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# Quantifying Landscape Fragmentation in the Lockyer Valley Catchment, Queensland: 1973 – 1997

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## ABSTRACT

Fragmentation has become a central issue in landscape ecology and conservation. The breaking up of large land areas into smaller patches is known to influence many ecological patterns and processes. Thus, landscape fragmentation needs to be assessed and monitored. In this study of the Lockyer Creek Catchment in Queensland, landscape fragmentation was quantified using 1973 and 1997 Landsat images and other thematic layers. Landscape metrics (focusing on the size, shape, density, and isolation of woody vegetation) were calculated using the *Patch Analyst (Grid)* extension of *ArcView GIS*. The nature of fragmentation was further characterised based on landscape features including land use/cover, tenure, slope, as well as distance to roads and streams.

Key metrics indicate that the landscape has become more fragmented within the 24-year study period. In particular, woody vegetation was found to decrease in total area by 14.5% with a 37% increase in the number of patches, and a 54% decrease in mean patch size. Some 57,178 hectares (ha) of woody vegetation were cleared for pasture, while 834 ha, 46 ha and 77 ha were cleared for cropping, urban development, and water bodies, respectively. The sites that were most susceptible to vegetation clearing were typically characterised by being freehold lands, with slopes between 8% to 30%, more than 1 km from major roads, and more than 1 km away from the stream network. However, this work has also raised questions related to catchment sustainability with 48% of the pre-existing woody vegetation on slopes greater than 18% and more than 40% of the pre-existing woody vegetation in the riparian zone (< 500m from streams) cleared during the study period.  Hence, landscape fragmentation can be quantified with relative ease within a GIS environment.  However, limitations currently exist in the interpretation of the magnitude of change and its influence on the local ecological processes and patterns.

**KEYWORDS**: GIS, landscape fragmentation, landscape structure, vegetation patch

## INTRODUCTION

Fragmentation is the breaking up of large habitat or land areas into smaller parcels (Forman, 1997, p. 406) by either natural or anthropogenic agents. It has been shown to have a negative influence on many species of plants and animals (Farina, 1998, p. 58), and is a worldwide process occurring at various spatio-temporal scales. It reduces biodiversity and increases the local extinction of flora and fauna. Fragmentation also increases the vulnerability of patches to external disturbances including windstorms or drought (Nilsson and Grelsson, 1995).

Understanding the nature and effect of fragmentation is important in resource management and biodiversity conservation. In particular, resource managers require spatial and temporal information to make decisions about landscape patch size, the dispersal or aggregation of activities, edge densities, and connectivity in the landscape (Franklin, 1994). Results from landscape ecological studies suggest that a broad-scale perspective incorporating spatial relationships is a necessary part of land-use planning (Turner, 1989). Moreover, biologists have a need to quantify community composition and diversity in fragments to better understand animal behaviour, prey and predation, movement and dispersal, and extinction.

The ability to quantify landscape structure, including those that are brought by fragmentation, is a pre-requisite to the study of landscape function and change (McGarigal and Marks, 1994). Quantitative measurements of landscape fragmentation allow accurate characterisation and analysis of key ecological processes. With the availability of satellite imagery capable of characterising large areas, as well as the development of advanced image processing and GIS based analysis, the opportunity to quantify landscape fragmentation and other landscape structure indices is increasingly becoming available. One of the requirements is to develop appropriate mapping and analytical techniques that are applicable to a variety of landscape conditions.

The objectives of this study were to:

- develop appropriate mapping and assessment techniques for quantifying and analysing landscape fragmentation; and
- to evaluate the landscape fragmentation of a particular catchment so as to gain insights on the nature and dynamics of landscape change.

## QUANTIFYING LANDSCAPE FRAGMENTATION

### Landscape Fragmentation

A *landscape* is defined as a heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout (Forman and Godron, 1986). It is composed typically of several types of landscape elements (patches). Patches represent relatively discrete areas (spatial) of relatively homogeneous environmental conditions. The size of a landscape varies, depending on what constitutes a mosaic of habitat or resource patches meaningful to a particular organism (McGarigal and Marks, 1994). Forman and Godron (1986) suggested a lower limit for landscapes to be a “few kilometers in diameter”.

