ASSESSMENT OF LANDSCAPE ECOLOGICAL METRICS:
SHAPE COMPLEXITY AND FRAGMENTATION OF THE ABANDONED STRIP MINE PATCHES IN TOBY CREEK WATERSHED

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ABSTRACT

The study of the structure and function of landscapes has been a demanding field that reveals issues in man and environment interactions. Various landscape metrics have been adopted to assess both natural and man-made processes which helped understanding patterns and functions of the landscape. This study examines two of those metrics: fragmentation and patch shape complexity. Two methods for each metric were applied to assess the recovering abandoned strip mine areas in Toby Creek watershed located in Northwestern Pennsylvania. Contagion and Patch-Per-Unit area (PPU) represented fragmentation, and Fractal Dimension and Square Pixel (SqP) represented patch shape complexity. Similar metrics were statistically analyzed in order to reveal differences and/or similarities.

BACKGROUND

Environmental sustainability is the underlying and fundamental goal for landscape ecology. It provides the concepts and methodologies necessary to understand interactions between natural and cultural landscapes. It implies that ecological knowledge is the fundamental scientific basis to plan and manage for sustainable systems. Holism and systems theory are also adopted; they open new perspectives and provide broader visions for planning. Landscape ecology stresses the connection between structure, function and change. Pattern (structure) and process (function) relationships are crucial to understand the functioning of landscapes. They are also important to model and anticipate ecological consequences of planning and design alternatives. The human dimension and activities are also considered as integral parts of the main processes of the landscape.

In this respect, landscape metrics are developed in order to describe landscapes' ecological condition. One most important notion is that landscape pattern strongly influences the ecological processes and characteristics. There is evidence that landscape structure has a close relationship with biotic abundance and diversity. Changes in landscape structure cause a change in function and vice-versa (Forman and Godron, 1986). The most effective manner for planners of the landscape to understand, plan and manage change is by developing a basic understanding of the dynamic interactions of structure and function. Landscape metrics are to bridge the gap between planning and ecology, therefore, identifying the main structural elements in the landscape, and its main landscape fluxes or processes are crucial tasks for understanding how landscapes function. The establishment of relationships between components enables the ecological consequences of proposed spatial solutions to be predicted.

The continuous development of landscape ecological metrics has left planners and researchers with a wealth of tools that help understanding many landscapes. Researchers have developed "refined" versions of some of the metrics in order to eliminate technical limitations of raster data models structure. Pixel size and the extents of a specific study area, for example, have been affecting many landscape metrics. Frohn (1998) developed several modified metrics that reduce, and possibly eliminate the effect of pixel size on the results.

STUDY OBJECTIVES

The number of the developed landscape metrics is, in many cases, overwhelming and confusing due to similarities that stem from the fact that they are developed to address case-specific situations. This study is an attempt to compare two sets of landscape ecological indices in order to test any differences and/or similarities between them, and therefore, reduce the number of the applied indices when used in similar studies. The two sets of indices represent fragmentation and patch shape complexity. The algorithm of the first set are provided from FRAGSTAT software and the methods of the second set are developed by Frohn (1998) in order to take into account the raster data model's characteristics.

LANDSCAPE METRICS

Fragmentation

Fragmentation is a step in a process that leads to the attrition of natural habitat patches **(Figure 1)**. It starts with the creation of small patches that are incompatible with the existing natural processes of the original habitat patch. Those small patches act like holes within the original habitat landscape (perforation). The incompatible patches increase in size until they merge with similar neighboring patches and start isolating the original habitat landscape (dissection). Fragmentation then occurs when the distance between the isolated habitat patches increases. Their size gradually decreases (shrinkage), which leads to the total loss of the original habitat patch (attrition).

