75.

Schoell, M. 1988. Multiple Origins of Methane in the Earth. Chemical Geology 71(1-3). 1-10.

The Pittsburgh Geological Survey (Pittsburgh, 2009). 2009. Natural Gas Migration Problems in Western Pennsylvania. Stray Gas Workshop. www.pittsburghgeologicalsociety.org/naturalgas.pdf

United States Energy Administration. January 8, 2013. 2012 Brief: Average wholesale natural gas prices fell 31% in 2012. http://www.eia.gov/todayinenergy/detail.cfm?id=9490

United States Geological Survey (USGS, 2011). National Map Viewer. National Elevation Dataset (1 arc-second, 30 meter). Accessed in 2011. http://viewer.nationalmap.gov /viewer/

United State Geological Survey (USGS, 2012). Last Updated May 2012. Geologic units in Clinton County, Pennsylvania. Mineral Resources On-Line Spatial Data, Pennsylvania Geology. http://mrdata.usgs.gov/geology/state/fipsunit.php?code=f42035

USDA NRCS. 2012. Soil Data Mart. Washington. DC: USDA Natural Resources Conservation Service. Accessed August, 2012. http://soildatamart.nrcs.usda.gov.

Ver Straeten, C. A., Griffing, D. H., Brett, C. E. 1994. The lower part of the Middle Devonian Marcellus "Shale," central to western New York State: Stratigraphy and depositional history: New York State Geological Association, 66th Annual Meeting Guidebook, p. 271–321.

Von Der Dick, E.E., Barrett, K.R., Bosman, D.A. 2002. Numerically Reconstructed Methane-Seep Signal in Soil Gases Over Devonian Gas Pools and Prospects (Northeast British Columbia); Surface Microseeps and Postsurvey Discovery. AAPG Studies in Geology 48: 193-207.

Wang, J., Haining, R., Zhidong, C. 2010. "Sample Surveying to Estimate the Mean of a Heterogeneous Surface: Reducing the Error Variance Through Zoning." International Journal of Geographical Information Science 24(4): 523-543.

Warner, N. R., Jackson, B. R., Darrah, H. T., Osborn, G. S., Down, A., Zhao, K., White, A., Vengosh, A. 2012. Geochemical evidence f**or** possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. Proceedings of the National Academy of Sciences of the United States of America. 109(30):11961–11966.

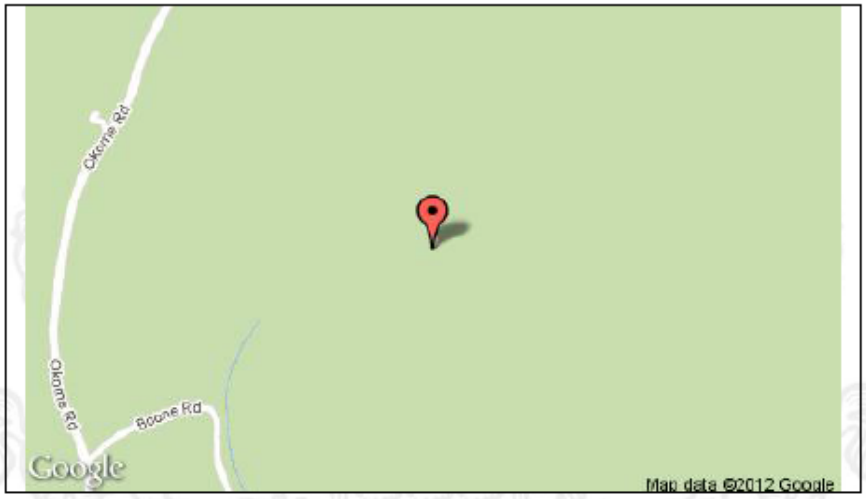
APPENDICES

Appendix I: Example of Pennsylvania Natural Diversity Index Inventory Report

PNDI Project Environmental Review Receipt Project Search ID: 20120211338613

1. PROJECT INFORMATION

Project Name: **Site 1**
Date of review: **2/11/2012 10:27:00 AM**
Project Category: **Hazardous Waste Clean-up, Site Remediation, and Reclamation,Other**
Project Area: **N/A**
County: **Lycoming** Township/Municipality: **Cummings**
Quadrangle Name: **JERSEY MILLS** ~ ZIP Code: **17776**
Decimal Degrees: **41.363979 N, -77.378386 W**
Degrees Minutes Seconds: **41° 21' 50.3" N, -77° 22' 42.2" W**



2. SEARCH RESULTS

Agency	Results	Response
PA Game Commission	No Known Impact	No Further Review Required
PA Department of Conservation and Natural Resources	No Known Impact	No Further Review Required
PA Fish and Boat Commission	**Potential Impact**	**FURTHER REVIEW IS REQUIRED, See Agency Response**
U.S. Fish and Wildlife Service	No Known Impact	No Further Review Required

As summarized above, Pennsylvania Natural Diversity Inventory (PNDI) records indicate there may be potential impacts to threatened and endangered and/or special concern species and resources within the project area. If the response above indicates "No Further Review Required" no additional communication with the respective agency is required. If the response is "Further Review Required" or "See Agency Response," refer to the appropriate agency comments below. Please see the DEP Information Section of this receipt if a PA Department of Environmental Protection Permit is required.

3. AGENCY COMMENTS

Regardless of whether a DEP permit is necessary for this proposed project, any potential impacts to threatened and endangered species and/or special concern species and resources must be resolved with the appropriate jurisdictional agency. In some cases, a permit or authorization from the jurisdictional agency may be needed if adverse impacts to these species and habitats cannot be avoided.

These agency determinations and responses are **valid for one year** (from the date of the review), and are based on the project information that was provided, including the exact project location; the project type, description, and features; and any responses to questions that were generated during this search. If any of the following change: 1) project location, 2) project size or configuration, 3) project type, or 4) responses to the questions that were asked during the online review, the results of this review are not valid, and the review must be searched again via the PNDI Environmental Review Tool and resubmitted to the jurisdictional agencies. The PNDI tool is a primary screening tool, and a desktop review may reveal more or fewer impacts than what is listed on this PNDI receipt. The jurisdictional agencies **strongly advise against** conducting surveys for the species listed on the receipt prior to consultation with the agencies.

PA Game Commission

RESPONSE: No Impact is anticipated to threatened and endangered species and/or special concern species and resources.

PA Department of Conservation and Natural Resources

RESPONSE: No Impact is anticipated to threatened and endangered species and/or special concern species and resources.

PA Fish and Boat Commission

RESPONSE: Further review of this project is necessary to resolve the potential impacts(s). Please send project information to this agency for review (see WHAT TO SEND).

PFBC Species: (Note: The PNDI tool is a primary screening tool, and a desktop review may reveal more or fewer species than what is listed below.)
Scientific Name: Sensitive Species**
Common Name:
Current Status: Special Concern Species*
Proposed Status: Special Concern Species*

U.S. Fish and Wildlife Service

RESPONSE: No impacts to federally listed or proposed species are anticipated. Therefore, no further consultation/coordination under the Endangered Species Act (87 Stat. 884, as amended; 16 U.S.C. 1531 *et seq.* is required. Because no take of federally listed species is anticipated, none is authorized. This response does not reflect potential Fish and Wildlife Service concerns under the Fish and Wildlife Coordination Act or other authorities.

* Special Concern Species or Resource - Plant or animal species classified as rare, tentatively undetermined or candidate as well as other taxa of conservation concern, significant natural communities, special concern populations (plants or animals) and unique geologic features.

** Sensitive Species - Species identified by the jurisdictinal agency as collectible, having economic value, or being susceptible to decline as a result of visitation.

WHAT TO SEND TO JURISDICTIONAL AGENCIES

If project information was requested by one or more of the agencies above, send the following information to the agency(s) seeking this information (see AGENCY CONTACT INFORMATION).

Check-list of *Minimum* Materials to be submitted:

____**SIGNED** copy of this Project Environmental Review Receipt
____Project narrative with a description of the overall project, the work to be performed, current physical characteristics of the site and acreage to be impacted.
____Project location information (name of USGS Quadrangle, Township/Municipality, and County)
____USGS 7.5-minute Quadrangle with project boundary clearly indicated, and quad name on the map

The inclusion of the following information may expedite the review process.
____A basic site plan(particularly showing the relationship of the project to the physical features such as wetlands, streams, ponds, rock outcrops, etc.)
____Color photos keyed to the basic site plan (i.e. showing on the site plan where and in what direction each photo was taken and the date of the photos)
____Information about the presence and location of wetlands in the project area, and how this was determined (e.g., by a qualified wetlands biologist), if wetlands are present in the project area, provide project plans showing the location of all project features, as well as wetlands and streams

4. DEP INFORMATION

The Pa Department of Environmental Protection (DEP) requires that a signed copy of this receipt, along with any required documentation from jurisdictional agencies concerning resolution of potential impacts, be submitted with applications for permits requiring PNDI review. For cases where a "Potential Impact" to threatened and endangered species has been identified before the application has been submitted to DEP, the application should not be submitted until the impact has been resolved. For cases where "Potential Impact" to special concern species and resources has been identified before the application has been submitted, the application should be submitted to DEP along with the PNDI receipt, a completed PNDI form and a USGS 7.5 minute quadrangle map with the project boundaries delineated on the map. The PNDI Receipt should also be submitted to the appropriate agency according to directions on the PNDI Receipt. DEP and the jurisdictional agency will work together to resolve the potential impact(s). See the DEP PNDI policy at http://www.naturalheritage.state.pa.us.

5. ADDITIONAL INFORMATION

The PNDI environmental review website is a **preliminary** screening tool. There are often delays in updating species status classifications. Because the proposed status represents the best available information regarding the conservation status of the species, state jurisdictional agency staff give the proposed statuses at least the same consideration as the current legal status. If surveys or further information reveal that a threatened and endangered and/or special concern species and resources exist in your project area, contact the appropriate jurisdictional agency/agencies immediately to identify and resolve any impacts.