*Landscape fragmentation* is the breaking up of large habitat or land areas into smaller parcels (Forman, 1997, p. 406). It is one of the central issues in landscape ecology and conservation planning. Fragmentation of habitat is known to have a negative influence on many species of plants and animals (Farina, 1998, p. 58). It also reduces biodiversity and increases the local extinction of flora and fauna. Many spatial and ecological characteristics result from or correlated with fragmentation (Forman, 1997, p. 412).

The fragmentation of the landscape is a result of the complex interactions between physical, biological, economic, political and social driving forces. Most landscapes have been influenced by human land use, and the resulting landscape mosaic is a mixture of natural and human-managed patches that vary in size, shape, and arrangement (Turner, 1989). Forman (1997, pp. 417-423) identified six major causes of land transformation: *deforestation, suburbanisation, corridor construction, desertification, agricultural intensification,* and *reforestation*.

### Quantifying Landscape Fragmentation

Quantifying landscape fragmentation is basically a change detection task. It involves two or more time frames -- the "before" and "after" conditions. In many cases, the assessment is focused on natural vegetation or forest areas rather than other patch types (e.g. agricultural crops). Based on the above definition, landscape fragmentation could be measured by the *size* (area) and *number* (count) of patches between two or more periods. Typically, a more fragmented landscape is characterised by numerous, much smaller, and more isolated vegetation patches.

Remote sensing and GIS are tools that can help quantify landscape change, including fragmentation (see for example, Skinner, 1995; Simpson, et al., 1994). Satellite remote sensing is known for its strength in multi-temporal data capture of relatively large areas, while GIS is popular as a powerful spatial analysis tool. Remotely sensed data can be digitally processed to yield land use/cover maps. In turn, these maps, as well as other thematic layers, can be integrated in a GIS environment for spatial analysis and modelling.

A number of landscape metrics (or indices) that describe the landscape structure (configuration and composition) can be formulated either in terms of the individual patches or of the whole landscape. The most commonly used metrics can be grouped as follows (McGarigal and Marks, 1994): *area metrics, patch density, patch size and variability metrics, edge metrics, shape metrics, core area metrics, nearest-neighbour metrics, diversity metrics,* and *contagion and interspersion metrics.* A full understanding of the landscape metric is required before it is used. Only after this should one attempt to draw conclusions about the structure of the landscape analysed.

## RESEARCH METHODS

### Study Area

The study area selected encompassed a total area of approximately 300,800 hectares of the Lockyer Valley Catchment in south-east Queensland, Australia (Figure 1). The Gatton shire, the catchment's biggest and most central local government authority, is located approximately 90 km west of Brisbane, the capital city of Queensland.

The Lockyer Valley encompasses some of the richest farming land in Australia supporting one of Queensland's most important centres of diversified agriculture. The activities in the catchment principally consist of crop cultivation, cattle grazing and timber production. Pasture dominates the land use/cover types (47%), followed by woody vegetation (41%) and crops (11%). The catchment has a local population of about 22,000 (EPA, 1999).

The area's topography varies from flat (mainly creek flats located at the centre to north-east side of the catchment) to ruggedly steep (mainly mountains and hills in the south-western and northern parts) land. Elevation within the catchment ranges from 27 to 1,106 metres above mean sea level. About 55% of the area is developed on sandstone parent materials, while some 25% of the area has been developed on tertiary basaltic flows. On the alluvial plains, highly fertile deep black cracking-clay soils and dark brown clay loams predominate. Elevated areas are typically dominated by shallow, stony, sandy or sodic soils with low fertility. The six different sub-catchments comprising the Lockyer Valley catchment have been shown to have a rate of vegetation clearing ranging from 4.2 to 197.5 hectares per year (DNR, 1999).

### Data Acquisition and Image Processing

A 75 km x 66 km subset was selected from a Landsat 5 Thematic Mapper (TM) digital image, taken on September 1997. The same image extent was utilised for the August 1973 Landsat 1 Multispectral Scanner (MSS) data. Adopting a post-classification change detection method, the study separately classified the 1973 and 1997 images using spatial masking and supervised classification techniques (employing a maximum likelihood classifier with prior probabilities).

The final classification yielded five classes for each image: *woody vegetation*, *pasture*, *crops*, *settlement*, and *water*. These class definitions were adopted, after modification, from the Queensland Statewide Land Cover and Trees Study (SLATS) project (DNR, 1999). A detailed account of the image processing techniques employed in this study was reported in Apan, et al. (2000).

