Remote Sensing Techniques for Monitoring Coal Surface Mining and
Reclamation in the Powder River Basin

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of the requirements for the degree
Master of Science

Matthew G. Alden
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Remote Sensing Techniques for Monitoring Coal Surface Mining and
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Abstract

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Remote sensing offers useful tools for monitoring surface mining operations and reclamation in the Powder River Basin, Wyoming. This research demonstrates how remote sensing techniques can be integrated into the monitoring process, allowing the regulatory agencies responsible for monitoring surface mining and reclamation to do so more efficiently and help avoid or minimize the adverse effects of mining. Data includes 3 anniversary date Landsat satellite images and GIS layers from the study area. A 3-phase methodology includes normalized difference vegetation index (NDVI) analysis, land cover mapping, and change detection. Image classification utilized the Tasseled Cap Transform and at-satellite brightness temperature and the K-means algorithm. Analysis indicates increased disturbance over the 14-year time horizon. The techniques used were useful for monitoring the progression of disturbance caused by mining, identifying and tracking reclamation sites, and assessing land cover changes.

Approved: _____________________________________________________________

James K. Lein

Professor of Geography
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Chapter 1 – Introduction

The United States produces more than one billion tons of coal annually. More than 40% of all U.S. coal production comes from the Powder River Basin, located in northeast Wyoming and southeast Montana (United States Department of Energy, 2008a). Wyoming coal production greatly exceeds that of any other U.S. state. More than 450 million tons of coal was mined in Wyoming in 2007; almost entirely from the Powder River Basin area. According to the 2008 Annual Energy Outlook, national coal production is expected to increase steadily for the next 30 years. Most of this increased production is expected to occur in the Powder River Basin. This is due to the low sulfur content of coal from the Powder River Basin.

Coal containing low levels of sulfur is desirable because the Clean Air Act of 1970 set limits on sulfur dioxide emissions from electric generating plants. These laws increased demand for coal mined from the western United States, which generally has a lower sulfur content compared to coal mined in the eastern U.S. Increased coal mining in the western U.S. and a greater level of mechanization in mines sparked an increase in surface mining operations (Montrie, 2003). The Buffalo Creek flood disaster in 1972, caused by the failure of a mine waste dam, killed over 125 people, and created much concern over public and environmental safety in regard to coal mining (Montrie, 2003). These factors led the U.S. Congress to pass the Surface Mining and Reclamation Act of 1977 (SMCRA). SMCRA established a permitting process for mine operators, as well as environmental standards for mining operations. Under these regulations, mine operators are required to post a performance bond that is held until the mined area is reclaimed.
These regulations create a need for government agencies to monitor mining operations and reclamation efforts.

Reclamation is conducted to return the land to its pre-mining condition, or to a comparable state. A successful reclamation program must include a monitoring component to identify areas of successful reclamation, as well as areas where management problems exist or where reclamation practices are failing (Lein, 2001). In some situations, conducting thorough manual field checks at every mining site within a resource manager’s jurisdiction may be impractical in terms of time, manpower, and financial considerations. Environmental monitoring via remote sensing imagery provides a cost-effective and efficient addition to monitoring programs. Utilizing remote sensing applications allows a single analyst to examine several features of mining operations without actually traveling to the mine.

Satellite imagery is becoming widely available to the general public. The United States Geological Survey (USGS) announced in April 2008, the entire archive of the Landsat earth observation satellites would soon be made available (USGS, 2008). The Landsat program consists of six satellites deployed by NASA from 1972 to 1999. These sensors provide repetitive coverage of the earth in several portions of the electromagnetic spectrum. New images will become available as they are acquired and processed. The increased availability of Landsat data greatly enhances the opportunities for the implementation of remote sensing techniques to environmental monitoring programs.
Study Question

The Powder River Basin is a major source of the coal consumed in the United States, and coal production is expected to increase during the next 30 years. Increase in coal production will increase the risk of environmental degradation. Monitoring the mining and reclamation of these lands is critical to ensure they will be returned to their natural state. Many of the government agencies charged with monitoring mining activities are already stressed by ever-growing workloads, as well as budgetary concerns.

Is remote sensing an effective tool for monitoring surface mining and its effects? The purpose of this research is to evaluate how remote sensing techniques can be utilized as a tool for monitoring surface mining operations.

Using the southern Powder River Basin as a model, this study intends to demonstrate how remote sensing techniques can be integrated into the monitoring process. By integrating remote sensing into a monitoring regime for the Powder River Basin, agencies charged with monitoring surface mining activities can do so more efficiently and help avoid potential adverse consequences of surface mining. The results of this study will also be used to describe the effect of increased coal production on the study area.
Chapter 2 – Coal Mining and Monitoring in the United States

This chapter first explains the different methods of surface mining, the types of environmental impacts often associated with them, and reclamation procedures. A discussion of the importance of coal in the United States and trends in U.S. coal production and mining regulation follows. Finally, mine and reclamation monitoring and the use of remote sensing as a monitoring tool for mining and reclamation operations are discussed.

Surface Mining Methods

Surface mining operations are conducted in a variety of ways depending on geologic factors, such as the depth and thickness of the coal seam to be extracted, and the geologic characteristics of the mining area. One critical issue is the stripping ratio. The stripping ratio is the amount of overburden (soil and rock overlying a mineral deposit) that must be moved to produce one ton of coal from a given seam. As the stripping ratio increases, so does the cost of production. The presence of overlying or underlying coal seams reduces the stripping ratio and thus increases the economic feasibility of mining in the area (United States Environmental Protection Agency, 2005).

Surface mining operations typically involve some sort of strip mining during the lifespan of a given mine. Strip mining, in general is characterized by the removal of overburden to expose the mineral for extraction. Surface mining is typically employed in situations where the overburden is relatively thin, or where underground mining would not be economically feasible. The main types of surface mining include: area mining, contour mining, mountaintop mining, and auger/highwall mining.
Area mining is typically conducted on flat or gently rolling terrain, and is used to extract coal over a large area. An area mine starts with an initial cut to expose the coal seam to be removed. The seam may then be removed, creating an open pit. Spoils and overburden are placed in a valley fill or some other disposal site. Materials that may be prone to leaching acid- or toxic-forming materials may be segregated from the rest of the overburden so that they may be isolated from exposure to oxygen and water. As the operation progresses, spoil from new cuts is used to backfill pits left from previous cuts (USEPA, 2005).

Contour mining takes place in mountainous or rolling hill areas where it is uneconomical or infeasible to remove all of the overburden from a particular coal seam, and mining is limited to the side of a mountain or to the end of a ridge line. Typically mining operations progress along the outcrop of a coal seam, removing overburden inward toward the mountaintop or ridge core until the highwall limit of that coal seam is reached. The highwall limit is determined by its stripping ratio. This results in mine cuts that wrap around mountaintops or ridge lines parallel to the contour of the land in a sinuous pattern dictated by topography (USEPA, 2005).

Mountaintop mining is an extreme version of area strip mining. In a mountaintop mining operation the over burden is removed to expose the coal seam. The rocky material is then deposited in hollows and valleys adjacent to the mine, creating a valley fill. After coal extraction is completed, the area is reclaimed as a flat space. This method of mining results in alterations of the topography and drainage of the area. Mountaintop mining is sometimes used to re-mine areas previously mined by underground techniques. In some
cases, coal from several seams may be extracted to maximize the profitability of mining the area (USEPA, 2005).

Auger mining and highwall mining are predominately secondary extraction techniques, used after mining with one of the other methods of surface mining. When the stripping ratio becomes too high to justify further excavation, the final boundary formed by the mine is called the highwall. Rather than abandoning or covering the mine, and leaving valuable minerals behind, augers and continuous highwall miners are used to recover a portion of the coal remaining in the highwall. A traditional auger uses open thread steel drill sections behind a cutting bit. The auger is positioned adjacent to the coal seam and breaks up the coal as it slowly rotates through the seam. As it does so, chunks of coal are drawn out through the open drill thread. Augers can penetrate a coal seam to a depth of approximately 130m (about 400ft), recovering between 30-40% of the coal (O’Hagan, 1997).