For a list of species known to occur in the county where your project is located, please see the species lists by county found on the PA Natural Heritage Program (PNHP) home page (www.naturalheritage.state.pa.us). Also note that the PNDI Environmental Review Tool only contains information about species occurrences that have actually been reported to the PNHP.

6. AGENCY CONTACT INFORMATION

PA Department of Conservation and Natural Resources
Bureau of Forestry, Ecological Services Section
400 Market Street, PO Box 8552, Harrisburg, PA. 17105-8552
Fax:(717) 772-0271

U.S. Fish and Wildlife Service
Endangered Species Section
315 South Allen Street, Suite 322, State College, PA. 16801-4851
NO Faxes Please.

PA Fish and Boat Commission
Division of Environmental Services
450 Robinson Lane, Bellefonte, PA. 16823-7437
NO Faxes Please

PA Game Commission
Bureau of Wildlife Habitat Management
Division of Environmental Planning and Habitat Protection
2001 Elmerton Avenue, Harrisburg, PA. 17110-9797
Fax:(717) 787-6957

7. PROJECT CONTACT INFORMATION

Name:_____
Company/Business Name:_____
Address:_____
City, State, Zip:_____
Phone:(_____)_____Fax:(_____)_____
Email:_____

8. CERTIFICATION

I certify that ALL of the project information contained in this receipt (including project location, project size/configuration, project type, answers to questions) is true, accurate and complete. In addition, if the project type, location, size or configuration changes, or if the answers to any questions that were asked during this online review change, I agree to re-do the online environmental review.

_____ _____
applicant/project proponent signature date

Appendix II: Tentative Approval and Official Documentation for Study

pennsylvania
DEPARTMENT OF CONSERVATION
AND NATURAL RESOURCES

Rachel Carson State Office Building
P. O. Box 8552
Harrisburg, PA 17105-8552
March 6, 2012

Bureau of Forestry 717-214-3814

Dear Mr. Hershey:

Your request to conduct research entitled, " Investigation of Soil Gas Concentration and Migration Surrounding Well Pads", on the Tiadaghton State Forest has been evaluated and tentatively approved. This research has been assigned the reference number **SFRA-1202.** The approval process will be finalized by your return of the enclosed Conditions Acceptance form, properly signed. The Conditions Acceptance form states your willingness to abide by the listed conditions. **Once you sign and return the Conditions Acceptance form, you will not receive any other documents indicating approval from the Bureau of Forestry; this letter serves as the official documentation**. Please ensure that all persons involved in the project understand these conditions.

1. Prior to commencing any work on the site, you will provide the district forester a minimum of five days advance notice, excluding holidays and weekends. At that time, all applicable permits will be in your possession.

2. **The use of rebar or metal fasteners or tags in trees is not permitted for marking sample points**. In addition, all marking, tagging, and other materials necessary to conduct this study must meet the district forester's approval. The use of roads normally closed to public travel requires the district forester's approval.

3. On completion of work at the site, you will obtain the district forester's approval of the site condition. You are responsible for any cleanup of marking and other materials used on the site and/or repair work to the site as required by the district forester within ten days of the conclusion of the project.

4. You will annually provide the Bureau of Forestry with an update of the previous year's project activities and findings.

5. You will provide the Bureau of Forestry with copies of any published reports, articles, publications and so forth that result from this research. In instances where Bureau of

Forestry staff are considered co-investigator(s), then appropriate drafts of the publication must be reviewed and agreed upon prior to submission for publication. If the project is abandoned, you will provide the Bureau of Forestry copies of the available information from the project.

6. You will provide the district forester and the Bureau of Forestry, Resource Planning and Information Division, copies of labels from any chemicals used in association with the project.

7. If requested, you agree to supply the Bureau of Forestry with copies of data collected at the site including tally sheets and field notes.

8. The Bureau of Forestry reserves the right to withdraw permission to conduct this research if the Bureau of Forestry determines that the interests of the Commonwealth of Pennsylvania or the Bureau of Forestry are no longer being served.

9. The Bureau of Forestry or the Commonwealth of Pennsylvania is not relinquishing any rights or interests with this agreement.

Sincerely,

Matthew J. Keefer
Chief, Division of Resource Planning and Inventory
Bureau of Forestry
Department of Conservation and Natural Resources

Enclosure

cc: Daniel A. Devlin
Michael B. Lester
Jeffery S. Prowant

Appendix III: Sample Data

Control Site 1: Sampling Period 1

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
5/13/2012	9:40:23am	1050.00	2.0	Burgoon Sandstone	DkB	116.25	64	0.58	30.18
5/13/2012	09:47:13am	0.00	2.0	Burgoon Sandstone	CnD	83.65	64	0.58	30.18
5/13/2012	09:52:38am	0.00	2.0	Burgoon Sandstone	CnD	118.20	64	0.58	30.18
5/13/2012	09:56:29am	450.00	2.0	Burgoon Sandstone	DkB	83.30	64	0.58	30.18
5/13/2012	10:00:52am	0.00	2.0	Burgoon Sandstone	DkB	115.81	64	0.58	30.18
5/13/2012	10:04:21am	0.00	2.0	Burgoon Sandstone	DkB	82.95	64	0.58	30.18
5/13/2012	10:07:16am	0.00	2.0	Burgoon Sandstone	DkB	118.37	64	0.58	30.18
5/13/2012	10:10:28am	0.00	2.0	Burgoon Sandstone	DkB	83.58	64	0.58	30.18
5/13/2012	10:18:27am	0.00	2.0	Burgoon Sandstone	DkB	185.40	64	0.58	30.18
5/13/2012	10:23:15am	0.00	2.0	Burgoon Sandstone	CnB	235.14	64	0.58	30.18
5/13/2012	10:28:28am	650.00	2.0	Burgoon Sandstone	CnB	186.93	71.6	0.43	30.17
5/13/2012	10:32:31am	0.00	2.0	Burgoon Sandstone	CnD	166.21	71.6	0.43	30.17
5/13/2012	10:35:34am	0.00	2.0	Burgoon Sandstone	CnD	188.32	71.6	0.43	30.17
5/13/2012	10:38:55am	0.00	2.0	Burgoon Sandstone	CnD	236.97	71.6	0.43	30.17
5/13/2012	10:41:52am	1400.00	2.0	Burgoon Sandstone	CnB	182.67	71.6	0.43	30.17
5/13/2012	10:45:36am	0.00	2.0	Burgoon Sandstone	DkB	165.77	71.6	0.43	30.17
5/13/2012	10:49:30am	0.00	0.4	Burgoon Sandstone	DkB	184.58	71.6	0.43	30.17
5/13/2012	10:55:47am	1900.00	2.0	Burgoon Sandstone	DkB	233.58	71.6	0.43	30.17
5/13/2012	11:03:05am	400.00	2.0	Burgoon Sandstone	DkB	183.09	71.6	0.43	30.17
5/13/2012	11:06:14am	0.00	2.0	Burgoon Sandstone	DkB	170.52	71.6	0.43	30.17
5/13/2012	11:09:05am	0.00	2.0	Burgoon Sandstone	DkB	185.85	71.6	0.43	30.17
5/13/2012	11:11:35am	0.00	2.0	Burgoon Sandstone	DkB	236.83	71.6	0.43	30.17
5/13/2012	11:14:29am	0.00	2.0	Burgoon Sandstone	DkB	301.39	71.6	0.43	30.17
5/13/2012	11:18:01am	2150.00	2.0	Burgoon Sandstone	DkB	188.14	71.6	0.43	30.17
5/13/2012	11:21:23am	0.00	2.0	Burgoon Sandstone	DkB	167.01	71.6	0.43	30.17
5/13/2012	11:43:32am	450.00	2.0	Burgoon Sandstone	CnB	264.61	71.1	0.45	30.15
5/13/2012	11:47:25am	0.00	2.0	Burgoon Sandstone	CnB	301.55	71.1	0.45	30.15
5/13/2012	11:51:02am	150.00	2.0	Burgoon Sandstone	CnB	298.85	71.1	0.45	30.15
5/13/2012	11:56:31am	0.00	2.0	Burgoon Sandstone	CnB	261.48	71.1	0.45	30.15
5/13/2012	12:00:34pm	0.00	2.0	Burgoon Sandstone	CnD	250.79	71.1	0.45	30.15
5/13/2012	12:04:46pm	0.00	2.0	Burgoon Sandstone	CnD	265.19	71.1	0.45	30.15
5/13/2012	12:08:11pm	0.00	2.0	Burgoon Sandstone		298.43	71.1	0.45	30.15
5/13/2012	12:12:15pm	0.00	2.0	Burgoon Sandstone	CnB	297.60	71.1	0.45	30.15
5/13/2012	12:14:42pm	0.00	2.0	Burgoon Sandstone	CnB	260.75	71.1	0.45	30.15
5/13/2012	12:16:55pm	0.00	2.0	Burgoon Sandstone	DkB	250.88	71.1	0.45	30.15
5/13/2012	12:19:33pm	1150.00	2.0	Burgoon Sandstone	DkB	263.10	71.1	0.45	30.15
5/13/2012	12:24:20pm	5150.00	2.0	Burgoon Sandstone	DkB	303.57	71.6	0.46	30.15
5/13/2012	12:29:20pm	1150.00	2.0	Burgoon Sandstone	DkB	300.19	71.6	0.46	30.15
5/13/2012	12:33:53pm	1150.00	2.0	Burgoon Sandstone	DkB	265.17	71.6	0.46	30.15
5/13/2012	12:37:21pm	1150.00	2.0	Burgoon Sandstone	DkB	250.46	71.6	0.46	30.15
5/13/2012	12:40:32pm	0.00	2.0	Burgoon Sandstone	DkB	264.77	71.6	0.46	30.15
5/13/2012	12:43:23pm	1150.00	2.0	Burgoon Sandstone	DkB	302.28	71.6	0.46	30.15
5/13/2012	12:48:02pm	1150.00	2.0	Burgoon Sandstone	DkB	263.14	71.6	0.46	30.15
5/13/2012	12:51:50pm	1150.00	2.0	Burgoon Sandstone	DkB	249.44	71.6	0.46	30.15

