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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 area 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 and tenure, slope, and 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 crop, settlement, and water bodies, respectively. The sites that were most subjected to vegetation clearing include those areas in freehold lands, with slope between 8% to 30%, approximately located between 1 km and above from the road, and in more than 1 km away from the stream network. Landscape fragmentation can be quantified with relative ease in a GIS environment. The main issue is 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.). Caused by either natural or anthropogenic agents, it has a negative influence on many species of plants and animals, and on ecological processes (Farina, 1998, p.58). A worldwide process occurring in various spatio-temporal scales, it reduces biodiversity and advances the local extinction of flora and fauna. Fragmentation also increases the vulnerability of patches to external disturbance, for instance windstorm or drought (Nilsson and Grelsson, 1995).

Understanding the nature and effects 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 may need to know community composition and diversity in fragments needed 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 prerequisite to the study of landscape function and change (McGarigal and Marks, 1994). Quantitative measurements of landscape fragmentation will allow accurate characterisation and analysis of key ecological processes. With the availability of satellite imagery capable of imaging 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 applied to a variety of landscape conditions.

The objectives of this study are as follows:

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.

It is a part of a broader study focusing on the spatio-temporal assessment of landscape change and environmental indicators in a catchment in Queensland, Australia.

LANDSCAPE FRAGMENTATION

RESEARCH METHODS

Study Area

With a total area of approximately 300,800 hectares, the study area covers the Lockyer Valley Catchment, south east Queensland, Australia (Figure 1). The Gatton shire, the catchment’s biggest and most central, is located approximately 90 km west of Brisbane, the capital city of Queensland.