Finally, over the last 30 years, continuous highwall miners have been developed (O’Hagan, 1997). They are closely related to the continuous miners used in longwall mining. The miner is attached to a launch vehicle oriented perpendicular to the coal seam. The miner breaks through the coal as the launch vehicle pushes it further into the coal seam. Coal is taken out of the mine on a conveyor positioned next to the miner. This equipment typically operates via remote control, eliminating the need for workers to work underground. Its advantages over auger mining include a higher recovery rate (up to 65%) and increased mobility for avoiding geological structures or other obstacles (O’Hagan, 1997).
Environmental Impacts of Surface Mining

The main environmental impacts of surface mining include the loss of habitat, erosion, acid rock drainage or acid mine drainage, and dust pollution. These impacts are caused primarily by the disturbance of the ground surface as overburden is removed to access the coal seam.

One of the major impacts of surface mining is the loss of wildlife habitat. The disturbance of the ground surface effectively destroys any wildlife habitat in the area. In many areas, mined lands are initially re-vegetated with grassland species to control erosion. This creates a less diverse habitat compared to the pre-mining conditions (USDOI, 2003a). Habitat loss is typically short-term in nature when reclamation is successful, however long-term loss of habitat can occur for some wildlife species as a result of reduced species diversity on reclaimed lands.

The disturbance of large areas of land can lead to erosion via wind and water. Sediment transported by water tends to be deposited in streambeds, and can potentially choke off streams, destroying the habitat. Federal regulations require mine operators to construct sedimentation pools or filtration ponds, through which all drainage from disturbed areas must pass. Diversion walls or banks may also be constructed to direct drainage water away from the mined area (USDOI, 2003b).

Acid mine drainage, sometimes simply referred to as acid drainage, is the seeping of acidic waters, which are produced when reactive sulfide materials are exposed to water and oxygen and are dissolved. The water that flows away from the drainage site contains high levels of metals, primarily iron, and a low pH. This water then flows into streams or the water table, raising the acidity of the stream and water resources. The lowering of
water pH has a negative impact on the environment, stressing plant and animal populations alike. In some situations entire stream systems are destroyed, as water acidity and dissolved solids may become too great for the survival of any aquatic life (Frank, 1983).

Many aspects of coal mining can lead to acid drainage. Acid drainage is routinely found in abandoned underground mine workings which have been allowed to fill with groundwater. However, acid drainage can occur nearly anywhere the land surface is disturbed, and mineral materials are exposed to water and oxygen. Water that flows through coal stocks, waste tailings, and active mining sites can become very acidic and contain high levels of toxic metals. In addition, the construction of roads, railroads, and other mine infrastructure also causes large surface disturbances that may add to acid drainage as precipitation runs off across the disturbed area (USEPA, 2005). Mine operators are typically required to carefully handle overburden materials containing potentially harmful chemical components. If the material is used for backfilling during reclamation, it must be placed at the bottom of the mine and covered with clay or another material to seal it from water infiltration. In some cases, the material may be disposed of at another location (USDOI, 2003a).

Air pollution is another major concern for coal mining operations. The majority of air pollution from surface mining operations results from the dust and exhaust emissions of large mining equipment and machinery. Particulate emissions are caused by several mining activities, such as blasting and moving overburden materials and coal. Large areas of disturbed land can also be a source of particulate material, as it is spread by wind. In
addition, blasting of overburden material occasionally causes a release of NO₂ gas which can be hazardous to human health (USDOI, 2003a).

The extent to which an area is degraded by mining activities depends on several factors. The proper and timely reclamation of a mined area is critical to minimizing the adverse impacts of surface mining. An effective monitoring program is of utmost importance to ensure the environment is properly restored.

Reclamation Procedures

Reclamation is the process of returning disturbed lands to their previous state or use, or to a comparable state. Reclamation is intended to stabilize the terrain, assure public safety, return the area to a useful purpose, and improve aesthetic quality.

Regardless of the desired post-mining land use designation, reclamation of lands disturbed by surface mining includes the following general stages:

- Backfilling the mined area with overburden
- Re-establishing the approximate original contour
- Replacing topsoil and preparing the surface for seeding
- Spreading approved seed mixtures
- Monitoring vegetation growth and fauna populations

Additional stipulations are included in site-specific mining and reclamation plans that are approved by the regulatory authority responsible for each mining permit. The Surface Mining Control and Reclamation Act (SMCRA) passed by Congress in 1977 serves as the main set of federal laws and regulations pertaining to surface mining and reclamation. Any surface mining operation conducted in the United States must adhere to these regulations, or to regulations set by the state in which mining is conducted, provided the state laws are at least as stringent as SMCRA regulations.
U.S. Coal Production and Mining Trends

More than 1.1 billion tons of coal were mined in the United States in 2007 (USDOE, 2008a), and of that total nearly 42% (479,496,000 tons) was mined in the Powder River Basin, located in northeast Wyoming and southeast Montana. Wyoming produced more than 453 million tons of coal – far more than any other U.S. state (USDOE, 2008a).

In the U.S., coal is predominately used for electricity generation. In 2006, more than 92% of all coal produced in the U.S. was burned to generate electricity. The remainder was used mainly for industrial purposes and coke plants (USDOE, 2008b). Coal is extremely important to United States energy demand. Nearly half (49%) of U.S. electricity is generated by burning coal, more than double the amount generated by any other source (USDOE, 2009).

According to the 2008 Annual Energy Outlook, national coal production is expected to increase steadily at about 1% per year through 2030. The Powder River Basin will likely experience greater increases in production than the nation as a whole. Coal production in the eastern U.S. is expected to decline steadily through 2030 (USDOE, 2008a).

Prior to the 1970s, the majority of coal mined in the United States was mined east of the Mississippi River, primarily in Pennsylvania, West Virginia, Kentucky, Ohio, and Illinois. With the passage of the Clean Air Act of 1970 limits were set on sulfur dioxide emissions from electric generating plants. Because coal mined in the east typically contains high amounts of sulfur the new regulations increased the demand for western coal. Wyoming coals, which have much lower sulfur contents than the coal mined in Appalachia and other eastern states were particularly attractive (Goodell, 2006). Western
coal production steadily increased from the 1970s through the 1990s and continues to do so today. Although coal production in the eastern U.S. increased through the 1980s and 1990s, decline has set in, and production is expected to decrease as mines become more expensive to operate (USDOE, 2008c).

Another major production shift has taken place in the coal industry in the way coal is mined. Since 1971 surface mining has nearly matched or out-produced underground mining methods (USDOE, 2008c). The cause for this shift is related to economic factors (Goodell, 2006). Surface mining operations require less initial capital expenditure prior to coal production when compared to underground mining operations that require the development of tunnels to create access for workers and machinery, and means to transport mined coal out of the shaft. This level of investment is not needed at a surface mining operation. The only obstacle between workers and the targeted coal seam is the layer of rock and soil covering the seam. This shift in mining methods is also related to the shift from eastern to western coals. Coal seams in the west often occur close enough to the surface that underground mines are not necessary (Goodell, 2006). The increase in surface mining operations led Congress to pass the Surface Mining Control and Reclamation Act of 1977. SMCRA has two major components; regulation of active mines and reclamation of abandoned mine lands.

The Need for Monitoring

Under SMCRA, mine operators are required to obtain permits before conducting surface mining. The permit application must detail the environmental conditions present at the site, how the mine will meet SMCRA standards and how the land will be used after
the area is mined. SMCRA also prohibits mining in National Parks and allows citizens to challenge proposed mining operations.