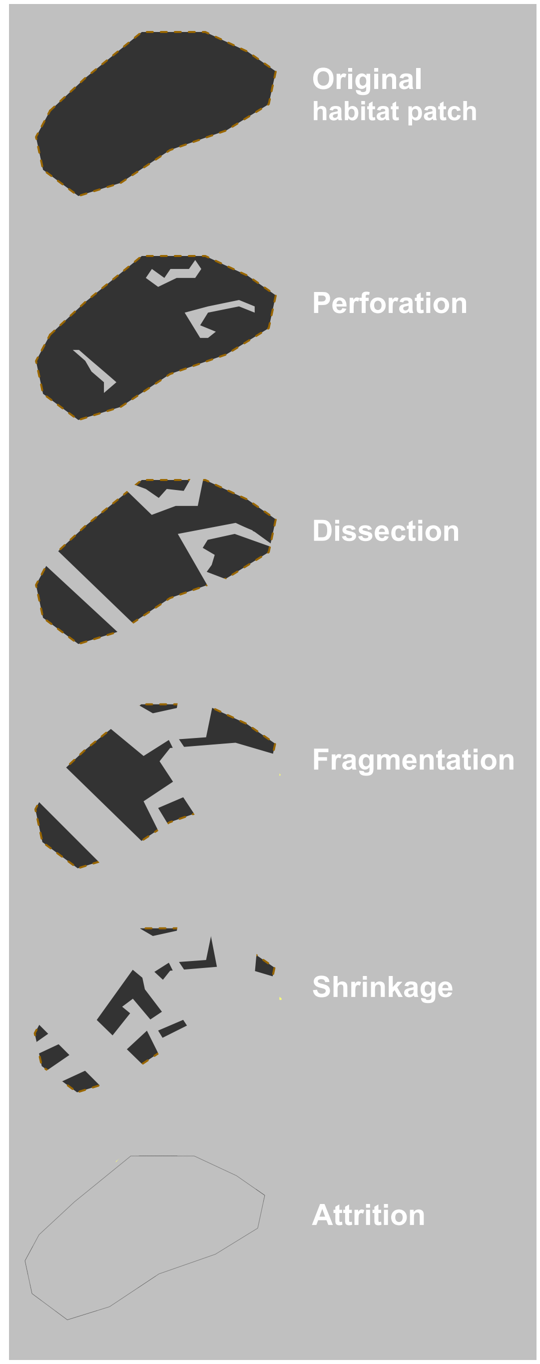


Figure 1.
Landscape fragmentation process.

Traditionally, fragmentation can be measured by means of Contagion (CONTAG). It is expressed in percentage. CONTAG approaches 0 when the patch types are maximally disaggregated and interspersed (maximum fragmentation). CONTAG = 100 when all patch types are maximally aggregated (single patch); i.e., when the landscape consists of single patch. In FRAGSTAT, it is described by the following formula:

$$\mathrm{CONTAG} = \left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left[(P_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]\cdot\left[\ln(P_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]}{2\ln(m)}\right](100)$$

$$(0 < \mathrm{CONTAG} \leq 100)$$

As an improved metric, Frohn (1998) introduced the Patch-Per-Unit area (PPU). PPU is expressed in unit area (km^2 in the case of the present study). PPU is lowest when the landscape is not fragmented. As the landscape becomes more fragmented PPU increases (Frohn, 1998). It is described by the following formula:

$$\mathbf{PPU = m/(n*\lambda)}$$

Where *m* is the total number of patches, *n* is the total number of pixels in the study area and λ is a scaling constant equal to the area of a pixel.

Patch Shape Complexity

The shapes of distributions of species vary widely, from circular to long and narrow, landscape ecology uses these shapes to gain insight into the dynamics of species, in other words, whether the species distribution is stable, expanding, contracting, or migrating. Even the migration route may often be inferred from the shape. (Forman and Godron, 1986).

Patch shape is undoubtedly important in the dispersal and foraging of organisms. For example, insects or vertebrates moving through a wood, or birds flying over it, are more apt to find a long narrow clearing that is oriented perpendicular to their direction of movement, whereas they may miss a round clearing. Conversely, the long narrow clearing parallel to their movement may also be missed. Hence, both patch shape and orientation are critical in the dispersal of animals and plants across a landscape. These and related questions have spawned an exciting field of study focusing on animal foraging strategies.

The shape of animal home ranges varies from circular to nearly linear, but usually elongated and described empirically or mathematically as polygonal or elliptical. Shape indices have been developed to detect the changes in the structure of patches from simple and compact (Circular/Square) versus irregular and convoluted. They are measured using relative amount of perimeter per unit area (Perimeter/Area ratio).

Traditionally, Patch shape complexity have been measured using Fractal Dimension (*Frac*). Its value varies between 1 and 2. Lower values indicate squared or more structured shape (usually man made), and higher values approaching 2 indicate more complex shapes (natural).

$$\mathbf{Frac = 2 * \ln [(P/4) / \ln (A)]}$$

$$(1 < Frac < 2)$$

Where *Frac* is the fractal dimension (patch shape complexity measure), *P* is the patch perimeter, and *A* is the patch area. *Frac* is at its minimum for any perfect square and cannot exceed 2 since the maximum perimeter of a raster cell is *4A* (in pixel units). *Frac* measures the deviation of the patch shape from an area of some reference geometry. In order for perimeter to increase in proportion to area, the shape of the boundary of a feature must become more complex as area increases.