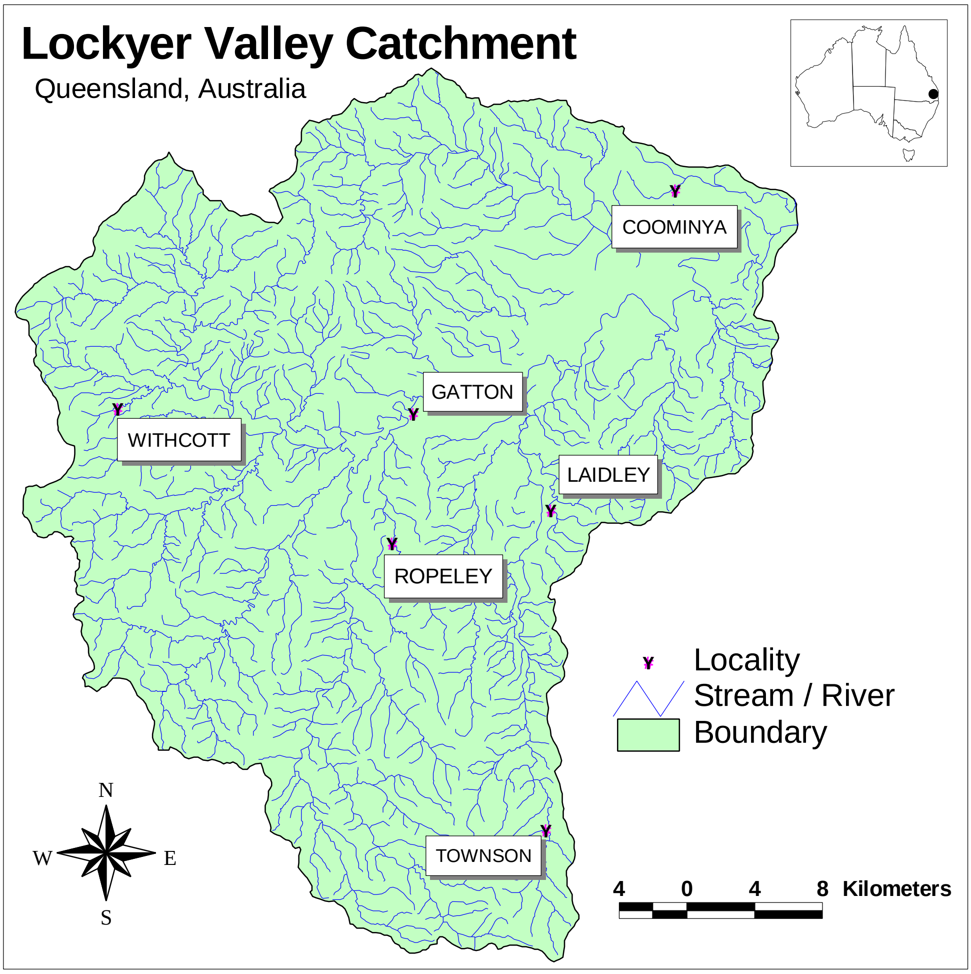

Figure 1. Location map of the study area (Apan, et al., 2000)

The Lockyer Valley encompasses some of the richest farming land in Australia supporting one of the 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). Elevation ranges from 27 to 1,106 meters above mean sea level. About 55% of the area is sandstone, while some 25% of the area is basalt. In alluvial plains, soils are generally of the deep black cracking-clay soils and dark brown clay loams. Other areas have generally shallow, stony, low in fertility, or sandy soils.

The six different sub-catchments comprising the Lockyer Valley catchment had a rate of vegetation clearing from 4.2 to 197.5 hectares per year (DNR, 1999). In all sub-catchments of the study area, the majority of woody vegetation areas is cleared for pasture (about 78% to 100% of all clearings).

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 (Figure 2). The same image extent was utilised for the August 1973 Landsat 1 Multispectral Scanner (MSS) data (Figure 3). Adopting a post-classification change detection method (refer to Yuan, *et al.*, 1998), 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's 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). Figure 4 shows the datasets used and the image processing steps involved in generating the final 1973 and 1997 land use/cover maps.

(large file image)
Figure 2. Landsat TM (1997) of the study area (Apan, et al., 2000)

(large file image)
Figure 3. Landsat MSS (1973) of the study area (Apan, et al., 2000)