Control Site 2

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
6/2/2012	09:18:54am	0.00	2.0	Burgoon Sandstone	DkB	300.74	61	0.64	29.76
6/2/2012	09:22:57am	0.00	2.0	Burgoon Sandstone	DkB	264.45	61	0.64	29.76
6/2/2012	09:28:30am	1250.00	2.0	Mauch Chunk Formation	DkB	247.81	59	0.58	29.78
6/2/2012	09:33:27am	50.00	2.0	Mauch Chunk Formation	CnB	264.47	59	0.58	29.78
6/2/2012	09:38:04am	1400.00	2.0	Mauch Chunk Formation	CnB	300.60	59	0.58	29.78
6/2/2012	09:44:24am	0.00	2.0	Mauch Chunk Formation	CnB	301.07	59	0.58	29.78
6/2/2012	09:48:47am	0.00	2.0	Mauch Chunk Formation	CnB	262.38	59	0.58	29.78
6/2/2012	09:53:31am	1300.00	2.0	Mauch Chunk Formation	CnB	249.84	59	0.58	29.78
6/2/2012	09:58:11am	0.00	2.0	Mauch Chunk Formation	CnB	263.18	59	0.58	29.78
6/2/2012	10:01:34am	0.00	2.0	Mauch Chunk Formation	CmB	301.04	59	0.58	29.78
6/2/2012	10:12:25am	2800.00	2.0	Mauch Chunk Formation	CnB	264.14	59	0.58	29.78
6/2/2012	10:19:19am	0.00	2.0	Burgoon Sandstone	CnB	251.57	59	0.58	29.78
6/2/2012	10:23:19am	0.00	2.0	Burgoon Sandstone	DkD	260.23	59	0.58	29.78
6/2/2012	10:27:14am	0.00	2.0	Burgoon Sandstone	DkD	299.82	57.9	0.62	29.79
6/2/2012	10:34:26am	0.00	2.0	Huntley Mountain Formation	DkD	282.95	57.9	0.62	29.79
6/2/2012	10:41:14am	0.00	2.0	Huntley Mountain Formation	DkD	263.31	57.9	0.62	29.79
6/2/2012	10:45:23am	0.00	2.0	Burgoon Sandstone	DkB	248.93	57.9	0.62	29.79
6/2/2012	10:49:32am	800.00	2.0	Burgoon Sandstone	DkB	262.23	57.9	0.62	29.79
6/2/2012	10:55:10am	0.00	2.0	Burgoon Sandstone	DkB	301.90	57.9	0.62	29.79
6/2/2012	11:02:00am	0.00	2.0	Burgoon Sandstone	DkB	236.23	57.9	0.62	29.79
6/2/2012	11:08:11am	0.00	1.5	Burgoon Sandstone	DkB	187.06	57.9	0.62	29.79
6/2/2012	11:59:00am	0.00	2.0	Mauch Chunk Formation	DkB	163.64	62.1	0.52	29.78
6/2/2012	12:03:09pm	0.00	2.0	Mauch Chunk Formation	CnB	186.41	62.1	0.52	29.78
6/2/2012	12:07:28pm	1350.00	2.0	Mauch Chunk Formation	CnB	237.72	62.1	0.52	29.78
6/2/2012	12:11:17pm	0.00	2.0	Mauch Chunk Formation	CnB	187.77	62.1	0.52	29.78
6/2/2012	12:15:56pm	0.00	2.0	Mauch Chunk Formation	CnB	166.92	62.1	0.52	29.78
6/2/2012	12:20:09pm	0.00	2.0	Mauch Chunk Formation	CnB	190.32	62.1	0.52	29.78
6/2/2012	12:23:40pm	0.00	2.0	Mauch Chunk Formation	CnB	243.17	62.1	0.52	29.78
6/2/2012	12:28:35pm	0.00	2.0	Mauch Chunk Formation	CnB	81.78	62.1	0.52	29.78
6/2/2012	12:31:54pm	0.00	2.0	Mauch Chunk Formation	CnB	117.94	62.1	0.52	29.78
6/2/2012	12:37:16pm	550.00	2.0	Mauch Chunk Formation	CnB	83.64	62.1	0.52	29.78
6/2/2012	12:42:08pm	0.00	2.0	Burgoon Sandstone	DkB	116.80	62.1	0.52	29.78
6/2/2012	12:48:22pm	0.00	2.0	Burgoon Sandstone	DkB	186.73	62.1	0.52	29.78
6/2/2012	12:54:55pm	150.00	2.0	Burgoon Sandstone	DkB	163.64	62.1	0.52	29.78
6/2/2012	01:02:25pm	900.00	2.0	Burgoon Sandstone	CnB	189.02	62.1	0.52	29.78
6/2/2012	01:08:31pm	900.00	2.0	Burgoon Sandstone	DkD	236.53	62.1	0.52	29.78
6/2/2012	01:12:57pm	900.00	2.0	Burgoon Sandstone	CnB	186.20	62.1	0.52	29.78
6/2/2012	01:17:33pm	900.00	1.5	Burgoon Sandstone	CnB	120.06	62.1	0.52	29.78
6/2/2012	01:22:47pm	2400.00	2.0	Burgoon Sandstone	CnB	85.14	62.1	0.52	29.78
6/2/2012	01:27:35pm	900.00	2.0	Burgoon Sandstone	CnB	85.97	68	0.43	29.76
6/2/2012	01:31:37pm	1150.00	2.0	Burgoon Sandstone	CnB	166.12	68	0.43	29.76
6/2/2012	01:37:24pm	5500.00	2.0	Mauch Chunk Formation	CnB	126.85	68	0.43	29.76

Control Site 3

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
6/23/2012	08:13:11am	3100.00	2.0	Mauch Chunk Formation	CmB	301.09	69.1	0.75	29.94
6/23/2012	08:16:57am	0.00	2.0	Mauch Chunk Formation	CmB	268.75	69.1	0.75	29.94
6/23/2012	08:20:21am	250.00	2.0	Mauch Chunk Formation	CnB	247.76	69.1	0.75	29.94
6/23/2012	08:24:16am	0.00	2.0	Burgoon Sandstone	CnB	264.11	71.1	0.68	29.96
6/23/2012	08:28:03am	0.00	2.0	Burgoon Sandstone	CnB	302.51	71.1	0.68	29.96
6/23/2012	08:33:28am	0.00	2.0	Burgoon Sandstone	CnB	297.98	71.1	0.68	29.96
6/23/2012	08:39:41am	0.00	2.0	Burgoon Sandstone	CnB	265.45	71.1	0.68	29.96
6/23/2012	08:45:05am	0.00	2.0	Burgoon Sandstone	CnB	249.75	71.1	0.68	29.96
6/23/2012	08:52:25am	0.00	2.0	Burgoon Sandstone	CnB	253.91	71.1	0.68	29.96
6/23/2012	08:57:32am	0.00	2.0	Burgoon Sandstone	DkD	297.93	71.1	0.68	29.96
6/23/2012	09:04:51am	0.00	2.0	Burgoon Sandstone	DkD	302.72	71.1	0.68	29.96
6/23/2012	09:10:41am	0.00	2.0	Burgoon Sandstone	CnB	263.45	71.1	0.68	29.96
6/23/2012	09:15:31am	1050.00	2.0	Burgoon Sandstone	CnB	248.53	71.1	0.68	29.96
6/23/2012	09:21:59am	0.00	2.0	Burgoon Sandstone	CnB	257.21	71.1	0.68	29.96
6/23/2012	09:29:23am	0.00	2.0	Burgoon Sandstone	DkD	299.44	73.9	0.64	29.95
6/23/2012	09:35:29am	0.00	1.5	Burgoon Sandstone	DkD	302.10	73.9	0.64	29.95
6/23/2012	09:39:25am	0.00	2.0	Mauch Chunk Formation	CnB	264.35	73.9	0.64	29.95
6/23/2012	09:47:58am	0.00	2.0	Mauch Chunk Formation	CmB	251.23	73.9	0.64	29.95
6/23/2012	09:52:59am	0.00	2.0	Mauch Chunk Formation	CmB	263.96	73.9	0.64	29.95
6/23/2012	09:56:17am	0.00	2.0	Mauch Chunk Formation	CmB	298.93	73.9	0.64	29.95
6/23/2012	10:33:47am	0.00	2.0	Mauch Chunk Formation	CmB	232.12	73.9	0.64	29.95
6/23/2012	10:36:58am	0.00	2.0	Mauch Chunk Formation	CmB	188.01	73.9	0.64	29.95
6/23/2012	10:39:47am	500.00	2.0	Mauch Chunk Formation	CnB	168.59	73.9	0.64	29.95
6/23/2012	10:43:42am	0.00	2.0	Burgoon Sandstone	CnB	189.19	73.9	0.64	29.95
6/23/2012	10:47:08am	1950.00	2.0	Burgoon Sandstone	CnB	236.14	73.9	0.64	29.95
6/23/2012	10:51:11am	500.00	2.0	Burgoon Sandstone	CnB	188.27	73.9	0.64	29.95
6/23/2012	10:57:12am	0.00	2.0	Burgoon Sandstone	CnB	166.87	79	0.42	29.95
6/23/2012	11:01:20am	0.00	2.0	Burgoon Sandstone	CnB	187.61	79	0.42	29.95
6/23/2012	11:04:46am	0.00	2.0	Burgoon Sandstone	CnB	234.15	79	0.42	29.95
6/23/2012	11:13:29am	0.00	2.0	Burgoon Sandstone	CnB	184.97	79	0.42	29.95
6/23/2012	11:19:25am	950.00	2.0	Burgoon Sandstone	CnB	163.50	79	0.42	29.95
6/23/2012	11:24:11am	0.00	2.0	Burgoon Sandstone	CnB	187.27	79	0.42	29.95
6/23/2012	11:29:44am	0.00	1.5	Burgoon Sandstone	CnB	230.34	79	0.42	29.95
6/23/2012	11:36:44am	0.00	2.0	Mauch Chunk Formation	CnB	185.59	79	0.42	29.95
6/23/2012	11:43:19am	0.00	1.5	Mauch Chunk Formation	CnB	163.18	79	0.42	29.95
6/23/2012	11:49:48am	0.00	1.5	Mauch Chunk Formation	CmB	186.30	79	0.42	29.95
6/23/2012	11:55:47am	0.00	2.0	Mauch Chunk Formation	CnB	116.65	79	0.42	29.95
6/23/2012	12:01:56pm	0.00	2.0	Mauch Chunk Formation	CnB	81.16	79	0.42	29.95
6/23/2012	12:06:44pm	0.00	2.0	Burgoon Sandstone	CnB	119.51	79	0.42	29.95
6/23/2012	12:10:41pm	0.00	2.0	Burgoon Sandstone	CnB	83.79	79	0.42	29.95
6/23/2012	12:13:40pm	0.00	2.0	Burgoon Sandstone	CnB	117.27	79	0.42	29.95
6/23/2012	12:19:30pm	0.00	1.5	Burgoon Sandstone	CnB	85.38	79	0.42	29.95
6/23/2012	12:24:08pm	0.00	2.0	Mauch Chunk Formation	CnB	117.44	81	0.35	29.95
6/23/2012	12:28:29pm	0.00	2.0	Mauch Chunk Formation	CnB	86.90	81	0.35	29.95