### Measurement and Analysis of Landscape Fragmentation

This study implemented three separate, but related methods of quantifying and analysing landscape fragmentation. These GIS based methods included the following: a) *landscape structure calculations, b) analysis of changes in the number of small patches of woody vegetation,* and *c) land use/cover transition and site factor overlays*.

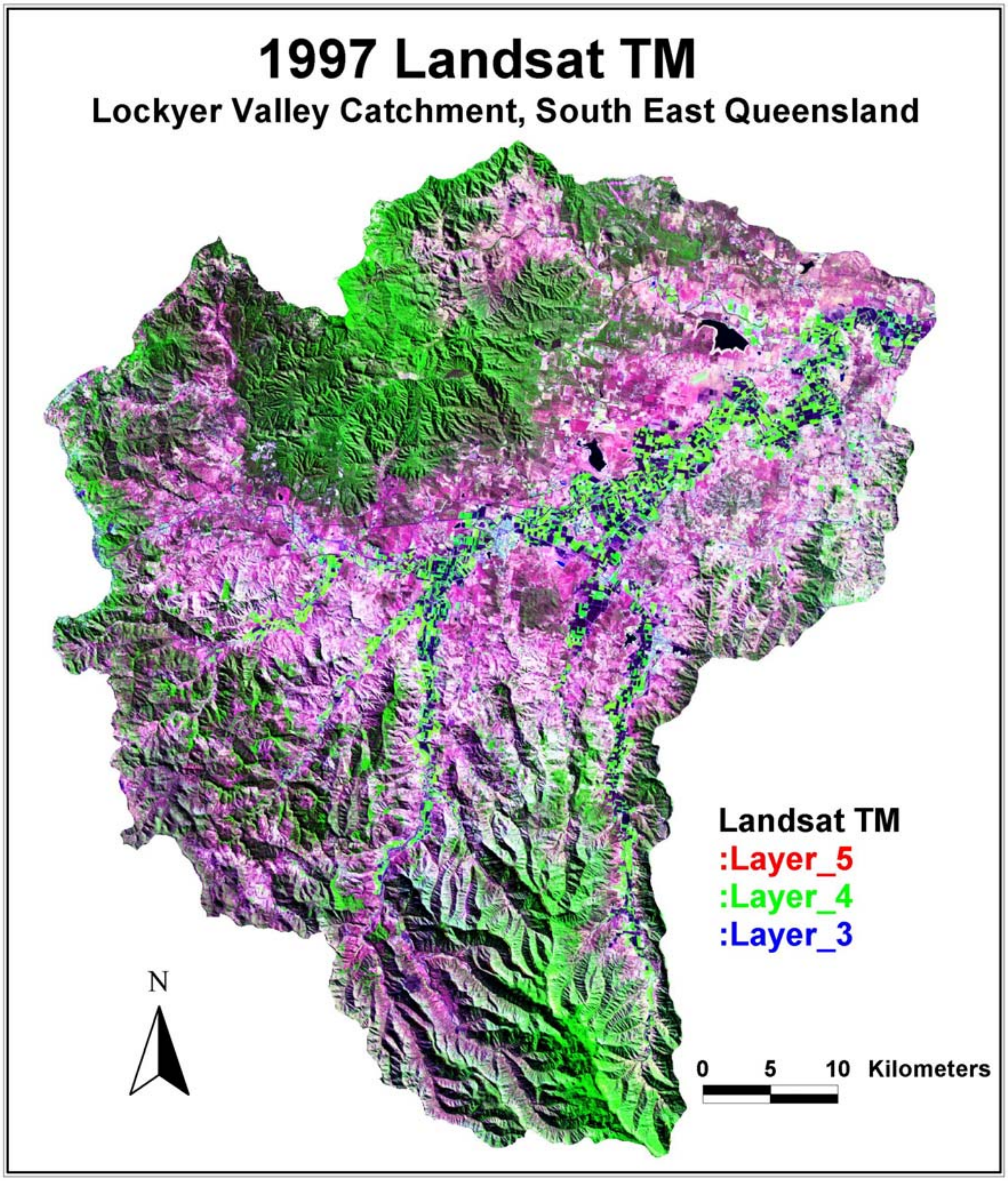


*Figure 1. Landsat TM (1997) of the study area (Apan, et al., 2000)*

The first two methods provided indicative measures of landscape fragmentation, while the last one attempted to assess the nature of fragmentation by identifying land use/cover transitions, and relating vegetation clearing to selected site factors. An initial attempt at applying the first method to the Lockyer Valley catchment has been previously reported (Apan, et al., 2000). The second method was developed to enhance the analysis at the patch level where most landscape pattern programs are weak due to intensive computing requirements.