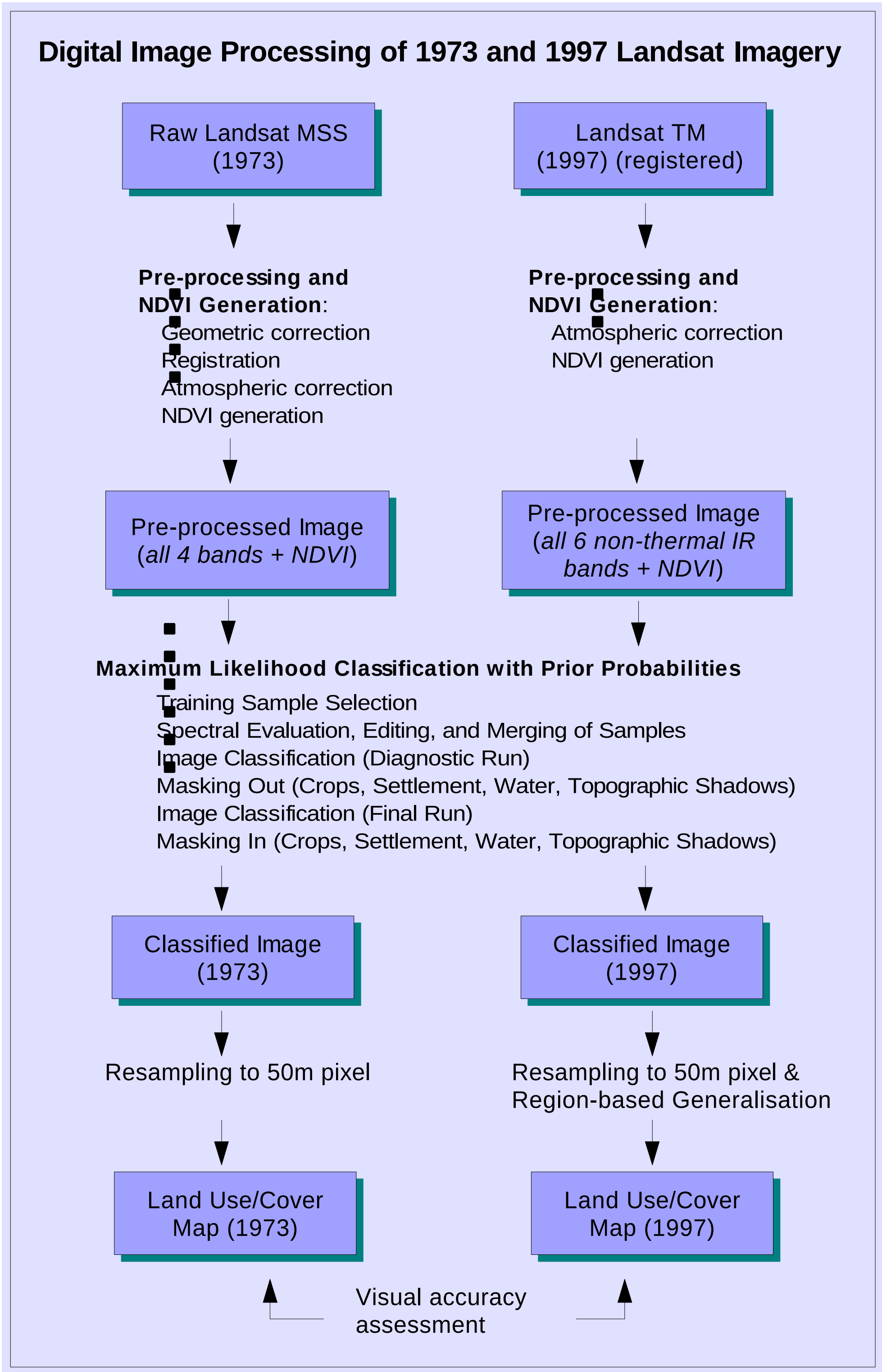

Figure. 4. Digital image processing of 1973 and 1997 Landsat imagery (Adapted from Apan, et al., 2000)

Measurement and Analysis of Landscape Fragmentation

This study implemented three separate, but related methods of quantifying and analysing landscape fragmentation (Figure 5). These GIS based methods included the following:

- landscape structure calculations;
- analysis of changes in the number of small patches of woody vegetation; and
- land use/cover transition and site factor overlays.

The first two methods provided indicative measures of landscape fragmentation, while the last one attempted to understand the nature of fragmentation by identifying land use/cover transitions, and relating vegetation clearing and selected site factors. Initial attempt in the application of the first method for the Lockyer Valley catchment was reported earlier by the same authors (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.