The improved metric, on the other hand, considers the perimeter area relationship for raster data structures and normalizes the ratio of perimeter and area to a value between 0 for squares and 1 (maximum perimeter, edge, deviation from that of a perfect square). The Square Pixel index (SqP) can be calculated by the following formula:

$$\mathbf{SqP = 1 - (4 * \sqrt{A} / P)}$$

$$(0 < SqP < 1)$$

THE STUDY AREA

Coal mining started in order to support the colonial iron industry, it helped to fuel the industrial revolution in the US and Andrew Carnegie's steel mills in the 1800s. Pennsylvania is the 4th largest coal producer in the US after Wyoming, West Virginia and Kentucky. The study area for the current project is located within Toby Creek watershed. Toby Creek sub-basin is one of the six polluted watersheds in the 200 square mile Clarion River Basin. It rises in Farmington Township in Northwest Clarion County and extends to the Southwest approximately 13 miles, entering Clarion River just North of Clarion Town **(Figure 2).** It is long and narrow (average width of 2.5 miles) and is fed by many smaller tributaries, it covers 37 square mile.

Toby creek watershed has been the subject of intensive mineral resource recovery operations for the past one hundred and fifty years (till the mid 70s). Primarily these activities have included the surface and underground extraction of bituminous coal and the drilling for petroleum and natural gas. Significant amounts of dissolved minerals in these waters have seriously disrupted the delicate biological environment. In addition, the water quality is such to preclude its use for human consumption or recreation. The pollution ultimately has its origin from abandoned mining operations. The resultant contamination is known as Acid Mine Drainage (AMD). In addition, land subject to clearing for strip mining is subject to severe erosion and increases the sediment load to receiving streams. This further reduces the capacity of the streams to sustain aquatic life. It has been mined for coal since the early 1800s, which left scars on the natural landscape and severely polluted many of the streams in the basin.

This situation could be handled by the following potential remediation:

1. Re-mining: This technique can be used to remove remaining coal and eliminate or reduce the AMD pollution sources and in some cases increase the exposure of alkalinity producing materials;

2. Interception and Diversion of Surface and Groundwater Sources: This technique includes the construction of diversion ditches, high-wall drains, grout curtains, deep mine seals, etc., that reduce infiltration of water into the deep mines and either eliminates or decreases the quantity of the discharges;

3. Passive Treatment Systems: Anoxic drains, reducing and alkalinity producing systems (RAPS), cattail bogs, retention ponds, aeration structures, etc., can be constructed to treat discharges from deep and surface mine sources;

4. Active Chemical Treatment: Existing active treatment facilities and potentially additional facilities can be used to address a number of discharges in the watershed; and,

5. Surface reclamation: Reclamation of surface mines in a manner that promotes controlled runoff and decreases infiltration into the deep mines eliminates or decreases the flow quantity of the discharges.

Many surface reclamation efforts have been carried out in the Toby Creek old surface mining