Control Site 4

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
8/11/2012	09:37:21am	0.00	2.0	Burgoon Sandstone	DkD	306.34	73	0.79	29.83
8/11/2012	09:43:24am	750.00	2.0	Burgoon Sandstone	DkB	270.35	73	0.79	29.83
8/11/2012	09:47:24am	0.00	2.0	Burgoon Sandstone	DkB	250.72	73	0.79	29.83
8/11/2012	09:51:47am	0.00	2.0	Burgoon Sandstone	DkB	262.07	73	0.79	29.83
8/11/2012	09:57:44am	0.00	2.0	Burgoon Sandstone	DkB	304.55	73	0.79	29.83
8/11/2012	10:03:07am	0.00	2.0	Burgoon Sandstone	DkB	298.63	73	0.79	29.83
8/11/2012	10:06:46am	0.00	2.0	Burgoon Sandstone	DkB	263.89	73	0.79	29.83
8/11/2012	10:09:29am	0.00	2.0	Burgoon Sandstone	DkB	247.19	73	0.79	29.83
8/11/2012	10:12:32am	0.00	2.0	Burgoon Sandstone	DkB	262.79	73	0.79	29.83
8/11/2012	10:16:14am	0.00	2.0	Burgoon Sandstone	DkB	299.83	73	0.79	29.83
8/11/2012	10:30:05am	0.00	2.0	Mauch Chunk Formation	DkD	251.41	77	0.69	29.83
8/11/2012	10:35:19am	0.00	2.0	Mauch Chunk Formation	DkD	263.21	77	0.69	29.83
8/11/2012	10:40:07am	0.00	2.0	Mauch Chunk Formation	DkD	301.49	77	0.69	29.83
8/11/2012	10:44:29am	0.00	2.0	Mauch Chunk Formation	DkD	299.93	77	0.69	29.83
8/11/2012	10:47:48am	0.00	2.0	Mauch Chunk Formation	DkD	262.97	77	0.69	29.83
8/11/2012	10:51:30am	0.00	2.0	Mauch Chunk Formation	DkD	250.88	77	0.69	29.83
8/11/2012	10:56:04am	0.00	1.0	Burgoon Sandstone	DkB	284.57	77	0.69	29.83
8/11/2012	10:59:12am	0.00	2.0	Burgoon Sandstone	DkD	300.45	77	0.69	29.83
8/11/2012	11:03:18am	0.00	2.0	Burgoon Sandstone	DkB	232.24	77	0.69	29.83
8/11/2012	11:07:19am	0.00	2.0	Burgoon Sandstone	DkB	184.75	77	0.69	29.83
8/11/2012	11:13:58am	600.00	2.0	Burgoon Sandstone	DkB	165.57	77	0.69	29.83
8/11/2012	11:18:37am	0.00	2.0	Burgoon Sandstone	DkB	185.31	77	0.69	29.83
8/11/2012	11:23:45am	0.00	2.0	Burgoon Sandstone	DkB	235.63	77	0.69	29.83
8/11/2012	11:27:01am	200.00	2.0	Burgoon Sandstone	DkB	186.59	79	0.5	29.82
8/11/2012	11:30:29am	0.00	2.0	Burgoon Sandstone	DkB	165.07	79	0.5	29.82
8/11/2012	11:33:46am	0.00	2.0	Burgoon Sandstone	DkB	188.84	79	0.5	29.82
8/11/2012	11:37:25am	0.00	2.0	Burgoon Sandstone	DkB	236.02	79	0.5	29.82
8/11/2012	11:40:11am	0.00	2.0	Burgoon Sandstone	DkB	188.87	79	0.5	29.82
8/11/2012	11:43:24am	0.00	2.0	Mauch Chunk Formation	DkD	167.74	79	0.5	29.82
8/11/2012	11:46:12am	0.00	2.0	Mauch Chunk Formation	DkD	185.11	79	0.5	29.82
8/11/2012	11:51:09am	0.00	2.0	Mauch Chunk Formation	DkD	233.91	79	0.5	29.82
8/11/2012	11:55:11am	0.00	2.0	Mauch Chunk Formation	DkD	184.07	79	0.5	29.82
8/11/2012	11:58:26am	0.00	1.5	Mauch Chunk Formation	DkB	164.42	79	0.5	29.82
8/11/2012	12:02:54pm	0.00	2.0	Mauch Chunk Formation	DkB	83.26	79	0.5	29.82
8/11/2012	12:07:29pm	0.00	2.0	Mauch Chunk Formation	DkB	115.89	79	0.5	29.82
8/11/2012	12:12:20pm	0.00	2.0	Mauch Chunk Formation	DkB	82.61	79	0.5	29.82
8/11/2012	12:17:01pm	0.00	2.0	Burgoon Sandstone	DkB	115.61	79	0.5	29.82
8/11/2012	12:19:52pm	0.00	2.0	Burgoon Sandstone	DkB	82.82	79	0.5	29.82
8/11/2012	12:23:35pm	0.00	2.0	Burgoon Sandstone	DkB	117.88	79	0.5	29.82
8/11/2012	12:27:07pm	0.00	2.0	Burgoon Sandstone	DkB	83.13	80.1	0.5	29.82
8/11/2012	12:30:27pm	150000.00	2.0	Burgoon Sandstone	DkB	117.49	80.1	0.5	29.82