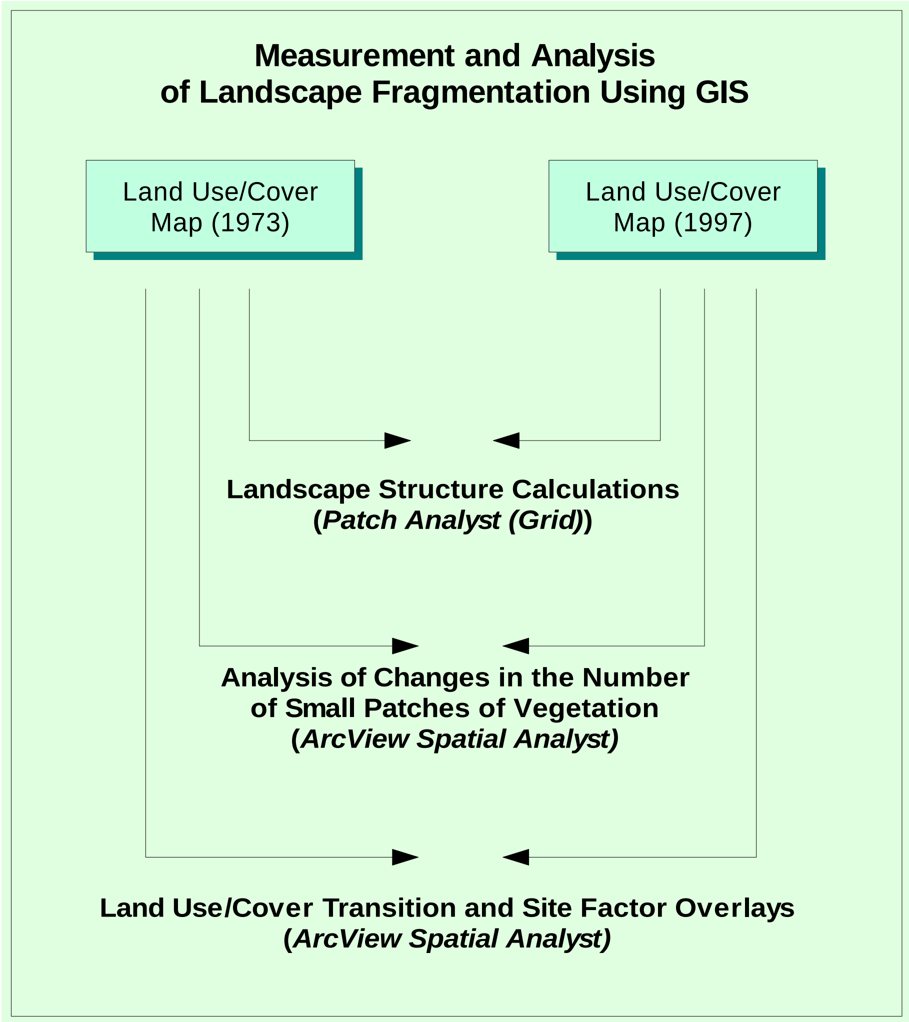

Figure 5. Measurement and analysis of landscape fragmentation

In this study, the first approach used to quantify landscape fragmentation and its change over time was the calculations of "metrics" or "indices" that describe the landscape structure. As reported earlier (Apan, et al., 2000), 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 McGarrigal and Marks

(1994). This study focused principally on the woody vegetation class that included one or more of the following indices:

- area metrics;
- patch density, patch size and variability metrics;
- shape metrics;
- nearest-neighbour metrics;
- diversity metrics; and
- contagion and interspersion metrics.

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 region as defined by the four orthogonal neighbours of each cell;
- 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
- 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 particularly 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%.

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
Patch Size CV[a] (%)	5,980.02	4,711.45
Largest Patch Index (%)[b]	47.20	20.36
Mean Shape Index[c]	1.30	1.33
Mean Patch Fractal[d]	1.04	1.04
Mean Nearest Neighbour Distance (m)[e]	89.12	99.01
Nearest Neighbour CV (%)	73.19	98.54
Mean Proximity Index[f]	84,214	21,446
Interspersion/Juxtaposition (%)[g]	19.90	12.06

[a] coefficient of variation; it is equal to 0 when there is no variability in patch size
[b] the percentage of total landscape area comprised by the largest patch
[c] 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
[d] 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
[e] the average edge-to-edge distance from a patch to the nearest neighbouring patch of the same type
[f] 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
[g] 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)

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 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 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. It supports the Patch Analyst's results, indicating the increased fragmentation of the landscape in the study period as evidenced by the significant increase in the number of vegetation patches coupled with the reduction of 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).

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

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 clearing (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) disclosed that the woody vegetation area was only 41% of the total 300,800 hectares. Previously (1973), it was about 56%.

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.

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 for the 24-year study period. Only minor clearing occurred for agricultural crops, settlement and water bodies. With regards to regrowth or regeneration, there were approximately 14,012 hectares of pasture in 1973 converted to woody vegetation (Table 4). Virtually no other land use/cover classes in 1973 had significant conversion to woody vegetation, except pasture.