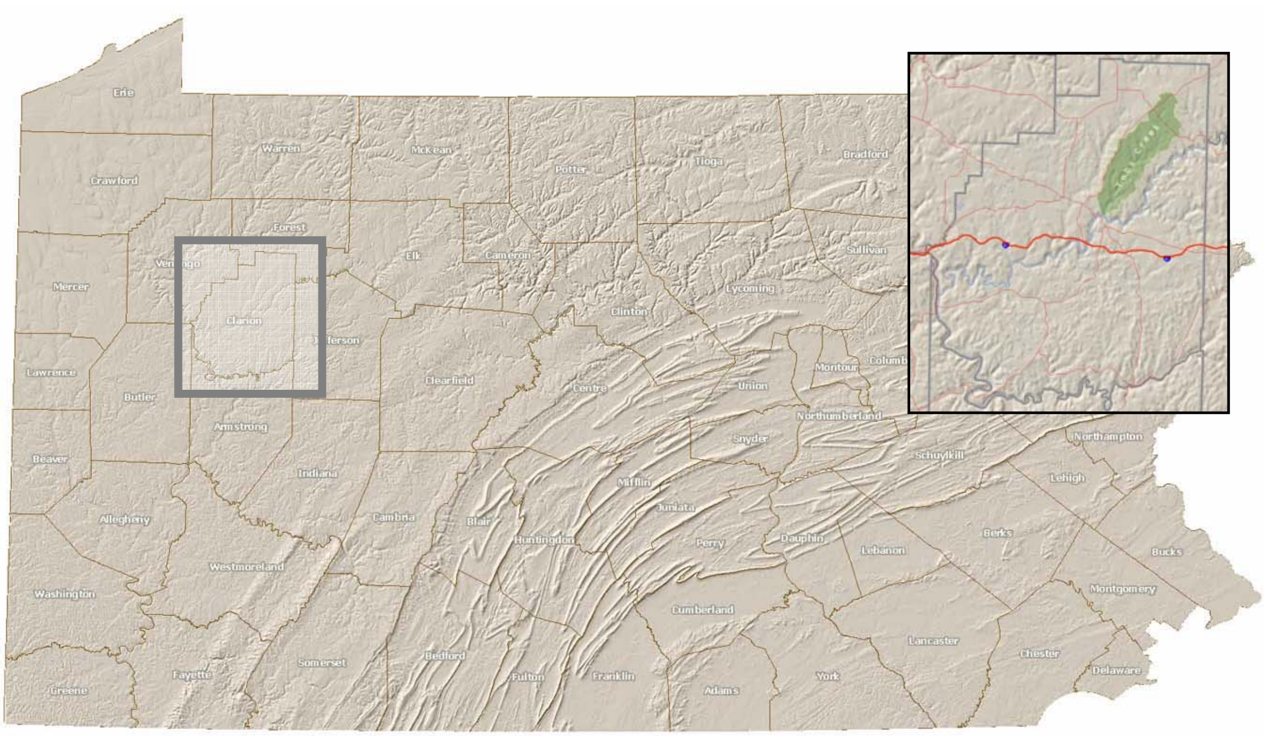


Figure 2.
The study area: Toby Creek watershed in Clarion County

areas. This study is aimed at assessing the efforts made in those areas and in comparing the results of the presented indices in describing the landscape under investigation.

MATERIALS AND METHODS

The available data consisted of topographic maps in the form of Digital Raster Graphs (DRG) and a multi-spectral satellite image of 1998 (SPOT XS). 21 strip mined areas were extracted from the DRGs using on-screen digitization. The resulting polygons were used as areas-of-interest (AOI) for subsequent functions. Based on the extracted AOIs, the SPOT image was classified using the clustering technique of unsupervised classification in ERDAS IMAGINE. Six classes were identified: deciduous forest, coniferous forest, mixed vegetation, light herbaceous, medium herbaceous and barren land. A reclassification procedure was then carried out in order to create class groups that represent two main categories: forested habitat (deciduous, coniferous and mixed vegetation), and un-reclaimed and recovering patches (light and medium herbaceous and barren land) **(Figure 3)**. The reclassification procedure was carried out in Spatial Analyst 9.0.