The passage of SMCRA created regulations pertaining to the reclamation mined lands. Mine operators are required to post a performance bond that is held until reclamation of the mined area is complete. Reclamation includes returning the land to the approximate original contour, mitigating disturbances to the hydrologic regime from erosion and acid drainage, reclaiming the land in a contemporaneous or timely fashion, and establishing a vegetative cover over the mined area. SMCRA also gave the government agencies authority to inspect mines and punish mine operators that violate SMCRA laws or the mining permit.

SMCRA established the Office of Surface Mining (OSM) within the Department of the Interior, which was initially in charge of enforcing SMCRA regulations in all states. Section 503 of SMCRA allows states to assume regulatory jurisdiction over surface mining and reclamation operations within their borders. In order to assume primacy a state must create a mining and reclamation program that is approved by the Secretary of the Interior. The state program must include regulations and sanctions that are at least as stringent as those set forth by SMCRA.

The enactment of these regulations created a need to monitor mining operations and reclamation efforts. A successful reclamation program must include a monitoring component to identify areas of successful reclamation, as well as areas where management problems exist or where reclamation practices are failing (Lein, 2001). Monitoring is the “intermittent surveillance of an area conducted to determine the extent of compliance with a predetermined standard or the amount of deviation from an
expected normal state” (Babu, 2000). Mining and reclamation monitoring seeks to detect changes in key environmental indicators as a way of assessing regulatory compliance. An indicator is a tool intended to inform a specific audience about the status of an object of interest (Lein, 2001). Indicators are quantifiable and help to simplify information. By observing the variation of an indicator across an area and over time, one is able to identify problems as they develop and determine what action to take, as well as determining if past actions have been successful.

In some situations, conducting manual field checks at every mining site within a resource manager’s jurisdiction may be impractical in terms of time, manpower, and financial considerations. Environmental monitoring via remote sensing can provide a cost-effective and efficient addition to monitoring programs.

Cost Advantage of Satellite Imagery

Satellite imagery is becoming widely available to the general public. In April 2008, the United States Geological Survey (USGS) announced plans to make the entire Landsat archive available via the world wide web by the end of 2008 (USGS, 2008b). The plan calls for the addition of new images as they are acquired and processed. The scenes are available for download through the Global Visualization Viewer. These data were previously available through the same viewing system; however, each downloaded image had to be purchased through the site at a cost of $425.00 per image.

The increased availability of Landsat data greatly enhances the opportunities for the implementation of remote sensing techniques to environmental monitoring programs. Repeat coverage is acquired every 16 days, and is frequent enough to support a wide
range of monitoring applications. Change detection can be conducted on a monthly, yearly or decadal basis, or at any other intervals. The Landsat archive contains more than 25 years of imagery which provides many opportunities for comparing changes in the environment or across the land surface. Monitoring is often conducted retrospectively, detecting changes in an object or area over time. This type of monitoring supports the use of satellite systems such as the Landsat system in data collection for a given indicator.

Remote sensing technology is not without limitations. Factors such as cloud cover over the desired area during satellite acquisition can render the scene virtually unusable. Occasionally, sensor malfunctions may result in data loss, or poor image quality. Frequency of data collection may be a concern for some applications which require more frequent observation. While remote sensing technology is not a complete replacement for manual field inspections, it could at least be used to identify areas of interest at mining sites, simplifying the inspection process. Some work has already been conducted to assess the use of remote sensing techniques for this purpose.

Remote Sensing Applied to Surface Mining and Reclamation

Although remote sensing technology has been available for many years, little work has been done involving its use for the monitoring if mining activities. Studies that have been conducted indicate remote sensing can be used to monitor some aspects of mining.

Prakash and Gupta found several techniques to be useful tools when mapping land use in a landscape altered by mining (1998). They found the normalized difference vegetation index (NDVI) which measures the health and vigor of live vegetation to be
most useful. NDVI images were differenced, or subtracted from one another, to produce an image of change over a four-year time horizon. Analysis with NDVI easily separated vegetated areas from areas with little or no vegetative cover. Drainage networks were identified best with edge enhanced images of the near-infrared and shortwave infrared bands (Landsat TM bands 4 and 5). A trio of false color composites was also useful for identifying numerous land uses, and for discriminating between land uses that have similar spectral signatures. Prakash and Gupta also had success creating land cover maps from these techniques and using them to compare changes throughout their study area.

Lein (2001) integrated the NDVI with brightness temperature to monitor the reclamation of strip mined sites in Ohio and found both to be effective indicators of mining activity. Regression analysis was employed in a test to establish a relationship between the two measures that could be used to characterize mining landscapes. This method was successful in identifying areas where vegetation had been removed and areas where vegetation had recently been established or was stressed.

Guild et al. (2004) used multi-date data gathered by the Landsat TM to detect deforestation and land conversion in the Amazon. This study was focused on the use of the tasseled cap transformation (TC) which is a commonly used indicator of vegetation health used for assessing vegetation and land cover changes. This study compared the use of the TC to create a composite image, principal component analysis with TC images, and differenced TC images subjected to unsupervised classification. The results showed that the classified TC composite worked best, achieving an overall accuracy of nearly 80%.
These studies indicate that remote sensing technology can be very useful for detecting and monitoring disturbance of the ground surface caused by surface mining. Vegetation indices are useful for determining which areas are vegetated and those that are not. Difference images and land cover classifications are useful for determining where land cover has changed within a given period of time.
Chapter 3 – Study Area

The study area is located to the east and southeast of the town of Wright, WY, in the southern Powder River Basin and covers an area of approximately 375 square miles (Figure 1). This study area was chosen because there are several mines in close proximity to each other, and because coal production here has risen greatly over the past 15 years.

Figure 1. Study Area Map

The Powder River Basin

The Powder River Basin is located in northeast Wyoming and southeast Montana (Figure 2). The landscape consists primarily of sagebrush and mixed-grass prairie, composed primarily of blue grama, western wheatgrass, junegrass, sandberg bluegrass,
needle-and-thread grass, rabbitbrush, and fringed sage, among forbs shrubs and grasses. The terrain is unglaciated, consisting of irregular and dissected plains. Mule deer, pronghorn antelope, and sage grouse populate the area, which is also used for grazing livestock (Chapman et al., 2004). The area is of ecological significance as the Powder River is, “one of the last undammed large prairie river systems left in the United States” (Kurtz, 2006).

Figure 2. Powder River Basin Locator Map

The Powder River Basin is home to a number of federally listed endangered, threatened, proposed, and candidate species. These include the Black-footed ferret
(endangered); Bald eagle (threatened); Ute ladies’-tresses, a member of the orchid family (threatened); Black-tailed prairie dog (candidate); and Mountain Plover (proposed). A 2003 federal study found that the issuance of federal coal leases would not adversely affect any listed species, and would not jeopardize either proposed or candidate species. The authors determined that in most situations habitat loss would be short-term. It was also noted that site-specific measures are typically included in mining and reclamation plans. These include, but are not limited to: avoiding bald eagle disturbance, restoring bald eagle foraging areas, restoring mountain plover habitat, and surveying for potentially affected species if the habitat exists in the pre-mining condition (USDOI, 2003b).

*Powder River Basin Coal*

The coal mined in the Powder River Basin was formed during the Paleocene Epoch when the area was covered by freshwater swamps. The circumstances surrounding the coal’s formation led to the low sulfur content typically observed in western coals. This coal is considered sub-bituminous and is softer than the bituminous coals mined in the eastern United States. This means that more coal must be burned – and mined – to generate the same amount of electricity generated from lesser amounts of eastern coal (Goodell, 2006).

Coal seams in the Powder River Basin are much thicker than those found in the eastern U.S. Many seams in the west are 60 feet thick or greater, compared to the 6 to 8 feet thick seams found in the eastern United States. Seams more than 100 feet thick are not uncommon, and a few seams have been discovered that are more than 200 feet thick.
One such seam is known as “Big George”. This seam lies in the western portion of the PRB, and is more than 280 feet thick in some spots; however, it is too deep to be recovered by today’s mining technology. In the coming years, a combination of rising coal prices and advances in mining technology may render this coal economically recoverable (Goodell, 2006).