Table 4. Regeneration/Regrowth of woody vegetation, Lockyer Valley Catchment, 1973-1997

Thematic Change	Area	
	(ha)	%
A. No change	109,219	88.60
B1. Pasture to Woody Vegetation	14,012	11.37
		*(99.75)**
B2. Crops to Woody Vegetation	6	0.00
		(0.04)
B3. Settlement to Woody Vegetation	7	0.01
		(0.04)
B4. Water to Woody Vegetation	23	0.02
		(0.17)
Total of B1-B4	14,047	11.40
Grand Total (A and Bs)	123,266	100

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

The area covered by woody vegetation change based on land tenure is presented in Figure 6. Approximately 51,829 hectares out of the total 58,136 hectares of cleared (woody vegetation to other land uses) lands correspond to *freehold lands*. This has the highest clearing among land tenure categories (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%).

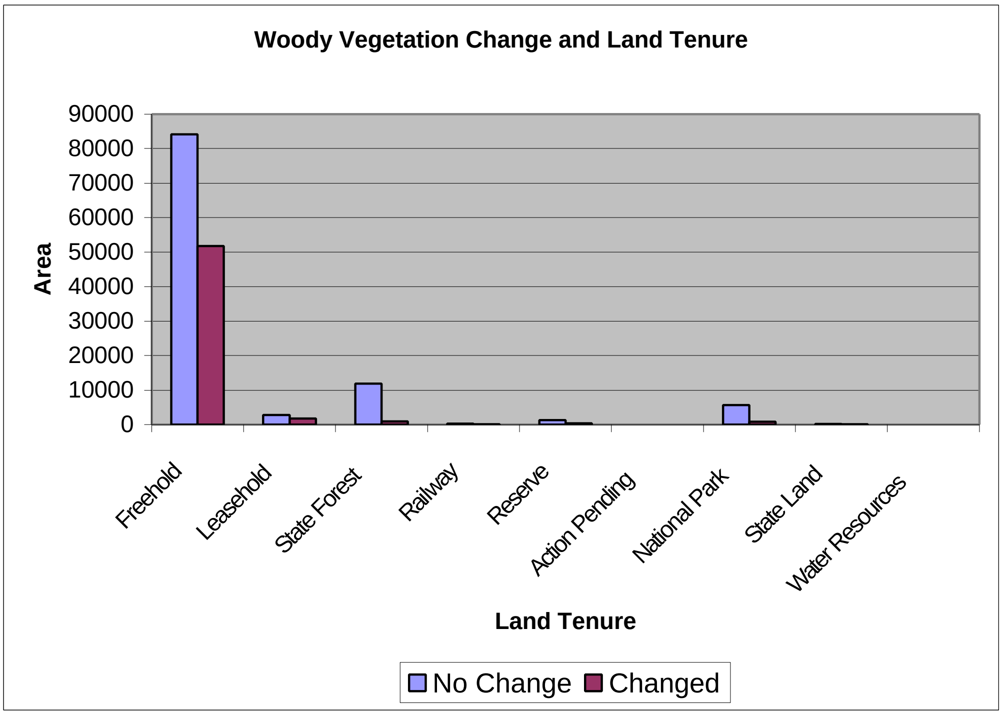

Figure 6. Vegetation change and land tenure, Lockyer Valler catchment, 1973-1997

The distribution of slope and woody vegetation change resembles a normal curve (Figure 7). Areas in "undulating to moderate" slopes (8-18% and 18-30%) dominate both the "changed" and "no change" categories. Flat and very steep areas account for the lowest proportions.