In this study, the first approach used to quantify landscape fragmentation and its change over time was the calculation of "metrics" or "indices" that describe the landscape structure. The program Patch Analyst (Grid) 1.1 (Rempel, et al. 1999; see also http://flash.lakeheadu.ca/~rrempel/patch), an extension to ArcView Spatial Analyst, was used to generate landscape indices. The extension includes patch analysis functions developed using Avenue code, and an interface to the FRAGSTATS spatial pattern analysis program developed by McGarigal and Marks (1994).

The second method involved the analysis of changes in the number of small (0.50, 1.00, 2.00 and 3.00 hectares) patches of woody vegetation. This was accomplished by a series of steps:

- grouping of connected regions as defined by the four orthogonal neighbours of each cell;
- an attribute query (e.g. "*select value = 1 and count <= 2*", where *value = 1* corresponds to woody vegetation, and *count* is the cell frequency equivalent to patch area); and
- the calculation of changes in the number of patches.

Thirdly, a combinatorial ("crosstabulation") map overlay in GIS was performed to create a thematic map depicting all the possible transitions of change (e.g. pasture to agricultural crops, woody vegetation to settlement, etc.) between the 1973 and 1997 images. All changes involving woody vegetation (i.e. from woody vegetation to pasture, agricultural crops, settlement, or water) were mapped and analysed. Conversely, transitions from land cover / use classes to woody vegetation (which could be natural regrowth or artificial regeneration) were also determined and quantified.

To further analyse the nature of landscape fragmentation, the areas of a) *woody vegetation change* and b) *no change in woody vegetation*, were overlaid with the following datasets representing site factors: *land tenure, slope, distance from stream,* and *distance from road*. The frequency distribution for each site factor and vegetation change (or no change) was calculated and interpreted.

## RESULTS

### Landscape Structure Calculations

The data (Table 1) on patch density, patch size, and largest patch index indicated that the woody vegetation has undergone considerable fragmentation during the study period. The *number of patches* has substantially increased, suggesting the breaking up of vegetation areas into smaller parcels (i.e. from 4,964 to 8000 patches). The *mean patch size* is also indicative of the vegetation fragmentation: it has decreased from 33.71 hectares in 1973 to just 15.44 hectares in 1997. Furthermore, the *largest patch index* supports this view: the percentage of the largest woody vegetation patch has decreased from 47.20% to 20.36%.

The mean shape index values for the 1973 and 1997 buffer zones are greater than 1 (Table 1), indicating that the average vegetation patch shape in all landscapes is non-square. Generally, however, there is no significant change in the shape index values. The 1997 patches are slightly less irregular in shape than the 1973 patches, i.e. from 1.30 to 1.33. The mean patch fractal value (1.04) for the 1973 data suggested a very slight convolution (complexity) of perimeters of vegetation patches. This value is the same as in 1997.

The mean nearest-neighbour distance values have increased from about 89.12 to 99.01 m (Table 1). This change indicates that the 1997 woody vegetation patches are more isolated than the 1973 patches, and that inter-patch connectivity has decreased. This is supported by the mean proximity index values (decreased from 84,214 to 21,446).

The 1973 woody vegetation class has a low interspersion and juxtaposition index (i.e. only 19.9%). This value indicates that the vegetation patches are not well interspersed in the landscape or equally adjacent to all other patch types. In contrast, the 1997 landscape has a much lower value (i.e. 12.06%), indicating a reduced interspersion and juxtaposition to other woody vegetation patches.

### Changes in the Number of Small Woody Vegetation Patches

With the exception of 0.50-hectare-and-below patches, the number of patches of woody vegetation for all patch size classes has increased for the 1997 image (Table 2). This supports the Patch Analysis results, and confirms increased fragmentation of the landscape during the study period as evidenced by the significant increase in the number of vegetation patches coupled with the reduction in total vegetation area. The notable exception for 0.50-hectare-and-below patch size is due to the region-based generalisation applied to the 1997 Landsat image to reduce the negative effect of sensor differences (see Apan, et al., 2000).