Virtually all coal mining in the Powder River Basin is accomplished via strip mining. When mining began in the basin, the coal seams were very shallow, covered only by about 20 feet of overburden. The seams slope downward toward the center of the basin, and occur at greater depths as mining progresses. As the seams become deeper and deeper, the strip ratio increases and mining becomes less economically viable. The mines eventually resemble pit mines, such as those found in copper or gold mining operations. As the mines grow deeper, highwalls must be cut back into a series of benches to stop or slow a rock fall or collapse, should one occur (Goodell, 2006).

There are five coal mines within the area: the Jacobs Ranch Mine, the Black Thunder Mine, the North Antelope/Rochelle Complex (NA/RC), the North Rochelle Mine and the Antelope mine. Annual production at these mines increased greatly between 1994 and 2006. In 1994, these five mines produced about 97 million tons of coal, and employed more than 1,300 workers. In 2006, production from these mines topped 255 million tons, and 2,947 miners were employed. The 255 millions tons of coal mined from those five mines in 2006 represented more than one-half of the 445 million tons produced in Wyoming that year, and nearly 22% of total U.S. coal production (USDOE 3, 2008). Table 1 contains individual data for the mines. The North Rochelle mine was acquired by the Arch Coal Company in 2004 and integrated into the company’s
adjacent Black Thunder mine. In total, these five mines produced over 2.4 billion tons of coal between 1994 and 2006 (WMA 1, 2007). Development of the new School Creek mine was announced in 2006, and scheduled to open in 2008, however, the opening of the mine has been pushed back to 2009 (Sukhomlinova, 2008).

Table 1: Coal production and employment, 1994-2006 (WMA, 2007)

<table>
<thead>
<tr>
<th>Mine</th>
<th>Year</th>
<th>Production (tons)</th>
<th>Employed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black Thunder</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>1994</td>
<td>31,616,222</td>
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<tr>
<td></td>
<td>2000</td>
<td>60,101,578</td>
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<tr>
<td></td>
<td>2006</td>
<td>92,517,728</td>
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<tr>
<td><strong>NA/RC</strong></td>
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<tr>
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<td>1994</td>
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<td><strong>Jacobs Ranch</strong></td>
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<td>2006</td>
<td>40,000,376</td>
<td>602</td>
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<td><strong>Antelope</strong></td>
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<td>8,258,590</td>
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<td>2000</td>
<td>22,968,729</td>
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<tr>
<td></td>
<td>2006</td>
<td>33,984,178</td>
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<td><strong>North Rochelle</strong></td>
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<tr>
<td></td>
<td>1994</td>
<td>220,909</td>
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<tr>
<td></td>
<td>2000</td>
<td>17,187,000</td>
<td>224</td>
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<td></td>
<td>2003</td>
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<td><strong>Total</strong></td>
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<td>97,421,425</td>
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Coal Mine Monitoring

SMCRA established the Office of Surface Mining (OSM), which was initially in charge of enforcing SMCRA regulations in all states. Section 503 of SMCRA allows states to assume regulatory jurisdiction over surface mining and reclamation operations within their borders. In order to assume primacy a state must create a mining and reclamation program that is approved by the Secretary of the Interior. The state program must include regulations and sanctions that are at least as stringent as those set forth by SMCRA. The Wyoming Coal Program was approved in 1980.

Under the Wyoming Coal Program, mining and reclamation activities are monitored by the Land Quality Division (LQD) of the Wyoming Department of Environmental Quality (WDEQ). The LQD is required to conduct irregular, monthly inspections of all active mines and reclamation sites. The United States Department of the Interior’s Bureau of Land Management (BLM) is also responsible for conducting quarterly inspections at mines developed on land leased by the federal government. The Mine Health and Safety Administration must also conduct periodic inspections of mines to ensure the safety of mine personnel.

Aerial inspections of mining operations are permitted under Wyoming mining law. These inspections may satisfy all or part of the monthly inspection requirement. Any potential violation observed must be investigated on-site within three days, or immediately if the violation would be grounds for the cessation of mining activities (WY mining law, CH 16, sec 1b). This portion of the Wyoming mining law provides a foundation for monitoring mining and reclamation via remote sensing.
A newsletter published by the WDEQ LQD in 1999 explained the most important aspects of surface mine inspections performed by the division. These included ensuring proper conservation of topsoil, proper handling of overburden, proper handling of waste materials, and proper construction of mining features and infrastructure. Included in the list was the act of determining if the areas disturbed by mining match the permit issued to the mining company and if the extent of disturbance does not exceed that which is approved. When a mining company mines outside the bounds of its permit, the DEQ and the company typically work to determine how much excess material was mined, and the company is forced to pay additional royalties for the material (Bleizeffer, 2007).

Reclamation in the Powder River Basin

Typically, mined lands in the Powder River Basin are reclaimed for livestock grazing and wildlife post-mining land uses, consisting of grasses and shrub species. The average time between the initial stripping of topsoil to the reseeding of mined sites is two to four years. Once re-vegetated, the landscape initially contains mostly grassland species. Areas designated for livestock grazing and wildlife habitat post-mining land uses are subject to the shrub restoration standard. This standard requires that shrubs be restored to a density of one shrub per square meter for 10% of the mined area for lands disturbed before August 6, 1996; and that shrubs on lands mined after August 6, 1996 must be restored to one per square meter for 20% of the mined (Ch 4 sec 2(d)). There is a minimum 10-year monitoring period prior to the final bond release. The return of sage brush species to pre-mining densities typically takes from 20 to 100 years (USDOI,
According to the Environmental Impact Statement prepared for the PRB by the BLM, a diverse and productive vegetation cover is established in about ten years. This temporary, but extended disturbance may reduce the carrying capacity for big game species throughout the affected area (USDOI, 2003a).

Recently, studies have been conducted to address the differences between mine reclamation and ecosystem restoration, and concerns that reclaimed areas may not function as soundly as undisturbed areas. The Society for Ecological Restoration (SER) defines ecological restoration as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (2004). The SER provides guidelines for determining when restoration has been accomplished, which are aimed toward ensuring the land will function comparably to an undisturbed area. The SER states that while reclamation activities may revegetate mined land, the resulting ecosystem may not function properly, or be capable of sustaining itself.

Sagebrush species such as big sagebrush (*Artemisa tridentate Nutt.*), particularly the Wyoming variety, were targeted as key vegetative species (Fortier et al., 2000). Such species are critical to restoring and maintaining the function, structure, and diversity of the landscape. These shrub species have evolved to exploit the limited resources available to plants in rangeland areas and are a fundamental component of ecological functionality in those areas (McKell, 1989). Studies conducted in the Powder River Basin have shown that many ecological indicators such as nutrient cycling processes and the return of microbial communities are supported by the reestablishment of sagebrush species (Stahl et al., 2006; Rana et al., 2007). The ecosystems resulting from reclaimed areas typically
function as well as non-disturbed areas, although plant community structure may vary between the two, as a reclaimed area will often be less diverse (Stahl et al., 2006).

**Monitoring Issues**

Coal is not the only natural resource found in abundance in Wyoming. Oil, natural gas, uranium, and gold are all found in relative abundance in the state. Wyoming is very dependant on the extraction of these resources as well as coal; over 50% of Wyoming’s revenue comes from royalties paid on its natural resources (Bleizeffer, 2006).

In recent years Wyoming has seen a boom in the development of natural gas-producing coal bed methane wells (CBM). Coal beds in the Powder River Basin and other western locations are typically saturated with water and methane gas. Drilling rigs are able to remove the water, ease pressure and collect gas caught in fissures and seams. Once removed from the well, the water is either stored in an impoundment or diverted to a tributary of the Powder River. The water removed from these wells often contains elevated levels of salts, barium, and other potentially toxic substances. The salinity of the water is often the chief concern because if the waters of the Powder River become too salty, farmers will not be able to use them for irrigating their crops (Bleizeffer, 2003).