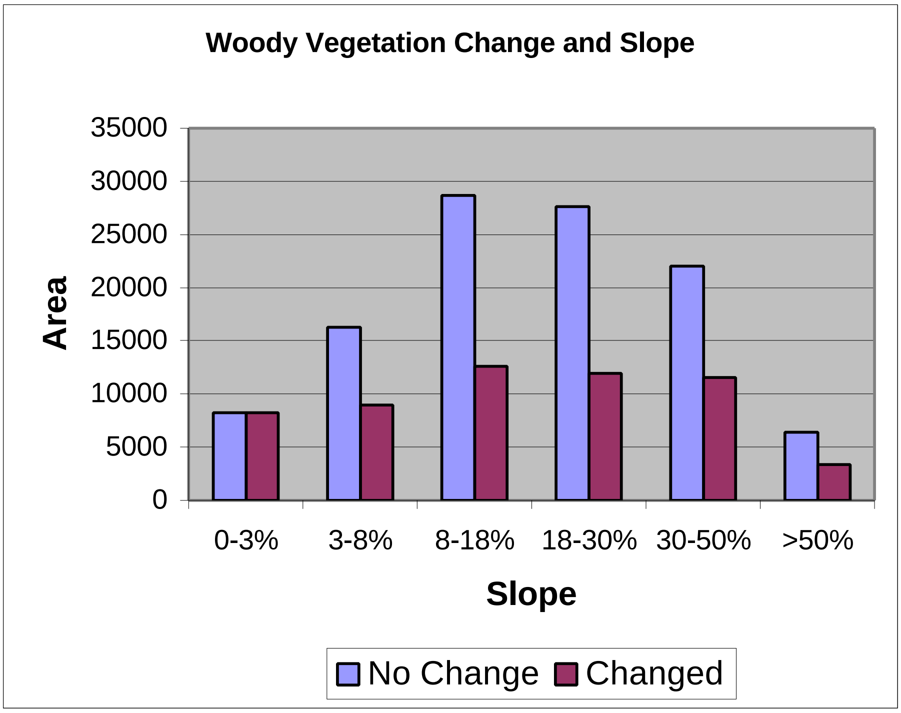

Figure 7. Woody vegetation change and slope, Lockyer Valler catchment, 1973-1997

The areas covered by woody vegetation change, in relation to distance from the road, are not skewed to any specific distance-from-the-road categories. However, for the "no change" woody vegetation areas, those areas in "1000-2000m" and ">2000m" classes have greater proportions. With regards to distance from the stream, the cleared areas peak on "1000-2000m" category, although other categories (i.e. "500-1000m", "2000-3000m", and ">3000") have substantial coverage.