### Land Use/Cover Transitions and Site Factors

The area of the 1973 woody vegetation has significantly decreased within the 24-year study period. The total woody vegetation cleared during the period (i.e. the 1973 woody vegetation areas converted into other land uses by 1997) was approximately 58,136 hectares, or an average of about 2,422 hectares per year (Table 3). The 1997 data (Table 1) showed that woody vegetation covered only 41% of the total catchment area (300,800 ha) compared to a 56% coverage in 1973.

*Table 1. Landscape structural change for woody vegetation, Lockyer Valley Catchment, 1973-1997*

| Indices | Year | |
|---|---|---|
| | 1973 | 1997 |
| **CLASS LEVEL: Vegetation** | | |
| Class Area (ha) | 167,355 | 123,516 |
| Percent of Landscape (%) | 55.64 | 41.06 |
| Number of Patches | 4,964 | 8,000 |
| Patch Density (# / 100 ha) | 1.65 | 2.66 |
| Mean Patch Size (ha) | 33.71 | 15.44 |
| Largest Patch Index (%)[a] | 47.20 | 20.36 |
| Mean Shape Index[b] | 1.30 | 1.33 |
| Mean Patch Fractal[c] | 1.04 | 1.04 |
| Mean Nearest Neighbour Distance (m)[d] | 89.12 | 99.01 |
| Mean Proximity Index[e] | 84,214 | 21,446 |
| Interspersion/Juxtaposition (%)[f] | 19.90 | 12.06 |

[a] the percentage of total landscape area comprised by the largest patch
[b] the average perimeter-to-area ratio; it is equal to 1 when all patches of the corresponding patch type are square; it increases without limit as the patch shapes become more irregular
[c] the average fractal dimension; it approaches 1 for shapes with very simple perimeters such as circles or squares; it approaches 2 for shapes with highly convoluted, plane-filling perimeters
[d] the average edge-to-edge distance from a patch to the nearest neighbouring patch of the same type
[e] measures the degree of patch isolation and fragmentation; it is equal to 0 if all patches of the corresponding patch type have no neighbours of the same type within the specified search radius (100 m in this study); it increases as patches become less isolated and the patch type becomes less fragmented in distribution
[f] measures the extent to which patch types are interspersed; it approaches 0 when the corresponding patch type is adjacent to only 1 other patch type and the number of patch types increases; it is equal to 100 when the corresponding patch type is equally adjacent to all other patch types (*i.e.* maximally interspersed and juxtaposed to other patches)

*Table 2. Patch size of woody vegetation vs. number of patches, Lockyer Valley Catchment, 1973-1997*

| Patch Size of Woody Vegetation | Number of Patches (1973) | Number of Patches (1997) |
|---|---|---|
| 0.50 hectare and below | 3,155 | 2,842 |
| 1.00 hectare and below | 5,852 | 6,836 |
| 2.00 hectares and below | 9,837 | 11,933 |
| 3.00 hectares and below | 12,636 | 15,522 |

The results (Table 3) show that woody vegetation was cleared mainly for pasture, comprising approximately 98.35% of the total cleared area. This represents approximately 57,178 hectares over the 24-year study period. Only minor clearing occurred for agricultural crops, settlement and water bodies. However, approximately 14,012 hectares of what was pasture land in 1973 had reverted to woody vegetation by 1997.

The area affected by woody vegetation change and classified according to land tenure is presented in Figure 2. Approximately 51,829 hectares out of the total 58,136 hectares of cleared (woody vegetation to other land uses) lands correspond to *freehold lands*. Hence, the majority of clearing occurs on freehold land (89% of the 58,136 hectares), followed by leasehold lands (3% of the 58,136 hectares). However, the "no change" vegetation area also recorded *freehold lands* as the dominant land tenure (84,121 hectares out of the total 109,219 hectares, or 77%).

The relationship between slope and woody vegetation change is normally distributed (Figure 3) with the "undulating to moderate" slope ranges (8-18% and 18-30%) dominating both the "changed" and "no change" categories. However, approximately 48% of clearing occurred on lands with a slope in excess of 18%. This large proportion of clearing on steep lands raises concerns over the longer term sustainability in these areas given the potential for land slips and soil erosion within the catchment.