The development of CBM wells has put a tremendous strain on the BLM as well as the Wyoming DEQ. From 2003 to 2006, oil and gas wells in Wyoming increased at a rate of approximately 5,000 per year. While the DEQ eventually added 31 employees, this increase in workload was not met by increased staff in the BLM. The BLM in Wyoming has experienced staff shortages due to retirements as well as an employee turnover rate up to 20% (Bleizeffer, 2006). A 2005 report from the United States
Government Accountability Office (GAO) found that the BLM was falling short of its responsibilities for wildlife concerns and cultural resources, chiefly because the BLM was pre-occupied processing energy permits. Currently, the Bureau is still under a federal mandate to process at least 3,000 CBM permits a year, and has not been able to increase its monitoring or enforcement capabilities (Bleizeffer, 2009).

The development of CBM in the region has put a great amount of strain on these agencies, and has affected their ability to monitor mines and enforce regulations within their jurisdictions. In many cases, the agencies are dependent on self-reporting of violations by mining or drilling companies, who have little incentive to do so. The stressed position of these agencies makes the use of remote sensing technology more viable as a way to simplify and streamline the inspection and monitoring process. While remote sensing cannot provide a complete substitute for mine inspections, it can help ease the process by identifying areas where potential violations may exist.

The Landsat system is well suited for determining the extent of disturbance as it supplies a bird’s eye view of the area which can then be compared to the permitted area using Geographic Information System (GIS) software and data. Individual mining features such as topsoil storage areas and solid waste disposal areas would be more difficult to identify due to the small size of these features compared to the 30 meter resolution of the Landsat sensor.
Chapter 4 – Methods

The process of utilizing Landsat TM data for monitoring surface mining in the PRB followed a multi-phase approach (Figure 3). Prior to beginning analysis, satellite images and GIS data pertaining to the study area were obtained, and preprocessing operations were completed. The first phase of analysis consisted of creating classified images using tasseled cap data with temperature data. Phase 2 included the calculation of NDVI and creating difference images to identify areas of degradation and improvement. The final phase of analysis consisted of identifying areas of change, the generation of mask images to determine the types of change that had occurred, and the inspection of possible problems or violations in the field. These phases are explained more thoroughly in the following sections.

Data Acquisition and Preprocessing

Prior to analysis, it was necessary to locate suitable satellite imagery and other GIS data for the study area. Three Landsat scenes were selected and downloaded from the USGS Landsat archive. The images acquired were captured in August of 1994, 2007, and 2008. Images from August were chosen so that the area could be studied while vegetation growth was at its peak, maximizing differences between vegetated and non-vegetated areas. The image dates selected were as close to anniversary dates as possible. Anniversary date images are captured on a common month and day of differing years, and are useful for reducing differences among atmospheric and phonological characteristics in vegetation between images. The images selected were free of cloud cover across the study area.
Figure 3. Research Study Phases
These two time series (1994-2007 and 2007-2008) were chosen so that different types of change could be examined. The 1994 to 2007 series indicates long-term changes that have occurred in this portion of the Powder River Basin, representing the extraction of over 2.4 billion tons of coal and other development that accompanies it. The 2007 to 2008 series was chosen for detecting short-term changes in the study area. Both of the time series should be useful for revealing mining trends on a mine-by-mine basis.

Prior to conducting image analysis, several steps were taken to help aid in the process. Geo-registration was checked to insure the images were properly aligned with each other. The study area was extracted from each image date as a subset. This was done both to shorten processing time and to reduce the amount of excess data produced by the analysis. Two subsets were made for each image date, one which consisted of the thermal band, and one that contained the other six bands.

The thermal band has a higher resolution than the other bands of the Landsat satellite. While the non-thermal bands have a spatial resolution of 30m, band 6 has a 60m resolution. Files used in conjunction with thermal data were resampled to match this coarser resolution.

Land Cover Mapping

Land cover mapping is the process of grouping common ground covers into categories or classes, such as urban lands, forested lands, and agricultural lands. Land cover maps are routinely used by planners and administrators to identify patterns of development and to assess which areas may require their attention (Campbell, 2002). Changes in land cover can be observed and quantified by comparing land cover maps
compiled from different dates, provided the classification system is consistent between the two. This study employed Tasseled Cap Transformation data and at-satellite brightness temperature to map the land cover of the study area for the three dates chosen.

**Tasseled Cap Transformation**

The Tasseled Cap Transformation (TC) is a linear transformation that projects soil and vegetation information into a single plane in multispectral data space. The transformation permits the user to view the major spectral components of an agricultural scene as a two-dimensional figure (Campbell, 2002).

The transformation consists of linear combinations of the six bands of the Landsat TM sensor to create a set of three new variables. The first variable is interpreted as brightness and is a weighted sum of all the bands. The second new variable is greenness which represents information pertaining to the abundance and vigor of living vegetation. The third variable represents soil wetness. The brightness and greenness components typically contain most of the information in a given scene (Campbell, 2002).

The TC was first defined for Landsat MSS, an earlier Landsat sensor, by Kauth and Thomas in 1976. The TC was later adapted for use with the six non-thermal bands of the Landsat TM sensor by Crist and Cicone in 1984. The weights for Landsat TM data are as follows:

$$\text{Brightness} = 0.3037 B1 + 0.2793 B2 + 0.4343 B3 + 0.5585 B4 + 0.5082 B5 + 0.1863 B7 \ (1)$$

$$\text{Greenness} = -0.2848 B1 - 0.2435 B2 - 0.5436 B3 + 0.7243 B4 + 0.0840 B5 - 0.1800 B7 \ (2)$$

$$\text{Wetness} = 0.1509 B1 + 0.1793 B2 + 0.3299 B3 + 0.3406 B4 - 0.7112 B5 - 0.4572 B7 \ (3)$$
A tasseled cap image was created for each image date. Of the three bands generated with the TC transformation, the best data for identifying mining features was found in the greenness band. While brightness and wetness values varied over different portions of a given mine, greenness values were very uniform, producing a mostly complete footprint of each mine. Because of these properties, the greenness band was selected for use in unsupervised classification while the brightness and wetness bands were excluded.

**At-Satellite Brightness Temperature**

Reflectance in the far infrared (thermal) band of Landsat data can be manipulated into an approximate measure of surface temperature. Although this method may slightly underestimate actual surface temperatures, it is still useful for studying the relative temperature differences across an area.

Brightness temperature is first converted into radiance values using the following equation:

$$L = \frac{(L_{\text{max}} - L_{\text{min}})}{255} \cdot DN + L_{\text{min}}$$  \hspace{1cm} (4)

$L$ is the radiance of a given pixel, $L_{\text{max}}$ is the maximum radiance detectable by the satellite, $L_{\text{min}}$ is the minimum reflectance measurable, and $DN$ is the digital number or brightness value of the pixel. Radiance is subsequently converted to temperature using the equation:

$$T = \frac{1282.7108}{\ln \left(\frac{666.093 + L}{L}\right)}$$  \hspace{1cm} (5)

$T$ is the apparent surface temperature, and $L$ is the radiance value of the pixel (Kogan, F, 1995).
Using the study area subset of the far infrared band, brightness values were converted to radiance, then to temperature in Kelvin, and finally to degrees Celsius. Temperature data were combined into a single file with tasseled cap data, and subsequently used in unsupervised classification.

**Unsupervised Classification**

Classification, as it relates to remote sensing, is the process of placing pixels into categories or classes (Campbell, 2002). Image classification is based on the idea that similar objects have similar spectral properties. Water, for example, reflects and absorbs light differently than grass, or concrete. Digital classification considers brightness over multiple bands of data—for each pixel within an image—to group similar pixels (or similar land uses/land covers) together.