Experimental Site 1

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
9/29/2012	11:48:07am	250.00	1.5	Burgoon Sandstone	DkB	266.34	64	0.5	29.97
9/29/2012	11:53:54am	4250.00	2.0	Burgoon Sandstone	DkB	251.26	64	0.5	29.97
9/29/2012	12:03:51pm	2650.00	2.0	Burgoon Sandstone	DkB	263.45	64	0.5	29.97
9/29/2012	12:08:52pm	0.00	2.0	Burgoon Sandstone	DkB	304.75	64	0.5	29.97
9/29/2012	12:13:52pm	0.00	2.0	Burgoon Sandstone	DkD	298.91	64	0.5	29.97
9/29/2012	12:19:44pm	650.00	2.0	Burgoon Sandstone	DkD	265.26	64	0.5	29.97
9/29/2012	12:25:21pm	50.00	2.0	Burgoon Sandstone	DkD	248.56	63	0.5	29.97
9/29/2012	12:28:59pm	1350.00	2.0	Burgoon Sandstone	CmB	262.68	63	0.5	29.97
9/29/2012	12:33:36pm	500.00	2.0	Burgoon Sandstone	CmB	300.79	63	0.5	29.97
9/29/2012	12:39:54pm	0.00	2.0	Burgoon Sandstone	CmB	299.99	63	0.5	29.97
9/29/2012	12:48:32pm	0.00	2.0	Burgoon Sandstone	CmB	256.99	63	0.5	29.97
9/29/2012	12:53:06pm	0.00	2.0	Burgoon Sandstone	CmB	251.09	63	0.5	29.97
9/29/2012	12:57:57pm	0.00	2.0	Burgoon Sandstone	DlE	264.11	63	0.5	29.97
9/29/2012	01:02:58pm	0.00	2.0	Burgoon Sandstone	DlE	283.77	63	0.5	29.97
9/29/2012	01:08:42pm	0.00	2.0	Burgoon Sandstone	DlE	302.62	63	0.5	29.97
9/29/2012	01:14:45pm	0.00	2.0	Burgoon Sandstone	DlE	268.73	63	0.5	29.97
9/29/2012	01:19:13pm	650.00	2.0	Burgoon Sandstone	DkB	250.80	63	0.5	29.97
9/29/2012	01:23:27pm	0.00	2.0	Burgoon Sandstone	DkB	266.00	63	0.5	29.97
9/29/2012	01:27:19pm	2400.00	1.5	Burgoon Sandstone	DkB	300.41	64	0.45	29.95
9/29/2012	01:33:04pm	1100.00	2.0	Burgoon Sandstone	DkB	302.56	64	0.45	29.95
9/29/2012	01:57:38pm	0.00	2.0	Burgoon Sandstone	CmB	192.57	64	0.45	29.95
9/29/2012	02:01:58pm	1200.00	2.0	Burgoon Sandstone	DkB	169.88	64	0.45	29.95
9/29/2012	02:06:53pm	0.00	2.0	Burgoon Sandstone	DkB	187.00	64	0.45	29.95
9/29/2012	02:10:14pm	0.00	2.0	Burgoon Sandstone	DkD	234.68	64	0.45	29.95
9/29/2012	02:14:14pm	0.00	2.0	Burgoon Sandstone	DkD	189.67	64	0.45	29.95
9/29/2012	02:18:39pm	0.00	2.0	Burgoon Sandstone	DkD	166.43	64	0.45	29.95
9/29/2012	02:26:46pm	200.00	2.0	Burgoon Sandstone	CmB	184.73	64.9	0.45	29.93
9/29/2012	02:33:54pm	1200.00	2.0	Burgoon Sandstone	CmB	233.39	64.9	0.45	29.93
9/29/2012	02:40:28pm	200.00	2.0	Burgoon Sandstone	CmB	187.88	64.9	0.45	29.93
9/29/2012	02:45:54pm	200.00	2.0	Burgoon Sandstone	CmB	164.94	64.9	0.45	29.93
9/29/2012	02:49:46pm	200.00	2.0	Burgoon Sandstone	CmB	187.83	64.9	0.45	29.93
9/29/2012	02:54:55pm	900.00	2.0	Burgoon Sandstone	DlE	236.26	64.9	0.45	29.93
9/29/2012	02:59:17pm	1250.00	2.0	Burgoon Sandstone	CmB	181.36	64.9	0.45	29.93
9/29/2012	03:04:41pm	1150.00	2.0	Burgoon Sandstone	CmB	169.34	64.9	0.45	29.93
9/29/2012	03:10:45pm	1500.00	2.0	Burgoon Sandstone	CmB	189.78	64.9	0.45	29.93
9/29/2012	03:16:59pm	1150.00	2.0	Burgoon Sandstone	CmB	225.84	64.9	0.45	29.93
9/29/2012	03:30:55pm	1150.00	2.0	Burgoon Sandstone	CmB	124.00	63	0.5	29.92
9/29/2012	03:36:35pm	3400.00	2.0	Burgoon Sandstone	CmB	84.15	63	0.5	29.92
9/29/2012	03:40:35pm	1200.00	2.0	Burgoon Sandstone	DkD	114.94	63	0.5	29.92
9/29/2012	03:46:46pm	1200.00	2.0	Burgoon Sandstone	CmB	84.55	63	0.5	29.92
9/29/2012	03:51:39pm	1700.00	2.0	Burgoon Sandstone	CmB	112.74	63	0.5	29.92
9/29/2012	03:55:49pm	6500.00	2.0	Burgoon Sandstone	CmB	86.79	63	0.5	29.92
9/29/2012	04:03:24pm	0.00	2.0	Burgoon Sandstone	CmB	115.62	63	0.5	29.92
9/29/2012	04:06:38pm	1200.00	2.0	Burgoon Sandstone	CmB	87.92	63	0.5	29.92

Control Site 1: Sampling Period 2

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
9/30/2012	11:13:19am	0.00	2.0	Burgoon Sandstone	CnD	298.47	55.9	0.75	29.86
9/30/2012	11:16:37am	0.00	2.0	Burgoon Sandstone	CnD	234.61	55.9	0.75	29.86
9/30/2012	11:21:07am	0.00	2.0	Burgoon Sandstone	CnB	299.38	55.9	0.75	29.86
9/30/2012	11:25:20am	0.00	2.0	Burgoon Sandstone	CnB	263.68	60.1	0.62	29.86
9/30/2012	11:27:55am	950.00	2.0	Burgoon Sandstone	DkB	250.89	60.1	0.62	29.86
9/30/2012	11:30:45am	200.00	2.0	Burgoon Sandstone	DkB	263.73	60.1	0.62	29.86
9/30/2012	11:34:48am	1550.00	2.0	Burgoon Sandstone	DkB	300.87	60.1	0.62	29.86
9/30/2012	11:40:42am	200.00	2.0	Burgoon Sandstone	DkB	299.00	60.1	0.62	29.86
9/30/2012	11:45:15am	0.00	2.0	Burgoon Sandstone	DkB	263.34	60.1	0.62	29.86
9/30/2012	11:48:24am	0.00	2.0	Burgoon Sandstone	DkB	253.24	60.1	0.62	29.86
9/30/2012	11:51:29am	0.00	2.0	Burgoon Sandstone	DkB	264.50	60.1	0.62	29.86
9/30/2012	11:53:56am	0.00	2.0	Burgoon Sandstone	DkB	301.53	60.1	0.62	29.86
9/30/2012	11:57:33am	0.00	2.0	Burgoon Sandstone	DkB	300.80	60.1	0.62	29.86
9/30/2012	12:00:30pm	0.00	2.0	Burgoon Sandstone	DkB	262.52	60.1	0.62	29.86
9/30/2012	12:03:16pm	0.00	2.0	Burgoon Sandstone	DkB	251.23	60.1	0.62	29.86
9/30/2012	12:06:12pm	50000.00	2.0	Burgoon Sandstone	CnB	264.28	60.1	0.62	29.86
9/30/2012	12:10:46pm	0.00	2.0	Burgoon Sandstone	CnB	300.40	60.1	0.62	29.86
9/30/2012	12:14:25pm	4200.00	2.0	Burgoon Sandstone	CnB	299.25	60.1	0.62	29.86
9/30/2012	12:25:21pm	0.00	2.0	Burgoon Sandstone	CnB	260.21	60.1	0.57	29.85
9/30/2012	12:29:54pm	50.00	2.0	Burgoon Sandstone	CnD	250.52	60.1	0.57	29.85
9/30/2012	12:34:03pm	0.00	2.0	Burgoon Sandstone	CnD	262.07	60.1	0.57	29.85
9/30/2012	01:33:50pm	1700.00	2.0	Burgoon Sandstone	CnB	184.19	57.9	0.65	29.84
9/30/2012	01:40:55pm	0.00	2.0	Burgoon Sandstone	DkB	167.22	57.9	0.65	29.84
9/30/2012	01:44:14pm	1200.00	2.0	Burgoon Sandstone	DkB	189.44	57.9	0.65	29.84
9/30/2012	01:49:00pm	650.00	2.0	Burgoon Sandstone	DkB	232.74	57.9	0.65	29.84
9/30/2012	01:54:35pm	2100.00	2.0	Burgoon Sandstone	DkB	185.21	57.9	0.65	29.84
9/30/2012	01:57:43pm	0.00	2.0	Burgoon Sandstone	DkB	167.88	57.9	0.65	29.84
9/30/2012	02:00:34pm	0.00	2.0	Burgoon Sandstone	DkB	185.22	57.9	0.65	29.84
9/30/2012	02:03:13pm	850.00	2.0	Burgoon Sandstone	DkB	235.87	57.9	0.65	29.84
9/30/2012	02:06:10pm	850.00	2.0	Burgoon Sandstone	DkB	187.86	57.9	0.65	29.84
9/30/2012	02:09:48pm	1050.00	2.0	Burgoon Sandstone	DkB	165.32	57.9	0.65	29.84
9/30/2012	02:12:52pm	0.00	2.0	Burgoon Sandstone	DkB	188.38	57.9	0.65	29.84
9/30/2012	02:15:42pm	0.00	2.0	Burgoon Sandstone	CnB	235.55	57.9	0.65	29.84
9/30/2012	02:18:51pm	0.00	2.0	Burgoon Sandstone	CnB	186.99	57.9	0.65	29.84
9/30/2012	02:21:51pm	0.00	2.0	Burgoon Sandstone	CnD	167.78	57.9	0.65	29.84
9/30/2012	02:24:51pm	0.00	2.0	Burgoon Sandstone	CnD	186.42	57	0.81	29.84
9/30/2012	02:28:07pm	1150.00	2.0	Burgoon Sandstone	CnD	116.31	57	0.81	29.84
9/30/2012	02:34:37pm	1150.00	2.0	Burgoon Sandstone	DkB	83.09	57	0.81	29.84
9/30/2012	02:39:19pm	2950.00	2.0	Burgoon Sandstone	DkB	117.87	57	0.81	29.84
9/30/2012	02:46:42pm	1150.00	2.0	Burgoon Sandstone	DkB	82.14	57	0.81	29.84
9/30/2012	02:49:31pm	0.00	2.0	Burgoon Sandstone	DkB	120.23	57	0.81	29.84
9/30/2012	02:52:15pm	1000.00	2.0	Burgoon Sandstone	DkB	84.59	57	0.81	29.84
9/30/2012	02:55:09pm	1150.00	2.0	Burgoon Sandstone	DkB	114.87	57	0.81	29.84
9/30/2012	02:57:52pm	1150.00	2.0	Burgoon Sandstone	CnD	83.19	57	0.81	29.84