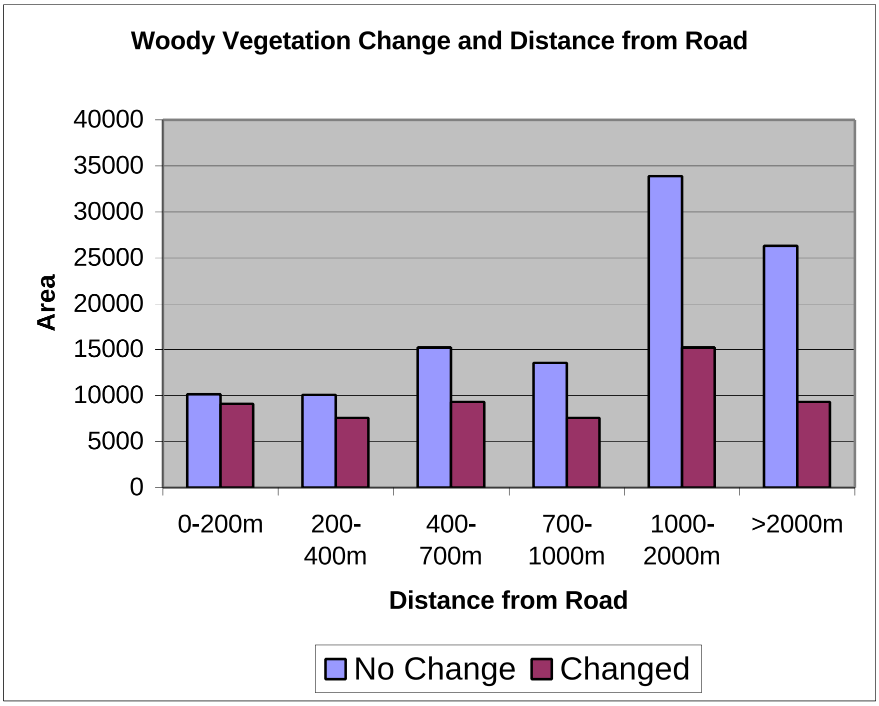

Figure 8. Woody vegetation change and distance from road, Lockyer Valler catchment, 1973-1997

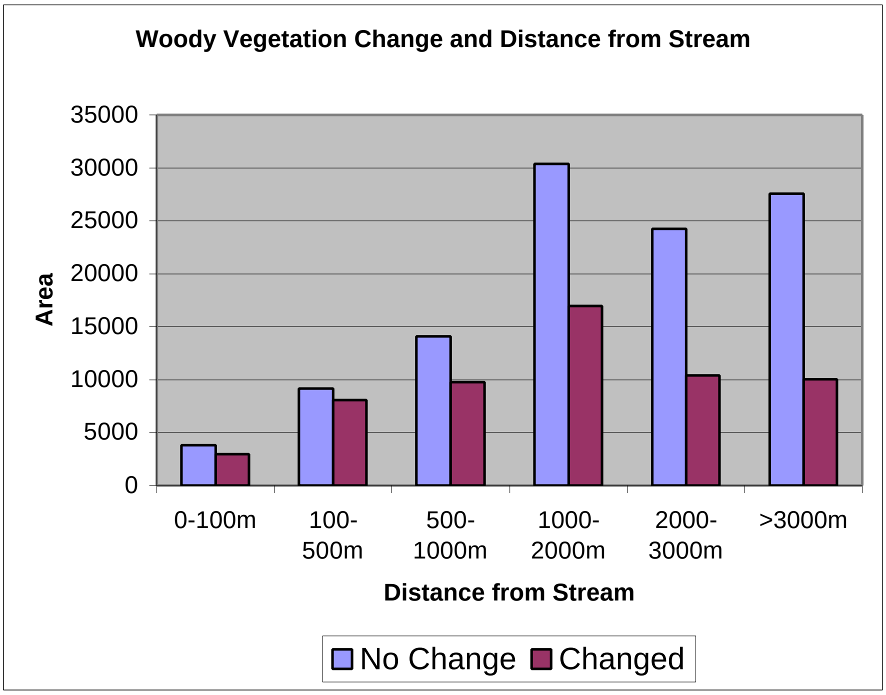

Figure 9. Woody vegetation change and distance from stream, Lockyer Valler catchment, 1973-1997

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, will be very 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 is 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 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, indicates the breaking up of the vegetation mosaics in landscape. However, for remotely sensed data, the prerequisite 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 very useful in producing a land use/cover transition matrix for the two-date images. All the possible transitions of change (e.g. pasture to agricultural crops, woody vegetation to settlement, agricultural crops to water, etc.) between the 1973 and 1997 images were easily calculated.

The attempt made in this study to characterise woody vegetation clearing in relation to some site factors provided some insights on the attributes of 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 advanced statistical techniques, such as logistic regression and chi-square test, could be easily extended from this currently attained 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) encourages the proliferation of less criteria-intensive land uses such as pasture.

From the study's characterisation of site factors involving woody vegetation change, the sites that were most subjected to vegetation clearing include those areas in freehold lands, with slope between 8% to 30%, approximately located between 1 km and above from the road, and in more than 1 km away from the stream network. However, this is only a rough list that should be subjected to more rigorous analysis. Natural landscapes are heterogenous and complex, and so with the socio-economic patterns of human activities, which makes landscape fragmentation analysis in this respect more complicated.