The two main types of image classification are supervised classification and unsupervised classification. Supervised classification requires the user to select training areas, which are representative of the desired classes to be identified. A classification algorithm then places each pixel into a category based on which training area or land cover category the pixel is most similar, spectrally. This requires strong aerial photography interpretation skills, and adds opportunity for human error. Unsupervised classification attempts to find natural groupings of pixels within an image without added input from the user. Following classification, the user must identify what each class represents, and determine whether it corresponds with its own land use/land cover class, or if it is part of another category. Unsupervised classification is advantageous in this study because the risk of operator error is much less, compared to supervised classification, and extensive knowledge of the study area is not necessary.
Unsupervised classification was conducted using the K-means algorithm. The K-means algorithm begins by arbitrarily locating a point for each desired class within a given image. Next, each pixel within the image is classified to the nearest cluster. In the third step, new mean vectors are calculated based on all the pixels in each class. The second and third steps are repeated until the change that occurs between each iteration reaches a user-defined threshold. This change can be defined as the distances mean cluster vectors move between iterations, or the number of pixels that change classes.

A classified image was created for each image date using the thermal band and the greenness portion of the tasseled cap transform. 15 classes were initially identified by the k-means algorithm. During post-classification analysis, some of these were combined and the number of classes was reduced down to four main land cover types present in the image. These included: Mine / Barren, Grassland, Shrub / Scrub Rangeland, Riparian and Reclaimed areas, and unclassified pixels. After combining classes, each class was assigned a color representative of the land cover type it symbolized. A mask image was created for the Mine / Barren landcover class from the final two image dates. These images show what land cover classes existed at new mining areas in the previous image date’s classification.

*Normalized Difference Vegetation Index Change Analysis*

The Normalized Difference Vegetation Index (NDVI) was developed in the late 1960s and has proven to be a useful indicator for measuring photosynthetic activity in vegetation. There is an inverse relationship between vegetation reflectance in the visible red and near infrared portions of the electromagnetic spectrum. Chlorophyll absorbs red
light while mesophyll tissue reflects infrared radiation. Healthy vegetation absorbs more red light and reflects more infrared light than unhealthy or strained vegetation. NDVI is very useful for revealing the latent information within this inverse relationship.

The Normalized Difference Vegetation Index is calculated as the difference between the red and infrared bands divided by the sum of the red and infrared bands. For Landsat data, this is simply: \[ \text{Band 3 (Red)} - \text{Band 4 (IR)} \]

\[ \frac{\text{Band 3 (Red)}}{\text{Band 3 (Red)} + \text{Band 4 (IR)}} \]

This difference / sum ratio reduces influences from the atmosphere, local topography, and image aspect or shading, which increases its value compared to other vegetation indices. While NDVI has been shown to work best in highly vegetated areas, such as forests, it can still be a useful tool in regions with less vegetative cover (Campbell, 2002; Pu et al., 2008).

Areas with live vegetation generally have values between 0.4 and 1.0, whereas other non-vegetated areas generally exhibit values lower than 0.4, and sometimes even negative values (Campbell, 2002). Similarly, areas with healthy vegetation would be expected to have higher values than areas with unhealthy or stressed vegetation.

Using the study area subsets, NDVI images were generated for each image date using the red and near infrared bands. Difference images were calculated by subtracting the earlier or initial state image, from final state image. The 1994 NDVI image was subtracted from the 2007 image, and the 2007 image from the 2008 image. The resulting images contained values from -0.8 to 0.8. Areas that had improved in terms of vegetative cover contained values greater than zero, while areas that had been disturbed or had decreased vegetative cover consisted of values less than zero.
Post-Classification and Processing Analysis

Following the creation of land cover maps and NDVI difference images, a comparison of the two was conducted. Areas of interest were identified by comparing the two classified images with the NDVI difference image created from each time series. Areas of interest were then checked by importing the images into Arc Map software and comparing them to GIS shapefiles of mining permits and mined out areas. Comparing these areas to color composite images from each date helped confirm where actual change had occurred. This analysis led to the identification of several change regimes. These included areas that had been disturbed by mining, areas previously disturbed by mining that were now revegetated, areas previously disturbed where vegetation had not recovered, and areas of no change. In practice, the final step of this process would be to field check areas where violations may exist.
Chapter 5 – Discussion of Results

This study was based on five coal mines in the southern Powder River Basin. This region provides nearly half of the coal mined in the United States and will likely see an increase in mining over the next 30 years. The government agencies responsible for monitoring mining and reclamation in the region are stressed by increased workloads from coal mining and other mineral extraction activities. Utilizing Landsat satellite images through the U.S.G.S. archive makes it possible to monitor surface mining and reclamation operations, and to characterize land cover changes as a result of mining.

The purpose of this study was to demonstrate and evaluate how remote sensing techniques can be utilized as a tool for monitoring surface mining operations, and how they could be integrated into the monitoring process. In addition, this study sought to characterize the effects of increased coal production on the area. Three Landsat images were acquired from three anniversary dates for analysis. These images were analyzed to detect disturbance caused by mining, identify reclamation sites, and to detect land cover change over the fourteen year time horizon. Indicators were employed that could be measured over time to monitor disturbance from surface mining. Monitoring the disturbance of ground surface can help assess the risk of adverse environmental effects from mining. The results indicate that remote sensing is a useful tool for monitoring disturbance from surface mining activities, and for assessing the relative vegetative health of reclamation sites, as well as land cover changes.
**NDVI Analysis**

The NDVI images of the study area produced clear and complete footprints of each mine within the area (Figure 4). Active mine areas were strongly associated with low NDVI values compared to the rest of the landscape. A striking pattern of change can be seen across the area from 1994 to 2008. All of the mines in the study area grew a great deal in the fourteen-year period. Mining operations make up a much greater percentage of the total land area in 2008, compared to 1994. Mining areas are clearly in evidence in the NDVI images in Figure 4. In this figure, low NDVI values correspond to the lighter tone and indicate areas were vegetation has been disturbed or removed. A comparison of the dates illustrates the intensification in mining activities between 1994 and 2008, and a shift in mining locations as they slowly progress toward the center of the Powder River Basin.

Areas with the highest NDVI values include reclaimed, or revegetated areas, and riparian zones near the rivers and streams in the study area. Areas undergoing active reclamation have higher values because they are often heavily seeded to compensate for a potentially low survival rate among planted species. Over-seeding an area increases the chance that it meets the bond release requirement despite a low rate of survival. Riparian zones exhibit high NDVI values because vegetation grows more densely in these areas.

The southern portion of the NDVI image from 2007 in Figure 4 contains much higher NDVI values than the 1994 or 2008 images. This is presumably due to differences in the precipitation patterns between the three years. While annual precipitation amounts were nearly identical for the area in 2007 and 2008, the summer of 2008 was much drier than the previous one (Table 2). The summer of 1994 also seems to have been drier than
2007, however precipitation data from July of 1994 is not available, so this cannot be completely confirmed. The difference in precipitation patterns causes the area to the southwest of the North Antelope / Rochelle mine to appear to have improved between 1994 and 2007 and degraded from 2007 to 2008, although the actual land cover in the area remains unchanged. The disparity in NDVI values between the years made the identification of newly disturbed and reclaimed areas somewhat difficult. Difference images generated by subtracting the NDVI image from one year with that of another year were very useful for this task.