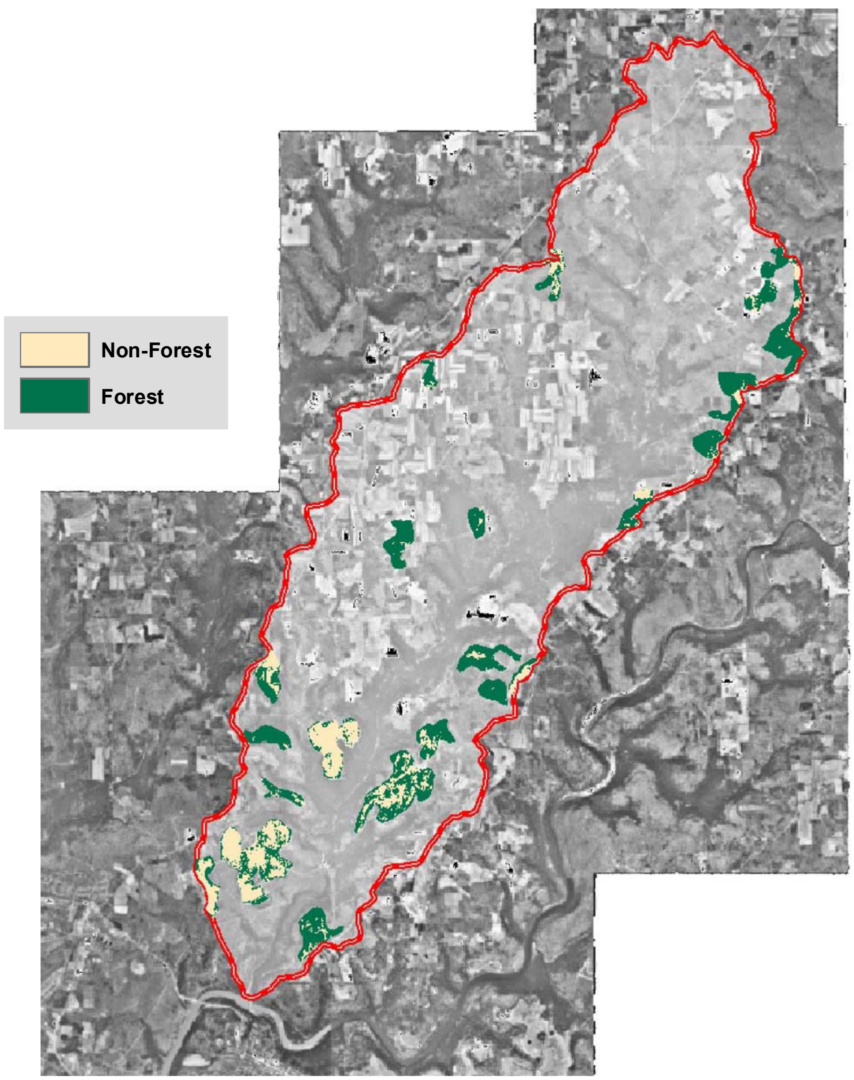


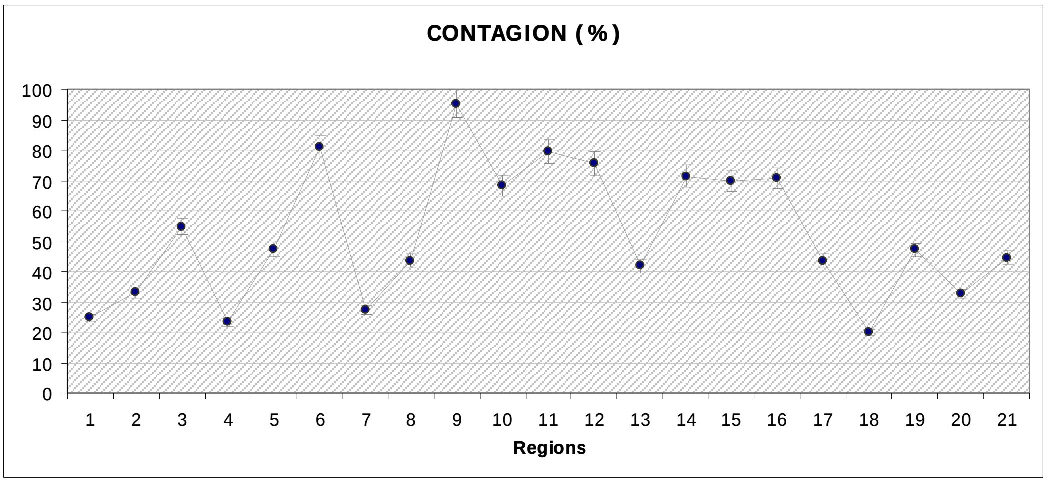
Figure 3.
The classified areas of interest (AOI) that were extracted from the SPOT 1998 satellite image.

The Fractal Dimension (*Frac*) and the shape complexity index (*SqP*) were then calculated for all of the 21 AOIs of the study area according to the formulae described earlier using Arc Macro Language (AML) in ArcInfo Workstation's GRID module. Contagion (*CONTAG*) was calculated using FRAGSTAT. The results of all analysis were then exported to Microsoft Excel where the Patch-Per-Unit area (*PPU*) was deduced from the exported geometry (total area and number of patches in each AOI). Excel was also used to summarize the results and to compute statistical figures that evaluate the correlation between the traditional and the modified fragmentation and shape complexity indices. The 21 AOIs served as replica samples for the correlation calculation between *CONTAG* and *PPU.* And the patches in every AOI served as sample replicas for the correlation calculation between *Frac* and *SqP*.

RESULTS AND DISCUSSION

Fragmentation Indices

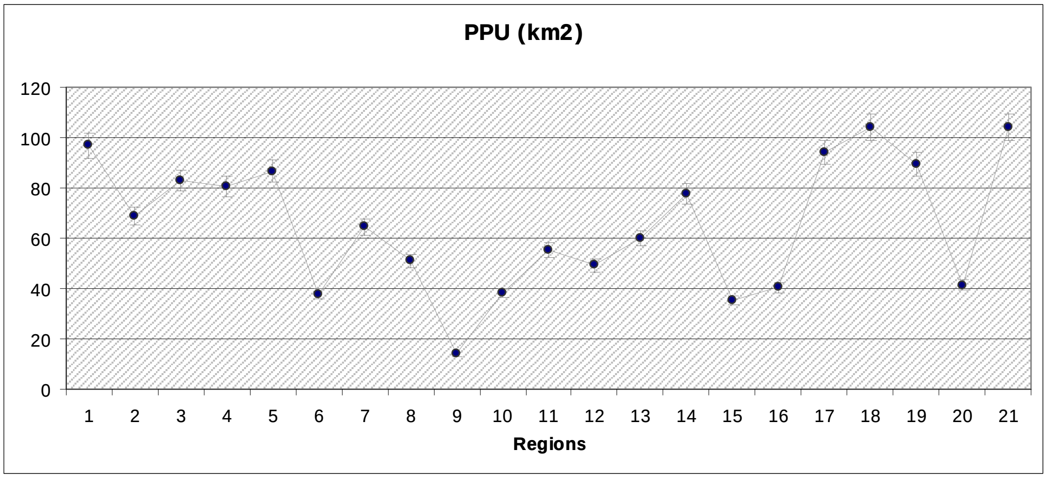
The calculation of Contagion revealed that 9 out of the 21 AOIs (more than 40%) are fragmented (Contag > 50%) (**Figure 4**). On the other hand, the modified fragmentation index Patch-Per-Unit area (PPU) showed that 11, or more than 52% were fragmented (greater than the mean