The absolute area affected by woody vegetation change was not correlated with distance from the road (Figure 4). However, a smaller proportion of the land in each distance category was cleared as distance from the closest road increased. Similarly, while the majority of woody vegetation cleared was located more than 1 km from streams, clearing in those areas close to the streams (<500m) represented a greater proportional (e.g. >40% in the <100 m range) of the pre-existing woody vegetation (Figure 5).

*Table 3. Woody vegetation change, Lockyer Valley Catchment, 1973-1997*

| Thematic Change | Area | |
|---|---|---|
| | (ha) | % |
| A. No change | 109,219 | 65.26 |
| B1. Woody Vegetation to Pasture | 57,178 | 34.17 *(98.35)** |
| B2. Woody Vegetation to Crops | 834 | 0.50 *(1.44)* |
| B3. Woody Vegetation to Settlement | 46 | 0.05 *(0.13)* |
| B4. Woody Vegetation to Water | 77 | 0.03 *(0.08)* |
| Total of B1-B4 | 58,136 | 34.74 |
| *Grand Total (A and Bs)* | 167,355 | 100 |

*Numbers in parenthesis represent the percentage computed for the total of B1-B4 only.

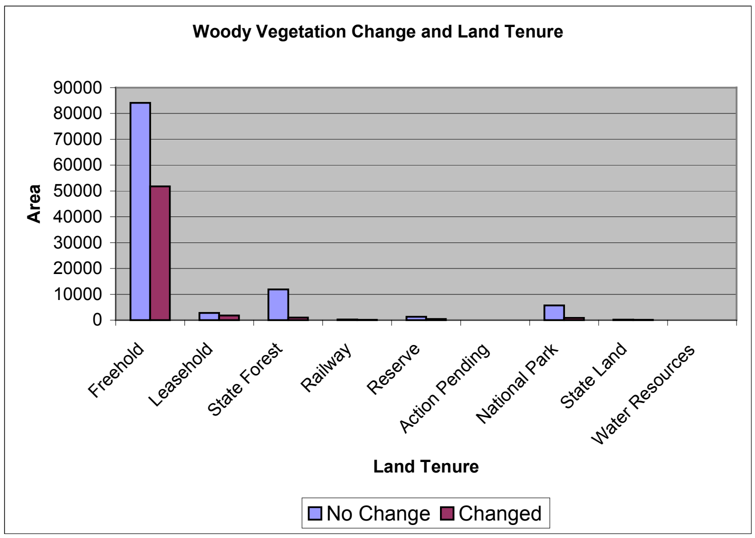


*Figure 2. Vegetation change and land tenure, Lockyer Valler catchment, 1973-1997*

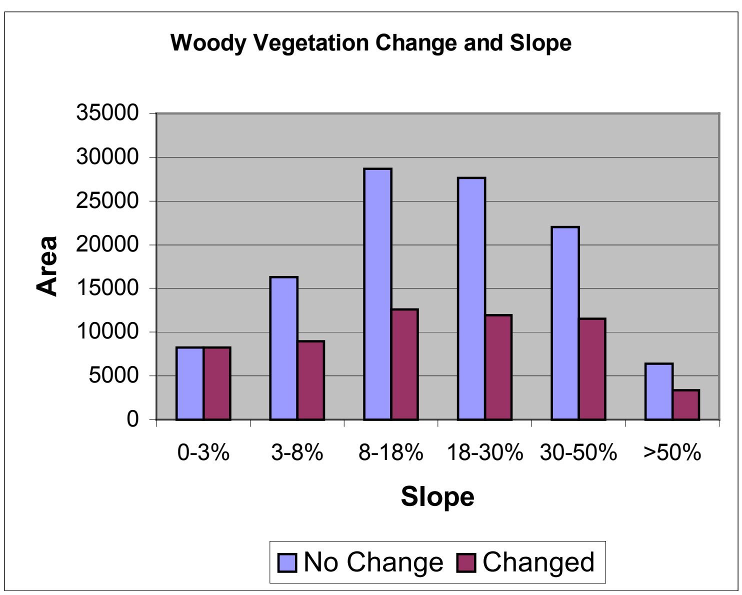


*Figure 3. Woody vegetation change and slope, Lockyer Valler catchment, 1973-1997*