Table 2. Monthly Precipitation at Wright, WY, 1994, 2007, and 2008 (NOAA)

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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</thead>
<tbody>
<tr>
<td>1994</td>
<td>0.63</td>
<td>0.66</td>
<td>0.21</td>
<td>1.54</td>
<td>0.91</td>
<td>1.42</td>
<td>n/a</td>
<td>0.40</td>
<td>0.81</td>
<td>4.29</td>
<td>1.16</td>
<td>0.13</td>
</tr>
<tr>
<td>2007</td>
<td>0.26</td>
<td>0.34</td>
<td>3.16</td>
<td>0.85</td>
<td>3.10</td>
<td>2.63</td>
<td>1.44</td>
<td>0.94</td>
<td>0.37</td>
<td>1.86</td>
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<td>0.79</td>
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<tr>
<td>2008</td>
<td>0.63</td>
<td>0.52</td>
<td>1.02</td>
<td>0.94</td>
<td>6.02</td>
<td>1.15</td>
<td>0.48</td>
<td>0.41</td>
<td>1.25</td>
<td>1.84</td>
<td>0.58</td>
<td>0.54</td>
</tr>
</tbody>
</table>

In the difference image created by subtracting the 2007 image from the 2008 image (Figure 5), newly disturbed areas have the lowest values while reclaimed areas typically consist of the highest. Vegetation that has not been altered between image dates comprises most of the image with values that fall between those of disturbed and reclaimed areas. New mining areas occur to the north and west of existing mine sites. Reclaimed areas fall directly behind the new mining sites, as reclamation tends to follow mining activities closely. Overall, the pattern reveals expanded disturbance in the study area and a trend of new mining occurring to the west and the north of existing mines.
Figure 4. 1994, 2007, and 2008 NDVI
Figure 5. 2007-2008 NDVI Change
In figure 6, the blue boxes highlight two areas that were identified as active reclamation sites. These areas have low values in the 2007 image, and have uniformly higher values in the 2008 image. This results in a high value in the difference image. The areas within the red boxes were identified as newly disturbed areas. They exhibit higher values in the 2007 image than in the 2008 image, resulting in a relatively low value in the NDVI Change image. The trend of mining extending to the north and west is enhanced in this image, as many newly disturbed areas appear in areas near the mines, signified by decreases in NDVI value. This is further proven by the presence of areas in the southern and eastern portions of the mine areas that show increases in NDVI values, signifying revegetation or reclamation.

The difference image created by subtracting the 2007 image from the 1994 NDVI image (Figure 7) illustrates the long-term changes that have occurred across the study area. These changes are very drastic as the image shows large tracts of land that have been disturbed. Large areas that were once undisturbed by the relatively small amount of mining that was occurring in the study area in 1994, are now dominated by extensive surface mines that are several miles long in some places. Given the great increase in coal production between the two dates, this would be expected. Conversely, areas where mines were located in 1994 are now greatly improved, as most of these areas were likely reclaimed during the 13-year period. A great amount of information can be drawn from NDVI analysis and change detection. Land cover mapping allows the analyst to confirm these findings and to assess the effects of increased mining on the landscape of the study area.
Figure 6. 2007 and 2008 NDVI and 2007-2008 NDVI Change
Figure 7. 1994-2007 NDVI Change
Land Cover Mapping

Land cover mapping was conducted as a means to assess the effect of increased mining on the landscape, as well as to track the progress of the mines themselves. Land cover mapping was accomplished by applying the K-means unsupervised classification algorithm to a composite image of the greenness band of the Tasseled Cap Transform and a measure of at-satellite brightness temperature. The classification found 15 spectrally unique classes, which were subsequently combined in four main land cover categories (Table 3). The results of land cover mapping confirm and support the findings of NDVI analysis.

Table 3. Classification System for Landcover Mapping

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine/Barren</td>
<td>Land disturbed by active mining and other non-vegetated areas.</td>
</tr>
<tr>
<td>Grassland</td>
<td>Land that supports a vegetative cover, such as pasture.</td>
</tr>
<tr>
<td>Shrub/Scrub</td>
<td>Land covered by sparse vegetation.</td>
</tr>
<tr>
<td>Reclaimed/Riparian</td>
<td>Areas undergoing the revegetation stage of reclamation and vegetated corridors near streams.</td>
</tr>
</tbody>
</table>

Land cover classification produced very clear results. A visual comparison of the three images shows a sharp increase in mining activity from 1994 to 2007 and 2008
(Figure 8). Using these images, several land cover change regimes are identified. The most striking trend is that of land that is undisturbed (Grassland or Shrub/Scrub) in an earlier image that has since been disturbed by mining. Some areas change from active mining sites to reclaimed areas, or to a grassland or shrub / scrub designation. Other areas classified as reclaimed have reverted to grassland or shrub / scrub classifications as vegetation has become stable and integrates into the surrounding area.

In 1994, the mines were much less developed than in 2007. Between the two dates, the Mine / Barren land cover class increased in size by more than 16,000 pixels, which equates to more than 60 km² of land that was converted to coal mines. Between 2007 and 2008, the number of pixels in the Mine / Barren category decreased slightly. This was most likely due to fewer misclassified pixels in the 2008 land cover classification, and not to decreased mining in the region as production increased from 2007 to 2008.

In the 1994 image, very little of the land surrounding mining areas is classified in the Riparian / Reclaimed designation. More reclaimed areas are visible in the 2007 and 2008 land cover characterizations. These areas are most frequently found near the Jacobs Ranch, Black Thunder, and North Antelope / Rochelle mines, while small amounts of reclamation can be observed at the Antelope mine. This is most likely attributable to the greater volume of production at the Jacobs Ranch, Black Thunder, and North Antelope / Rochelle mines compared to the Antelope mine, as increased coal production typically coincides with greater surface disturbance and consequently increased reclamation efforts. Most of these areas are in the southern or eastern portions of the mining areas. This is supported by the trend of mining activities slowly migrating to the north and west,
Figure 8. 1994, 2007, and 2008 Land Cover Characterization
toward the center of the Powder River Basin. Once the land is mined, reclamation should follow closely behind and would therefore be expected to occur to the south and east of active mining operations.

Drainage patterns in the southern portion of the study area were clearly impacted by mining activities between 1994 and 2007. In the 1994 image a stream flows through the North Antelope / Rochelle mine. In the 2007 image this stream is no longer visible, and the area through which it ran is now dominated by the mine. Likewise, a portion of stream that flowed just north of the Antelope mine in 1994 is mostly absent in the 2007 land cover image.

The results of land cover mapping illustrate increased surface disturbance across the study area caused by increased mining from 1994 to 2008. Direct comparison of land cover maps produced from two different image dates was useful for visually assessing change, however determining exactly where that change occurred and exactly which land cover types had been converted proved to be more difficult. Class masks were used to aid in this process and to learn more about the land cover changes that took place across this portion of the southern Powder River Basin over the 14-year time horizon.

Class masks are useful for observing areas where land cover has changed between image dates. These images show areas that a class occupies in a later image as compared to the previous image date. For example, a mask of the 2007 Mine / Barren class compared to the 1994 land cover classification shows what land cover types were present in 1994 in areas that were being mined in 2007 (Figure 9). This mask shows that most of the land that was converted to mines was previously classified under the Grassland or Shrub / Scrub designations. It can be concluded then, that the extensive development of
surface mines was done so primarily at the expense of grassland and shrub/scrub areas. One area near the western portion of the North Antelope / Rochelle Complex indicates a stream that has been altered or destroyed by mining activity. Another such area exists in the northern portion of the Antelope mine.

A mask for the Mine / Barren designation from the 2007 – 2008 time series allows the user to quickly identify lands within the study area that were disturbed by mining over the previous year (Figure 10). The trend of mining toward the center of the PRB is seen very clearly in this mask image. The Black Thunder and Jacobs Ranch mines both have new mine areas just to the west of their operations. The North Antelope / Rochelle mine exhibits newly developed mine areas to the north, predominately and also some slight disturbance to the west of the mine.