Minimum	20.0779
Maximum	95.3127
Mean	52.1413
Standard Deviation	21.9160

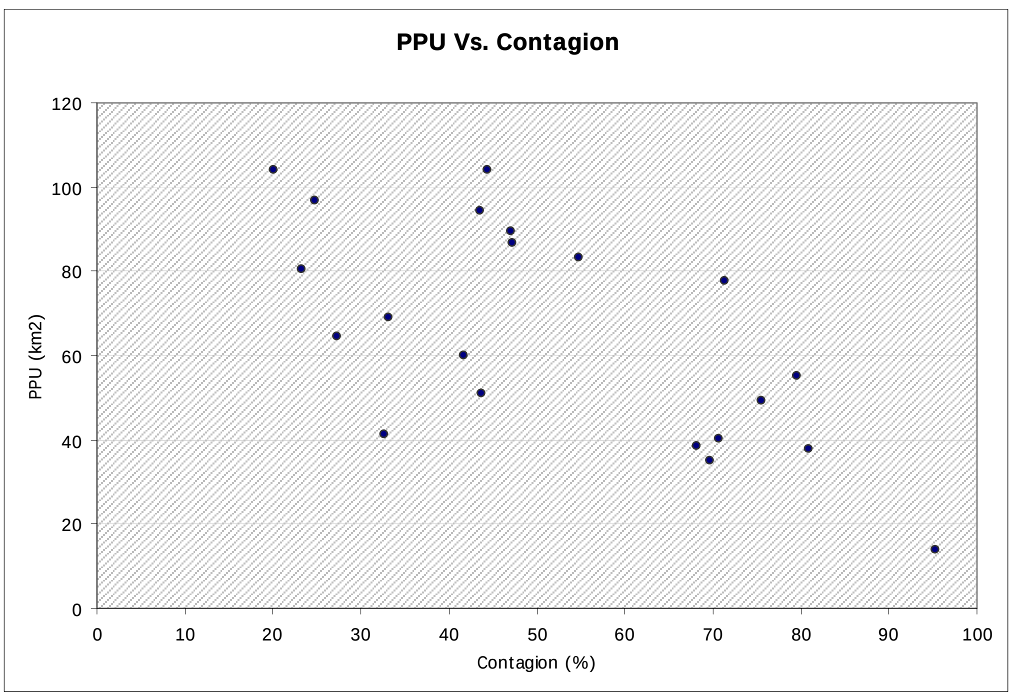
Figure 4.
Results of the contagion (*CONTAG*) calculation for all 21 AOIs. Lower contagion percentages show maximum fragmentation while highest percentages show more clumped landscape.

(65.36)) (**Figure 5**). A calculation of the correlation revealed that there is a significant difference between the two fragmentation indices ($r = -0.663$, $P = 0.00106$) (**Figure 6**). PPU takes into consideration the shape and size of the pixel, while CONTAG is a more generic form of fragmentation calculation. It is suggested that the use of the modified index PPU would be more reliable in describing fragmentation in the landscape of the study area and similar locations.



Minimum	13.9289
Maximum	104.1482
Mean	65.3618
Standard Deviation	25.9190

Figure 5.
Results of the Patch-Per-Unit area (*PPU*) calculation for all 21 AOIs. Higher *PPU* values indicate maximum fragmentation while lower values show more clumped landscape.



r	-0.663
r2	0.439569
P	0.00106

Figure 6.
Correlation calculation between Patch-Per-Unit area (PPU) and Contagion. Lower PPU values and higher contagion percentages depict more fragmented landscapes, while higher PPU and lower contagion percentages mean lesser fragmented landscapes.

Patch shape complexity indices:

The Fractal Dimension (Frac) and the Square Pixel were calculated for every AOI. The first AOI is presented here as an example of the results. The calculation of the Fractal Dimension revealed that all the values were less than 1.5 which indicates a tendency of more squared, or artificial, patch forms (**Figure 7**). This result is also confirmed by the Square Pixel (SqP) calculation where more than 89% of the AOIs were less than 0.5, or squared form (**Figure 8**).