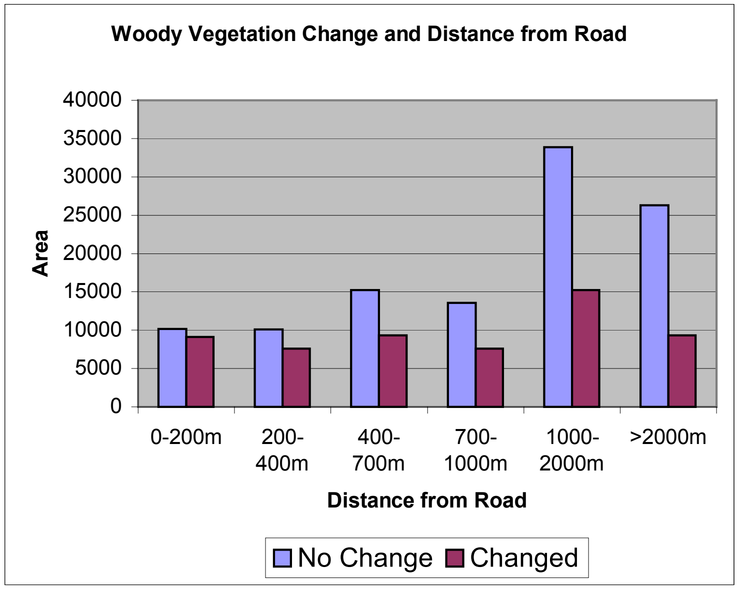


*Figure 4. Woody vegetation change and distance from road, Lockyer Valler catchment, 1973-1997*

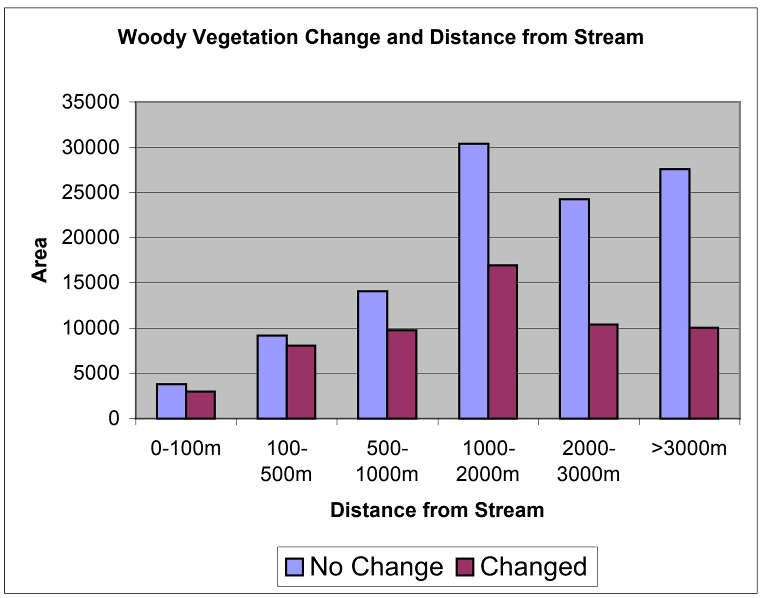


*Figure 5. Woody vegetation change and distance from stream, Lockyer Valler catchment, 1973-1997*

# DISCUSSION

## Methods for Quantifying and Analysing Landscape Fragmentation

The Patch Analyst (Grid) program used in this study provided a wide range of indices relevant to the analysis of landscape fragmentation. While it can provide 40 metrics of landscape structure, the simple a) *area metrics* and the b) *patch density, patch size and variability metrics* in class or category level (e.g. woody vegetation class) were found sufficient to yield quantitative measures of landscape fragmentation. While the package has provisions for calculating metrics on an individual patch level (patch A *vs*. patch B), its implementation using datasets generated from satellite image, in a catchment scale, is demanding due to intensive computing requirements. Considering that many landscapes cover a large area of numerous, irregularly shaped patches (this study has 10,408 patches), the development of alternative techniques may be desirable.

One technique implemented in this study that enhanced the analysis of individual patches was the use of "region grouping" of raster cells, followed by an attribute query (e.g. "*select value = 1 and count <= 2*") that focused on the number of patches for patch size groups. A direct comparison of the number of patches between two-date images yielded information related to landscape fragmentation. For example, the difference of the 1973 and 1997 images, which is approximately 1,000 patches, confirmed the breaking up of the vegetation mosaics within the landscape. However, for remotely sensed data, the pre-requisite is to normalise the effects of differing sensor spatial resolution (see Barnsley, et al., 1997).