Masks can also help to confirm the locations of lands currently undergoing reclamation. Reclaimed lands and riparian areas were inseparable following unsupervised classification. Using a mask of the Riparian / Reclaimed class was helpful for separating the two land cover types. The locations of riparian features are unlikely to change on a yearly or decadal basis, whereas the locations of reclaimed lands should change rather frequently as reclamation sites become stable and move into the Grassland or Shrub / Scrub designations. In Figure 11, red areas within the mask indicate those where mining activities were taking place during the previous year. Comparing this mask with an NDVI difference image from the same time series provides even more confidence in the identification of areas where reclamation efforts are occurring.
Figure 9. 1994-2007 Mine / Barren Class Change
Figure 10. 2007-2008 Mine / Barren Class Change
Figure 11. 2007-2008 NDVI Change and Riparian / Reclaimed Class Change
Monitoring Support and Evaluation

The techniques applied in this study can be utilized in a variety of ways in a monitoring capacity with regard to surface mining. The most obvious is the tracking of disturbance caused by surface mining. Reclamation efforts can also be monitored and compared to vegetation health at other reclamation sites and at undisturbed areas. Additionally, these techniques can be used to track changes in land cover over time to aid in future planning for a given region.

NDVI analysis produced very clear, complete footprints of each mine within the study area. These footprints are very useful for monitoring the progression of surface mining. By integrating an NDVI image with a GIS shapefile of permitted mining areas, one can quickly spot any areas of disturbance outside of the permitted area (Figure 12). If a potential violation is found, it can then be examined on-site immediately, or at the next monthly inspection. This process could be performed on a monthly or bi-monthly basis, as new Landsat images are captured, processed, and made available for download.

NDVI analysis could also be used to track the progression of reclamation on a site-by-site basis. Tracking month-to-month NDVI values relative to the surrounding area would give an idea of the success of reclamation efforts. Year-to-year change detection by NDVI image differencing could also be utilized to track the long-term success of reclamation. Both of these methods would be useful for identifying areas where vegetation may be stressed, or where reclamation may be failing.
Figure 12. 2008 NDVI and Mining Permits and Leases
Using a combination of these techniques, one would also be able to identify particular mines where reclamation efforts may be systematically failing, or are sub-satisfactory. Mine development in the study area progressed to the north and west of most of the mines, which created a zone of new disturbance at the face of the mines which could be thought of as the *disturbance zone*. Conversely, lands to the immediate south and east of mines were comprised mainly of recovering areas which could be thought of as a *reclamation zone*. Areas within the reclamation zone that display widespread degradation or decrease in NDVI relative to undisturbed vegetation may be identified as areas where reclamation efforts are failing.

Land cover mapping proved to be a useful tool for examining long term changes over the study area. Mask images provide a great deal of information regarding the types of change occurring in the area of interest by allowing the user to track the land covers that are converted to mining areas. Comparing mask images with NDVI difference images helped confirm land cover classes, and aided in separating riparian features from reclamation sites. This method could be used to examine land cover changes every five to ten years as a way to recap what changes have occurred in the region.

This process is not without limitations. The spatial resolution of the Landsat sensor is one of the main limiting factors. The 30m resolution is too coarse for the identification of most mining features of interest to regulators, such as overburden storage areas and spoils piles. Landsat imagery is not appropriate for examining the construction of water impoundments, erosion control measures, stream diversions, roads and rail spurs, or the contours of reclaimed areas. However, tracking disturbance from mining allows the risk of environmental impacts to be assessed on a continual basis.
Another problem with Landsat data is the unpredictability of weather patterns. The Landsat TM satellite captures repeat coverage of a given area every 16 days. If cloud cover is present over the area of interest at the time the satellite passes over, the resulting data are not usable. In some instances cloud cover may be present in several consecutive images, creating a lack of data for months at a time. Unusual weather patterns can also affect the results of these techniques, as seen in the case of the 2007 NDVI image, which was affected by above average precipitation.

Occasionally, sensor malfunctions may result in data loss, or poor image quality. Frequency of data collection may be a concern for some applications which require more frequent observation. While remote sensing technology cannot completely diminish the need for manual field inspections, it can be used to identify areas of interest at mining sites, helping to simplify the inspection process.
Chapter 6 - Conclusion

The Powder River Basin is a major source of the coal consumed in the United States, and coal production is expected to increase during the next 30 years. Increased coal production increases the risk of environmental degradation. Monitoring the mining and reclamation of these lands is critical to ensure they are returned to their pre-mining state or a comparable ecological trajectory. Many of the government agencies charged with monitoring mining activities are already stressed by ever-growing workloads, as well as budgetary concerns. The purpose of this research was to evaluate how remote sensing techniques can be utilized as a tool for monitoring surface mining operations. By integrating remote sensing into a monitoring regime for the Powder River Basin, agencies charged with monitoring surface mining activities can do so more efficiently and help avoid potential adverse consequences of surface mining.

Landsat images were acquired from 1994, 2007, and 2008 for analysis. The Normalized Difference Vegetation Index was used to map active mining and reclamation areas, and NDVI difference images were created to assess the growth of mining operations over the 14-year time span. Unsupervised classification was performed using the greenness band of the Tasseled Cap Transform and at-satellite brightness temperature to generate land cover maps for each of the three years.

The results of this study illustrate the environmental changes brought on by increased coal mining in the Powder River Basin. Nearly 60km² of wildlife habitat and agricultural land was disturbed by mining from 1994 to 2008. In addition, some of the streams in the study area have been negatively impacted or destroyed by mining.
activities. While these changes may have been authorized by mining permits, monitoring mining activities is critical to minimize the negative effects on the environment.

The remote sensing techniques used in this study were shown to be useful tools, capable of aiding in the process of monitoring disturbance from surface mining activities. Normalized Difference Vegetation Index analysis provided clear, complete footprints of active mines that can be used to determine if mining disturbance exceeds what is permitted. Differencing NDVI images from anniversary dates helped to quickly identify areas where vegetation had increased or decreased. Land cover mapping with Tasseled Cap Transformation data and thermal data was a practical method of monitoring long-term changes in land cover and use. When used in conjunction with NDVI change data, land cover masks were also helpful for monitoring disturbance and reclamation in the study area on an annual basis.

There were 965 coal-producing surface mines in the U.S. in 2007, in 25 states (USDOE, 2008b). More than half (544) of all coal-producing surface mines were in three states: Kentucky, Pennsylvania, and West Virginia. Regulatory agencies in these states may be able to benefit from integrating remote sensing into their monitoring programs. These techniques are also applicable to other types of surface mining operations. These techniques could be used to delineate the extent of surface mining anywhere there is some sort of vegetative cover surrounding the mining area.

Coal production in the United States has exceeded one billion tons annually since 1994. Coal production is expected to continue to grow steadily for at least the next twenty years, and an increasing amount of that production is expected to come from surface
mines. In addition, more than 5 billion metric tons of industrial metals and metal ores are mined each year in the United States (USGS, 2008a), providing virtually endless opportunities for monitoring aided by remote sensing.

By passing SMCRA, Congress recognized that while the mining of coal and other minerals may be an essential part of the U.S. economy and way of life, it is critical that the lands disturbed during mining are reclaimed so that they may be useful in the future, and not pose dangers to environmental or human health. For the laws and regulations set forth by SMCRA to function as intended, monitoring and enforcement programs are necessary to ensure those rules are adhered to by mining companies.

As remote sensing technology advances, its potential role in monitoring surface mining and reclamation will be enhanced. This study provides a basis upon which future research can build. Future research in this area could include attempts to detect changes to mines and reclaimed lands on a monthly basis, and determining how NDVI changes throughout the year. In addition, monitoring using a sensor with a smaller spatial resolution may enable the user to identify smaller mining features such as waste overburden piles, or top soil storage areas. A satellite with a finer resolution may also allow for better monitoring of reclamation areas.
References


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Map Resources


Coal Mine Permits and Licenses for Wyoming – United States Department of the Interior Bureau of Land Management. Downloaded from ftp://piney.wygisc.uwyo.edu/data/energy/coal_permits_licenses.zip

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Roads - Wyoming Natural Resources Data Atlas. Downloaded from http://www.wygisc.uwyo.edu/24k/road.html

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