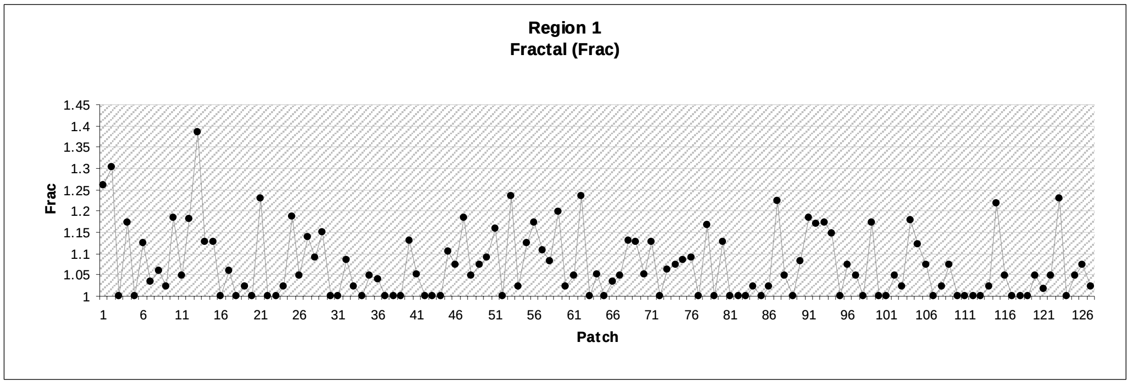


Figure 7.
The result from calculating the fractal dimension (Frac) for the first AOI. Higher values indicate more squared and man-made shapes, while the lower values show more natural patch shapes.

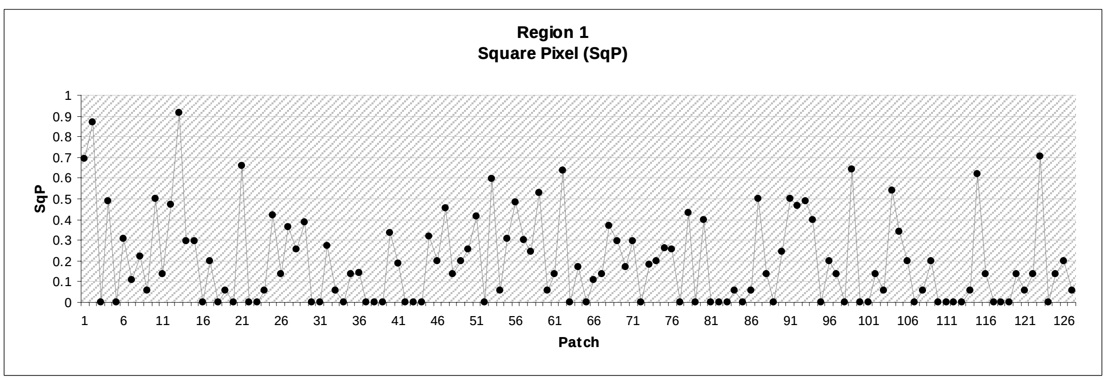


Figure 8.
The result from calculating the modified patch shape complexity index (SqP) for the first AOI. Values closer to 1 indicate more structured and man-made shapes while those closer to 0 are represent more natural patch shapes.

The calculation of correlation, on the other hand, showed a strong positive and significant relationship between both of the patch shape complexity indices. For all 21 AOIs the mean r-value was 0.96 (**Figure 9**).

Based on the Square Pixel area metric (SqP), about 81% (17) out of the 21 AOIs had 50% or more of their patches with low SqP values (less than 0.5) (**Figure 10**).