Analysing land use/cover transitions is essential to the improved understanding of landscape fragmentation. The combinatorial (crosstabulation) grid overlay in GIS was found useful in producing a land use/cover transition matrix for the two-date images. All of the possible change transitions (e.g. pasture to agricultural crops, woody vegetation to settlement, agricultural crops to water, etc.) between the 1973 and 1997 images were readily calculated using this technique.

The attempt made in this study to characterise woody vegetation clearing in relation to site factors provided some insights to the factors and significance of catchment attributes on woody vegetation change. Using combinatorial grid overlay and simple percentage calculations, the technique provided descriptive statistics and useful graphical summaries of woody vegetation change and site factors. However, it is difficult to make concrete inferences from the data using this technique alone. The use of more advanced statistical techniques, including logistic regressions and chi-square tests, may be necessary to infer beyond this level (e.g. Apan and Peterson, 1998).

### Landscape Fragmentation in the Lockyer Valley

This study suggests that the structure of the landscape in the Lockyer Valley catchment has significantly changed during the 24-year study period. While the 1973 landscape in the study area showed signs of human-induced fragmentation, the 1997 landscape was significantly more fragmented. Within the study period, some 58,136 hectares of woody vegetation were converted to either pasture, agricultural cropland, water, or settlement, which resulted to the proliferation of small, less connected vegetation patches. Although there are some areas where revegetation has occurred, the coverage is relatively small (14,012 hectares). Thus, it is obvious that there is an imbalance between deforestation and revegetation.

Much of the woody vegetation clearing in the Lockyer Valley catchment between 1973-1997 is due to pasture (57,178 hectares or 98.25% of all clearing). This could be partly explained by the landscape attributes itself: opportunities for other land uses in the area are being constrained by the biophysical characteristics of the site, perhaps significantly by soil and landform limitations. Lack of other economic alternatives (e.g. lands for arable farming) may also be encouraging the proliferation of less intensive land uses such as pasture.

From the study's characterisation of site factors involving woody vegetation change, the areas where most vegetation clearing occurred were typically freehold lands, with slopes between 8% to 30%, located more than 1 km from roads, and more than 1 km away from the stream network. It should be noted that this work has only investigated a small number of factors which could be related to clearing patterns. As natural landscapes and socio-economic patterns of human activities are heterogenous and complex, more rigorous analysis would be required to confirm any causal relationships associated with landscape fragmentation. However, the relative proportion of pre-existing woody vegetation which has been shown to have been cleared within the riparian zone (e.g. <100 m from streams) and on steep (>18%) slopes raises serious questions in relation to both the catchment health and the longer term potential for land degradation by upland clearing in this area.

## CONCLUSIONS

Quantifying landscape fragmentation from multi-date satellite imagery is relatively uncomplicated. Landscape pattern programs are available and capable of producing numerous quantitative measures of the structural attributes of the landscape. While the package has provisions for calculating metrics on an individual patch level, its implementation using satellite image of a large catchment scale may be impractical due to intensive computing requirements. This study developed a simple GIS technique based on region grouping of image raster cells, in tandem with attribute query that focused on the number of patches for patch size groups. In addition, the combinatorial grid overlay in GIS was found to be useful in analysing land use/cover transitions. The same technique, coupled with simple percentage area calculations, was also useful in relating woody vegetation clearing to some site factors.

This study reveals the degenerating condition of the natural landscapes in the Lockyer Valley catchment. Apart from the significant decrease in vegetation areas mainly due to clearing for pasture, the woody vegetation areas have become more fragmented and are characterised by the proliferation of much smaller, less connected vegetation patches. This work has quantified the nature of woody vegetation fragmentation and shown that clearing has predominantly been occurring on freehold lands, with slopes between 8% to 30%, located more than 1 km from local roads, and more than 1 km away from the stream network. Although this general trend on land use/cover change in the region has already been reported elsewhere (e.g. Catterall and Kingston, 1993; DNR, 1999), the present study's focus on the landscape fragmentation and structural change (and not merely on land use/cover change) has added a new dimension.

## ACKNOWLEDGMENT

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