Experimental Site 2

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
10/13/2012	12:52:56pm	1000.00	2.0	Burgoon Sandstone	CnB	300.93	48.9	0.41	30.42
10/13/2012	12:55:49pm	0.00	2.0	Burgoon Sandstone	CnB	265.28	48.9	0.41	30.42
10/13/2012	12:59:39pm	150.00	2.0	Burgoon Sandstone	CnB	248.14	48.9	0.41	30.42
10/13/2012	01:03:43pm	0.00	2.0	Burgoon Sandstone	DlE	262.92	48.9	0.41	30.42
10/13/2012	01:09:48pm	350.00	2.0	Burgoon Sandstone	DlE	300.59	48.9	0.41	30.42
10/13/2012	01:16:18pm	0.00	2.0	Burgoon Sandstone	DlE	290.90	48.9	0.41	30.42
10/13/2012	01:21:16pm	0.00	2.0	Burgoon Sandstone	DlE	263.44	48.9	0.41	30.42
10/13/2012	01:28:14pm	0.00	1.0	Huntley Mountain Formation	DlE	257.92	51.80	0.38	30.37
10/13/2012	01:34:08pm	0.00	2.0	Huntley Mountain Formation	DlE	265.04	51.8	0.38	30.37
10/13/2012	01:39:08pm	250.00	2.0	Huntley Mountain Formation	DlE	296.83	51.8	0.38	30.37
10/13/2012	01:46:31pm	100.00	2.0	Huntley Mountain Formation	DkD	303.80	51.8	0.38	30.37
10/13/2012	01:52:21pm	0.00	2.0	Burgoon Sandstone	DlE	258.20	51.8	0.38	30.37
10/13/2012	01:59:04pm	0.00	2.0	Burgoon Sandstone	DkD	250.09	51.8	0.38	30.37
10/13/2012	02:03:08pm	100.00	2.0	Huntley Mountain Formation	DkD	262.65	51.8	0.38	30.37
10/13/2012	02:09:01pm	100.00	2.0	Huntley Mountain Formation	DkD	242.20	51.8	0.38	30.37
10/13/2012	02:13:55pm	100.00	2.0	Huntley Mountain Formation	DkD	300.56	51.8	0.38	30.37
10/13/2012	02:21:11pm	0.00	1.5	Burgoon Sandstone	DlE	270.67	51.8	0.38	30.37
10/13/2012	02:30:07pm	0.00	2.0	Burgoon Sandstone	CnB	250.98	52	0.37	30.37
10/13/2012	02:42:41pm	650.00	2.0	Burgoon Sandstone	CnB	262.06	52	0.37	30.37
10/13/2012	02:46:57pm	0.00	2.0	Burgoon Sandstone	CnB	302.73	52	0.37	30.37
10/13/2012	03:04:20pm	50.00	2.0	Burgoon Sandstone	CnB	236.73	52	0.37	30.37
10/13/2012	03:08:39pm	1200.00	2.0	Burgoon Sandstone	CnB	188.31	52	0.37	30.37
10/13/2012	03:12:33pm	750.00	2.0	Burgoon Sandstone	CnB	165.96	52	0.37	30.37
10/13/2012	03:16:12pm	1200.00	2.0	Burgoon Sandstone	DlE	184.58	52	0.37	30.37
10/13/2012	03:23:24pm	1200.00	2.0	Burgoon Sandstone	DlE	237.52	52	0.37	30.37
10/13/2012	03:26:59pm	0.00	1.0	Burgoon Sandstone	DlE	191.34	52	0.38	30.35
10/13/2012	03:32:55pm	50.00	1.0	Huntley Mountain Formation	DlE	165.34	52	0.38	30.35
10/13/2012	03:41:05pm	1200.00	1.5	Huntley Mountain Formation	DlE	188.23	52	0.38	30.35
10/13/2012	03:47:43pm	0.00	2.0	Huntley Mountain Formation	DlE	232.07	52	0.38	30.35
10/13/2012	03:54:15pm	0.00	1.5	Burgoon Sandstone	CnB	186.84	52	0.38	30.35
10/13/2012	03:58:35pm	0.00	2.0	Burgoon Sandstone	CnB	156.94	52	0.38	30.35
10/13/2012	04:05:37pm	0.00	1.0	Burgoon Sandstone	DlE	184.05	52	0.38	30.35
10/13/2012	04:13:05pm	0.00	2.0	Burgoon Sandstone	CnB	178.35	52	0.38	30.35
10/13/2012	04:20:46pm	1200.00	2.0	Burgoon Sandstone	CnB	166.57	52	0.38	30.35
10/13/2012	04:26:21pm	1200.00	2.0	Burgoon Sandstone	CnB	184.98	52	0.38	30.32
10/13/2012	04:31:11pm	1200.00	2.0	Burgoon Sandstone	CnB	119.52	52	0.38	30.32
10/13/2012	04:34:27pm	1200.00	2.0	Burgoon Sandstone	CnB	88.09	52	0.38	30.32
10/13/2012	04:38:15pm	1200.00	2.0	Burgoon Sandstone	DlE	118.52	52	0.38	30.32
10/13/2012	04:42:16pm	750.00	2.0	Burgoon Sandstone	CnB	82.70	52	0.38	30.32
10/13/2012	04:47:16pm	1350.00	2.0	Burgoon Sandstone	CnB	117.68	52	0.38	30.32
10/13/2012	04:51:56pm	1350.00	2.0	Burgoon Sandstone	CnB	84.84	52	0.38	30.32
10/13/2012	04:55:47pm	750.00	1.5	Burgoon Sandstone	CnB	118.07	52	0.38	30.32
10/13/2012	05:09:14pm	5000.00	2.0	Burgoon Sandstone	CnB	86.48	52	0.38	30.32

Experimental Site 3

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
10/14/2012	12:28:06pm	2000.00	2.0	Burgoon Sandstone	DeC	298.99	63	0.52	30.05
10/14/2012	12:35:08pm	0.00	2.0	Burgoon Sandstone	DeC	301.67	63	0.52	30.05
10/14/2012	12:39:07pm	0.00	2.0	Burgoon Sandstone	DeC	265.80	63	0.52	30.05
10/14/2012	12:45:10pm	0.00	2.0	Burgoon Sandstone	DeC	223.02	63	0.52	30.05
10/14/2012	12:52:05pm	0.00	2.0	Burgoon Sandstone	DeC	182.14	63	0.52	30.05
10/14/2012	12:56:10pm	0.00	2.0	Burgoon Sandstone	CmB	207.25	63	0.52	30.05
10/14/2012	01:01:38pm	0.00	1.5	Burgoon Sandstone	CmB	262.63	63	0.52	30.05
10/14/2012	01:07:17pm	0.00	2.0	Burgoon Sandstone	CmB	185.54	63	0.52	30.05
10/14/2012	01:10:41pm	0.00	2.0	Burgoon Sandstone	CmB	120.76	63	0.52	30.05
10/14/2012	01:14:50pm	1050.00	2.0	Burgoon Sandstone	DeC	168.70	63	0.52	30.05
10/14/2012	01:18:53pm	350.00	2.0	Burgoon Sandstone	DeC	189.24	63	0.52	30.05
10/14/2012	01:23:17pm	0.00	2.0	Burgoon Sandstone	DeC	237.89	63	0.52	30.05
10/14/2012	01:26:54pm	1650.00	2.0	Burgoon Sandstone	CmB	187.62	64.9	0.5	30.01
10/14/2012	01:45:03pm	0.00	2.0	Burgoon Sandstone	CmB	117.18	64.9	0.5	30.01
10/14/2012	01:55:21pm	0.00	2.0	Burgoon Sandstone	CmB	250.24	64.9	0.5	30.01
10/14/2012	01:58:47pm	0.00	2.0	Burgoon Sandstone	CmB	261.05	64.9	0.5	30.01
10/14/2012	02:03:58pm	100.00	2.0	Burgoon Sandstone	CmB	300.73	64.9	0.5	30.01
10/14/2012	02:14:25pm	1200.00	2.0	Burgoon Sandstone	CmB	234.15	64.9	0.5	30.01
10/14/2012	02:17:53pm	1200.00	2.0	Burgoon Sandstone	CmB	183.03	64.9	0.5	30.01
10/14/2012	02:22:23pm	1200.00	1.0	Burgoon Sandstone	CmB	165.34	64.9	0.5	30.01
10/14/2012	02:25:54pm	1200.00	2.0	Burgoon Sandstone	KlC	186.16	66.9	0.49	29.99
10/14/2012	02:32:57pm	200.00	2.0	Mauch Chunk Formation	KlC	300.56	66.9	0.49	29.99
10/14/2012	02:35:59pm	50.00	2.0	Mauch Chunk Formation	KlC	265.59	66.9	0.49	29.99
10/14/2012	02:39:32pm	0.00	2.0	Burgoon Sandstone	KlC	248.42	66.9	0.49	29.99
10/14/2012	02:42:14pm	50.00	2.0	Burgoon Sandstone	CmB	265.14	66.9	0.49	29.99
10/14/2012	02:45:03pm	1250.00	2.0	Burgoon Sandstone	CmB	303.04	66.9	0.49	29.99
10/14/2012	02:58:29pm	0.00	2.0	Mauch Chunk Formation	KlC	236.06	66.9	0.49	29.99
10/14/2012	03:02:21pm	50.00	1.0	Mauch Chunk Formation	CmB	301.21	66.9	0.49	29.99
10/14/2012	03:05:40pm	0.00	2.0	Mauch Chunk Formation	CmB	268.29	66.9	0.49	29.99
10/14/2012	03:08:55pm	100.00	2.0	Burgoon Sandstone	KlC	252.04	66.9	0.49	29.99
10/14/2012	03:12:40pm	800.00	2.0	Burgoon Sandstone	CmB	264.56	66.9	0.49	29.99
10/14/2012	03:17:37pm	1200.00	2.0	Burgoon Sandstone	CmB	168.95	66.9	0.49	29.99
10/14/2012	03:20:47pm	200.00	2.0	Burgoon Sandstone	KlC	188.62	66.9	0.49	29.99
10/14/2012	03:24:19pm	1250.00	2.0	Burgoon Sandstone	CmB	115.30	66.9	0.51	29.95
10/14/2012	03:28:17pm	1250.00	2.0	Burgoon Sandstone	CmB	81.67	66.9	0.51	29.95
10/14/2012	03:31:21pm	2000.00	2.0	Burgoon Sandstone	CmB	117.75	66.9	0.51	29.95
10/14/2012	03:35:29pm	1250.00	2.0	Burgoon Sandstone	CmB	184.31	66.9	0.51	29.95
10/14/2012	03:38:27pm	1250.00	2.0	Burgoon Sandstone	CmB	164.99	66.9	0.51	29.95
10/14/2012	03:44:08pm	1550.00	2.0	Burgoon Sandstone	CmB	87.71	66.9	0.51	29.95
10/14/2012	03:49:46pm	1250.00	2.0	Burgoon Sandstone	CmB	87.70	66.9	0.51	29.95
10/14/2012	03:56:24pm	1250.00	1.5	Burgoon Sandstone	CmB	83.27	66.9	0.51	29.95