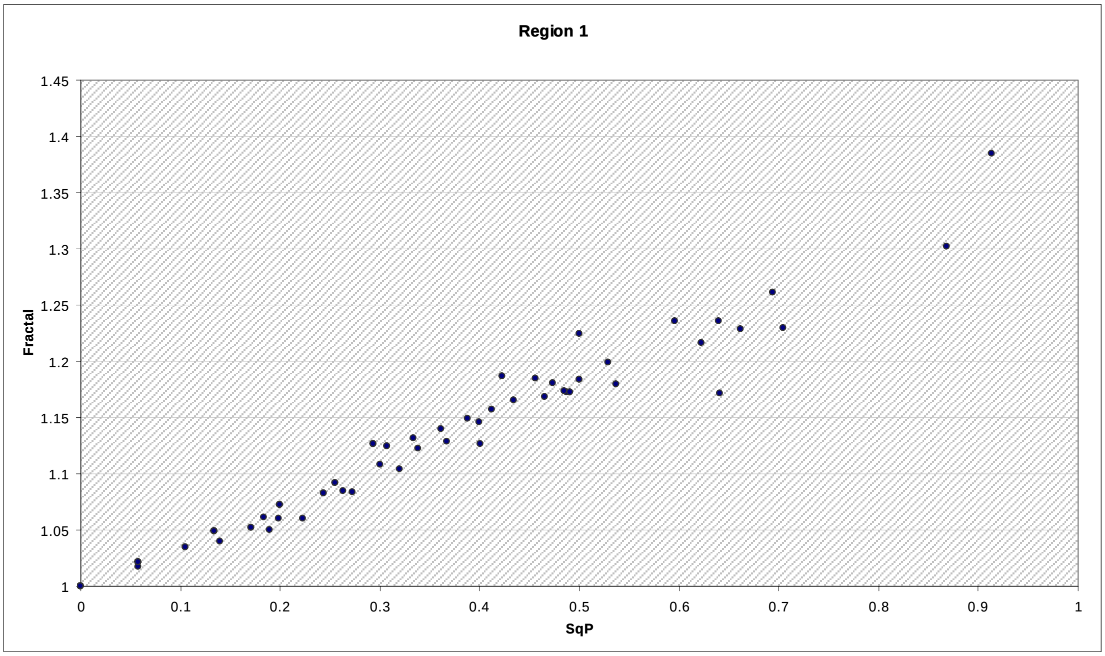


Figure 9.
This figure is showing the high positive correlation between the traditional patch shape complexity index, fractal dimension, and the modified index, Square Pixel area (SqP). The correlation was calculated using all patches from the 21 AOIs (mean r-value = 0.96).

CONCLUSIONS AND RECOMMENDATIONS

This study aimed at uncovering the uncertainty when selecting proper landscape ecological metrics that best describe specific phenomena especially when using remotely sensed data. Two indices were tested: fragmentation and patch shape complexity. Contagion (CONTAG) and Patch Per Unit area (PPU) were calculated for the study area. They represented the fragmentation metrics and their results were significantly different. Their correlation was relatively low. Fractal dimension (Frac) and the Squared Pixel (SqP), on the other hand, were evaluated. Both represented the patch shape complexity metrics and both suggested that all of the selected strip mined areas were not fragmented. No significant difference existed between both methods and they were highly correlated. Those results suggest that, for the selected study area and with the spatial resolution of the adopted remotely sensed data, the use of either the fractal dimension or the modified index Square Pixel (SqP) would reveal the same findings as of describing the patch shape complexity. As for the fragmentation of the selected study area, it is suggested to adopt the modified index Patch Per Unit area (PPU). It describes the patch shape based on the squared shape of the pixel or the smallest unit of a raster satellite image (Frohn, 1998).

In both cases, the results of this study suggest that, despite the efforts in restoration of some of the strip mines in the Toby Creek watershed, most of them are still fragmented and have a less complex patch shape. This raises the issue of relevance of the selected landscape metrics to describe specific ecological processes. Other factors should also be taken into consideration when making decisions regarding the management of damaged and/or recovering landscapes.

It is recommended to expand the study to include other indices that describe the ecological function and the processes of the landscape, and possibly confront them with the structure indices described earlier. This confrontation might reveal significant relationships, similarities or differences, which will definitively facilitate landscape management decision making process.

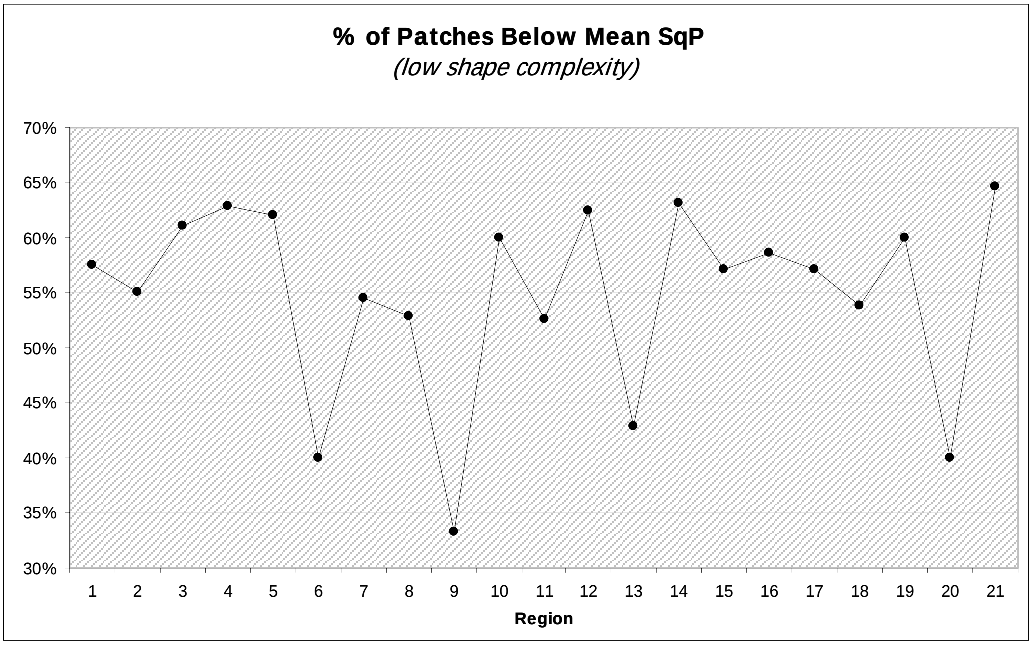


Figure 10.
This figure is showing the percentage of patches that are below the mean of SqP, i.e. squared, more structured or more man-made shapes.

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