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 will 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.

The combinatorial grid overlay in GIS was found very useful in analysing land use/cover transitions. The same technique, coupled with simple percentage area calculations, was also useful in characterising woody vegetation clearing in relation to some site factors. The use of advanced statistical techniques, such as logistic regression and chi-square test, could be easily extended from the approach attained in this study.

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 conversion to pasture, the woody vegetation areas have become more fragmented: they are characterised by the proliferation of much smaller, less connected vegetation patches. This work was able to quantify and analyse the nature of fragmentation of woody vegetation. The sites that were most subjected to vegetation clearing include those areas in freehold lands, with slope between 8% to 30%, approximately located between 1 km and above from the road, and in 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, 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.

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REFERENCES

Apan A. and Peterson, J., 1998. Probing Tropical Deforestation: Use of GIS and Statistical Analysis of Georeferenced Data. Appl Geog, 18: 137-152.

Apan, A., Raine, S. R. and Paterson, M.S., 2000. Image Analysis Techniques for Assessing Landscape Structural Change: A Case Study of the Lockyer Valley catchment, Queensland, Proc. of the 10th Australasian Remote Sensing and Photogrammetry Conference, August 21-25, Adelaide, Remote Sensing and Photogrammetry Association, Australia, pp. 438-455.

Barnsley, M. J., Barr, S.L., and Tsang, T., 1997. Scaling and generalisation in land cover mapping from satellite sensors. In: P.R. Van Gardingen, G.M. Foody, and P.J. Curran (Editors), Scaling-up: From Cell to Landscape. Cambridge University Press, Cambridge, pp. 173-199.

Benson, B. J. and Mackenzie, M.D., 1995. Effects of sensor resolution on landscape structure parameters. Landscape Ecol, 10: 113-120.

Catterall, C. P. and Kingston, M., 1993. Remnant Bushland of Southeast Queensland in the 1990s: Its Distribution, Loss, Ecological Consequences and Future Prospects. Institute of Applied Environmental Research, Griffith University and Brisbane City Council, Brisbane.

DNR, 1999. Land Cover Change in Queensland, 1991-1995, June 1999 Report. Statewide Land Cover and Trees Study, Department of Natural Resources, Brisbane.

EPA (Environmental Protection Agency), 1999. State of the Environment Queensland 1999. Environmental Protection Agency, Brisbane.

ESRI (Environmental Systems Research Institute), 1997. ArcView GIS. Environmental Systems Research Institute, Redlands, California.

ESRI (Environmental Systems Research Institute), 1996. ARC/INFO (GIS software). Environmental Systems Research Institute, Redlands, California.

Farina, A., 1998. Principles and Methods in Landscape Ecology. Chapman and Hall, London, pp.

Forman, R.T.T. and Godron, M., 1986. Landscape Ecology. John Wiley & Sons, New York, 619 pp.

Franklin, J.F., 1994. Developing information essential to policy, planning and management decision-making: The promise of GIS. In: V. Alaric Sample (Editor), Remote Sensing and GIS in Ecosystem Management, Island Press, Washington DC, pp. 18-24.

Knight, D.H., 1987. Parasites, lightning, and vegetation mosaic in wilderness landscapes. In: M. G. Turner (Editor), Landscape Heterogeneity and Disturbance. Springer-Verlag, New York, pp. 59-83.

Mcgarigal, K. And Marks, B.J., 1994. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure (Vesion 2.0). Forest Science Department, Oregon State University, Corvallis.

Nilsson, C. and Grelsson, G. (1995). The fragility of ecosystems: a review. Journal of Applied Ecology, 32:677-692.

Rempel, R.S., Carr, A., and Elkie, P., 1999. Patch analyst and patch analyst (grid) function reference. Centre for Northern Forest Ecosystem Research, Ontario Ministry of Natural Resources, Lakehead University, Thunder Bay, Ontario.