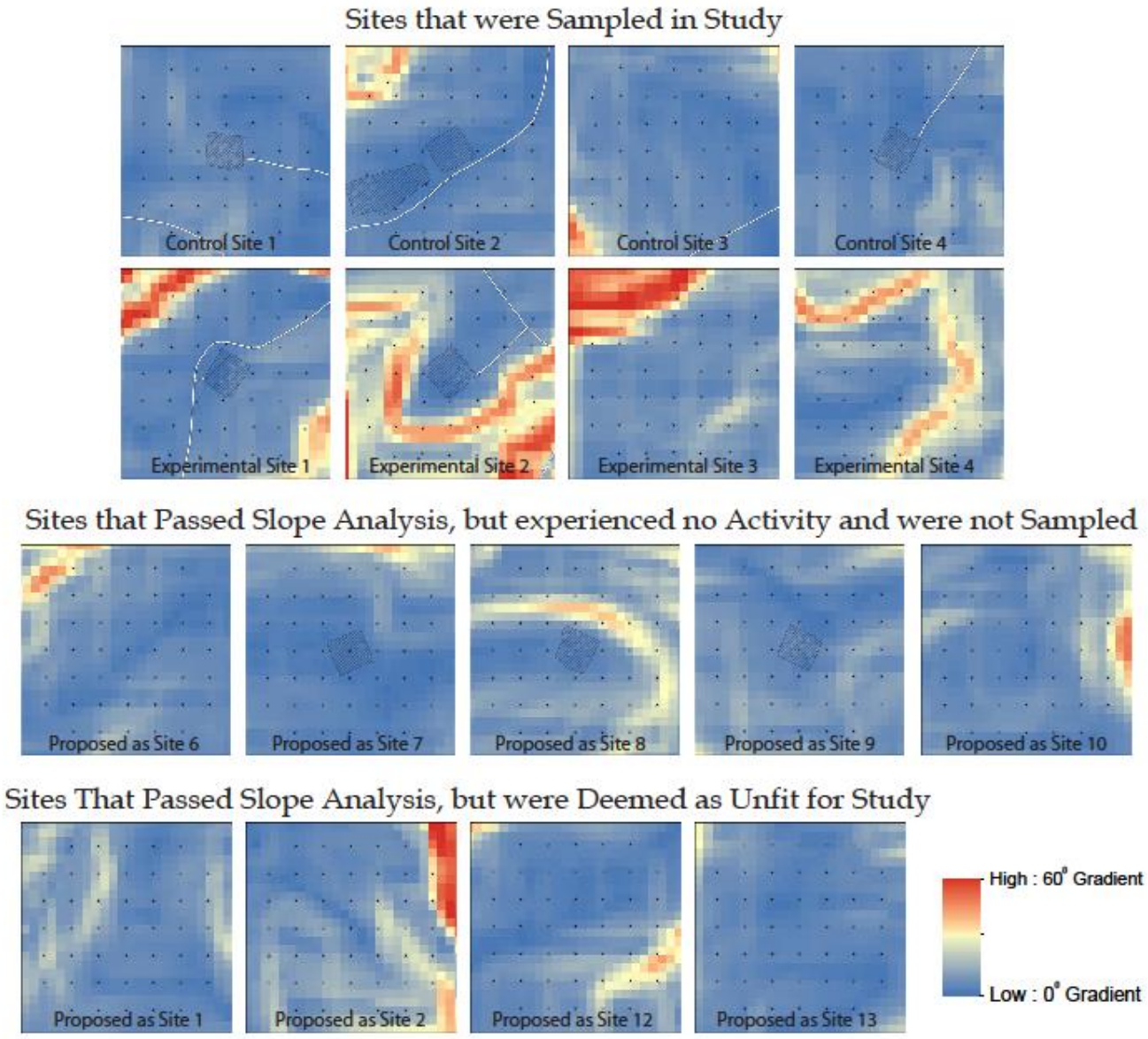
Experimental Site 4

Sample Date	Time	PPM Reading	Plunger Depth (ft)	Bedrock Geology Name	Soil Type	Dist. to Wellhead (m)	Temp °F	Humidity	Pressure
11/11/2012	11:34:55am	0.00	2.0	Mauch Chunk Formation	DkB	249.47	42.1	0.82	30.32
11/11/2012	11:38:23am	0.00	2.0	Mauch Chunk Formation	DkB	265.55	42.1	0.82	30.32
11/11/2012	11:43:32am	0.00	2.0	Mauch Chunk Formation	DlE	297.61	42.1	0.82	30.32
11/11/2012	11:49:34am	0.00	1.0	Mauch Chunk Formation	HmD	296.31	42.1	0.82	30.32
11/11/2012	11:54:23am	0.00	2.0	Mauch Chunk Formation	DlE	259.02	42.1	0.82	30.32
11/11/2012	12:00:07pm	0.00	2.0	Mauch Chunk Formation	DlE	249.37	42.1	0.82	30.32
11/11/2012	12:05:47pm	0.00	2.0	Mauch Chunk Formation	DlE	263.42	42.1	0.82	30.32
11/11/2012	12:10:23pm	0.00	2.0	Mauch Chunk Formation	HmD	300.47	42.1	0.82	30.32
11/11/2012	12:15:50pm	0.00	2.0	Mauch Chunk Formation	HmD	300.76	42.1	0.82	30.32
11/11/2012	12:20:13pm	0.00	2.0	Mauch Chunk Formation	HmD	263.09	42.1	0.82	30.32
11/11/2012	12:24:46pm	0.00	2.0	Mauch Chunk Formation	HmD	250.44	45	0.76	30.31
11/11/2012	12:29:00pm	0.00	2.0	Mauch Chunk Formation	HmD	261.31	45	0.76	30.31
11/11/2012	12:32:56pm	0.00	2.0	Mauch Chunk Formation	HmD	292.13	45	0.76	30.31
11/11/2012	12:39:19pm	1050.00	2.0	Mauch Chunk Formation	HmD	300.97	45	0.76	30.31
11/11/2012	12:42:45pm	1050.00	2.0	Mauch Chunk Formation	HmD	266.38	45	0.76	30.31
11/11/2012	12:46:34pm	0.00	2.0	Mauch Chunk Formation	DlE	248.94	45	0.76	30.31
11/11/2012	12:51:37pm	1050.00	2.0	Mauch Chunk Formation	DkB	264.52	45	0.76	30.31
11/11/2012	12:55:48pm	2000.00	2.0	Mauch Chunk Formation	DkB	304.06	45	0.76	30.31
11/11/2012	01:01:39pm	850.00	2.0	Mauch Chunk Formation	DkB	301.06	45	0.76	30.31
11/11/2012	01:05:40pm	1050.00	2.0	Mauch Chunk Formation	DkB	262.47	45	0.76	30.31
11/11/2012	01:35:47pm	0.00	1.0	Mauch Chunk Formation	DkB	169.39	46.9	0.74	30.3
11/11/2012	01:39:28pm	0.00	2.0	Mauch Chunk Formation	DkB	190.43	46.9	0.74	30.3
11/11/2012	01:44:21pm	0.00	2.0	Mauch Chunk Formation	DlE	233.01	46.9	0.74	30.3
11/11/2012	01:48:29pm	250.00	2.0	Mauch Chunk Formation	DkB	184.30	46.9	0.74	30.3
11/11/2012	01:53:10pm	0.00	2.0	Mauch Chunk Formation	DkB	163.95	46.9	0.74	30.3
11/11/2012	01:56:48pm	100.00	1.5	Mauch Chunk Formation	DlE	182.31	46.9	0.74	30.3
11/11/2012	02:02:19pm	0.00	1.0	Mauch Chunk Formation	HmD	237.75	46.9	0.74	30.3
11/11/2012	02:06:10pm	950.00	2.0	Mauch Chunk Formation	DlE	190.16	46.9	0.74	30.3
11/11/2012	02:24:01pm	1050.00	2.0	Mauch Chunk Formation	DlE	178.85	48	0.74	30.28
11/11/2012	02:29:56pm	1400.00	2.0	Mauch Chunk Formation	DlE	187.18	48	0.74	30.28
11/11/2012	02:35:50pm	4550.00	2.0	Mauch Chunk Formation	HmD	237.41	48	0.74	30.28
11/11/2012	02:41:19pm	200.00	2.0	Mauch Chunk Formation	DlE	190.37	48	0.74	30.28
11/11/2012	02:49:45pm	1400.00	2.0	Mauch Chunk Formation	DkB	167.50	48	0.74	30.28
11/11/2012	02:55:24pm	1400.00	2.0	Mauch Chunk Formation	DkB	190.31	48	0.74	30.28
11/11/2012	02:59:18pm	100.00	2.0	Mauch Chunk Formation	DkB	235.46	48	0.74	30.28
11/11/2012	03:03:04pm	1250.00	2.0	Mauch Chunk Formation	DkB	189.97	48	0.74	30.28
11/11/2012	03:10:20pm	1250.00	2.0	Mauch Chunk Formation	DkB	89.11	48	0.74	30.28
11/11/2012	03:14:13pm	0.00	2.0	Mauch Chunk Formation	DkB	118.11	48	0.74	30.28
11/11/2012	03:18:19pm	0.00	2.0	Mauch Chunk Formation	DkB	82.92	48	0.74	30.28
11/11/2012	03:21:36pm	1250.00	2.0	Mauch Chunk Formation	DkB	111.95	48	0.74	30.28
11/11/2012	03:25:12pm	850.00	2.0	Mauch Chunk Formation	DkB	78.71	50	0.71	30.28
11/11/2012	03:31:02pm	0.00	2.0	Mauch Chunk Formation	DkB	119.16	50	0.71	30.28
11/11/2012	03:34:15pm	1450.00	2.0	Mauch Chunk Formation	DkB	80.37	50	0.71	30.28
11/11/2012	03:38:14pm	1450.00	2.0	Mauch Chunk Formation	DkB	114.91	50	0.71	30.28

Appendix IV: Combustible Gas Indicator (CGI) Calibration Readings

Site Name	100% Gas Calibration	25,000 ppm Calibration	Date
Control Site 1: Sampling Period 1	100%	28,500	5/13/2012
Control Site 2	99%	29,000	6/2/2012
Control Site 3	99%	27,000	6/23/2012
Control Site 4	99%	27,000	8/11/2012
Experimental Site 1	99%	26,500	9/29/2012
Control Site 1: Sampling Period 2	99%	26,500	9/30/2012
Experimental Site 2	99%	27,000	10/13/2012
Experimental Site 3	100%	27,000	10/14/2012
Experimental Site 4	100%	27,000	11/10/2012

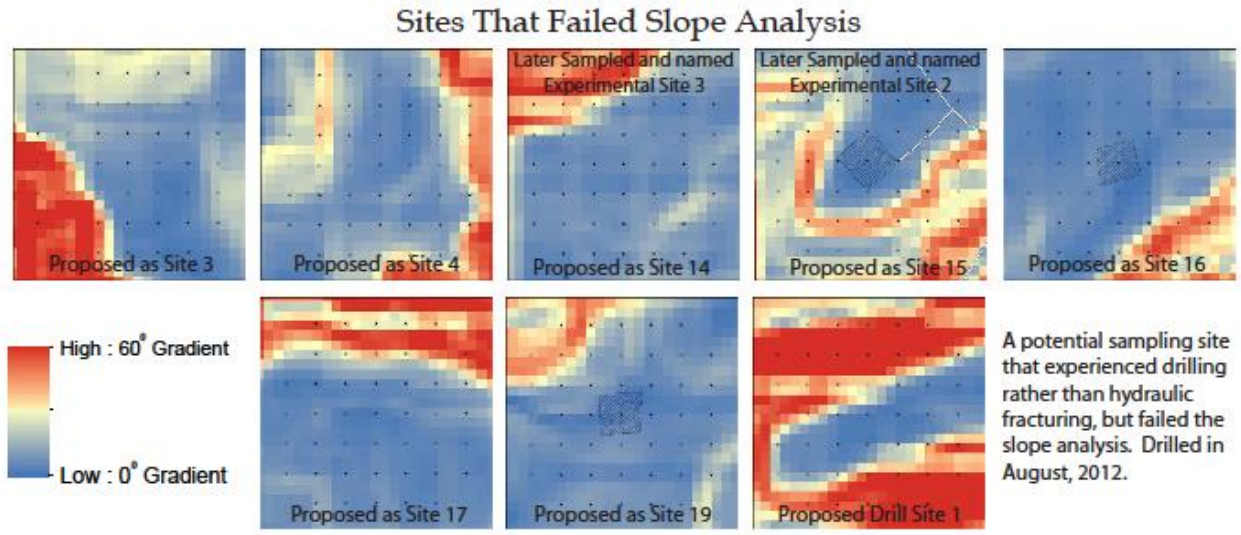
Appendix V: Slope Analysis



Elevation Dataset: (USGS, 2011)

The slope analysis for this study was an observational process. The proposed sample locations at each site were projected in ArcMap on top of a digital surface showing slope which was derived from a USGS digital elevation model. Sites that showed a relatively high number of samples with a gradient over 30^0 were removed from sampling consideration initially as taking

samples at these sites would prove to be challenging and the soils are rocky which aerates the soil and makes it difficult to create bar holes for sampling.



Elevation Dataset: (USGS, 2011)

Altogether there were 23 sites that went through this analysis. The only sites that originally passed the initial slope analysis which were actually sampled were the control sites (3 of which were expected to be experimental sites). Two of the sites that initially failed the slope analysis were later sampled after DCNR said that they would experience hydraulic fracturing (experimental sites 2 and 3). There were three other sites that DCNR had later supplied, 2 of which were deemed feasible to sample and were sampled. The third site, which was being drilled rather than hydraulically fractured, and was not considered for sampling as it showed numerous samples on very steep slopes. There were 4 sites that did pass the slope analysis, but were not considered for sampling because they had already been drilled or because they were too near to other well sites that were already drilled.

Appendix VI: Unexpected Difficulties

Timber Rattlesnake photographed from encounter.

There were some unexpected difficulties that were encountered during sampling. The following paragraphs give an overview of some of the challenges faced when performing the tasks required for this study. After sampling Control Site 1 on May 13th (originally expected to be Experimental Site 1) the author went to sample a different site (which was originally expected to be the Control Site 1). Shortly into sampling at this site a close encounter with a rattlesnake occurred. Sampling at the site was never completed and all sampling was cancelled until a solution to the snake problem was determined.

Snake gaiters were found as the solution to the snake problem.

After doing some research on snakes and snake protection the most logical solution was the purchase of snake gaiters. It was found that rattlesnakes rarely bite above the ankle and therefore protection up to the knee would provide plenty of protection in any future encounters. Luckily, there were no more snake encounters and it was found that the snake gaiters had an additional benefit of working as shin-guards and were very helpful in pushing through the more dense vegetation, as sampling at Experimental Site 1 (prior to having snake gaiters) had led to some shin bruising.

Extremely dense vegetation at proposed sites 8 and 9. Thankfully there was not much activity at these sites as the dense vegetation would have made it nearly impossible to sample.

The environmental characteristics at some of the sites showed some of the biggest challenges. While steep slopes were quite challenging at times and led to the most missed samples, dense vegetation was definitely more frustrating and at times walking through vegetation would better be described as pushing through vegetation. It sometimes took over 15 minutes to go the mere 83.3 meters between samples as the vegetation became so dense at times to the point of being trapped in place; there were numerous times where this happened and the only way to the next sampling location was to turn around and find a different, more roundabout path.

Bear sighting at Control Site 3 prior to sampling.

Other forms of wildlife also posed a concern. A man who ran a company that clears right-of-ways for transmission lines warned that there were bears in the area that could become aggressive if their cubs were nearby. His recommendation was to be loud every now and then as bears will typically avoid the presence of humans. This was easy as the use of a plunger bar is quite loud and is done regularly throughout sampling. That said, a bear was seen walking into Control Site 3 as the author was preparing sampling equipment at his automobile.

Appendix VII: Statistics Related to Soil and Bedrock Type

Soil Type	CmB	CnB	CnD	DeC	DkB	DkD	DlE	HmD	KlC
Number of values	57	95	16	8	127	33	33	11	7
Minimum	0	0	0	0	0	0	0	0	0
25% Percentile	0	0	0	0	0	0	0	0	0
Median	500	0	0	0	0	0	0	0	100
75% Percentile	1250	900	0	875	1100	25	625	1050	200
Maximum	6500	50000	1150	2000	150000	1200	1400	4550	1200
Mean	822.8	1070	146.9	425	1717	96.97	304.5	604.5	250
Std. Deviation	1106	5171	391.8	734.8	13290	274.1	490.9	1374	427.2
Std. Error	146.5	530.6	97.94	259.8	1179	47.72	85.46	414.4	161.5
Lower 95% CI of mean	529.3	16.54	-61.89	-189.4	-617.3	-0.233	130.5	-318.7	-145.1
Upper 95% CI of mean	1116	2123	355.6	1039	4050	194.2	478.6	1528	645.1
Sum	46900	101650	2350	3400	218000	3200	10050	6650	1750

Bedrock Type	Mb	MdHm	Mmc
Number of values	275	12	100
Minimum	0	0	0
25% Percentile	0	0	0
Median	0	75	0
75% Percentile	1150	100	775
Maximum	150000	1200	5500
Mean	1265	158.3	443
Std. Deviation	9525	336.3	916.9
Std. Error	574.4	97.09	91.69
Lower 95% CI of mean	133.8	-55.35	261.1
Upper 95% CI of mean	2395	372	624.9
Sum	347750	1900	44300

Appendix VIII: Author's Note Regarding the Gas Leak Found at Control Site 4

On a personal note, working as a gas line inspector in a previous job, I know that the gas leak instance found at Control Site 4 is not a significant concern when considering protection of life. A gas leak over a plastic transmission line like this one is rarely considered a significant concern, as catastrophic failure of a plastic line is practically unheard of, not to mention that right-of-ways are almost always created as a buffer to prevent any migration from moving to a confined space. All gas lines are required to be inspected annually; high-pressure transmission lines that run through populated areas are required to have distance buffers to any building and additional inspections are required on these lines.

A leak in an unpopulated area like the one seen here (assuming there were no readings over 500,000 ppm) would just be inspected and inventoried into a database until the company that owns the transmission line decides to repair the leak. If a reading greater than 500,000 ppm were measured in a subsequent inspection, that leak would be marked for repair within a required period of time (usually within 2 weeks). The only time a leak is marked for immediate repair is if any reading is found within 5 feet of a building (other rules also apply that require a line to be repaired immediately if a specified concentration of gas is found under any type of manhole). If the leak is within 5 feet of a building, or if a gas line inspector believes that the leak presents itself to be a potential hazard (ie: the gas may be further than 5 feet away from a building, but shows a high reading; or the leak is found under an impervious surface and has increased the potential for migration) the inspector will immediately survey inside the building for combustible gas (evacuate the area if gas is found inside) and then immediately call for a repair crew to come fix the leak. Note that the standards mentioned here may not be ubiquitous throughout the industry, but are likely to be similar as natural

gas inspection companies usually have standards that are more stringent than what federal laws require.