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Assessment of a method for mapping woody plant density in a grassland matrix

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Determining patterns of land degradation, and by inference the ecological processes at play, is critical to designing and implementing strategies and tactics to halt degrading practices and restore already degraded areas. In this paper we describe the application of a new image analysis technique to determine the presence and density of shrubs in a grassland matrix and evaluate its use for assessing rates and patterns of shrub increase, a common form of land degradation in rangelands throughout the world. By analysing a series of images derived from aerial photography to identify and separate objects (shrubs) in progressive steps, we were able to detect accurately individual shrubs with canopies greater than 9 m^2 (about 85% of the sample population). The method also was moderately successful in predicting canopy area of individual trees. This approach offers land managers and policy-makers a tool for defining both temporal patterns and rates of shrub increase as well as for defining the current extent of an invasion as a basis for targeting control technologies.

Keywords: aerial photography; shrub invasion; remote sensing; image analysis; Geographic Information System; density slicing

Introduction

The conversion of grassland to woodland as a result of shrub increase is a process of concern to rangeland managers around the world (Archer, 1994). As shrubs increase, forage for livestock production is reduced, habitat for native species is altered and local and regional hydrology can change. The scale of this problem is such that it has likely received more research and management attention than any other rangeland management problem (Scifres, 1987).

There are two general types of shrub increase in rangelands. First, thickening of native shrubs in open savannas and grasslands leads to conversion to scrublands and

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is generally viewed as an acceleration of existing successional processes (Archer, 1989; Harrington, 1991; Skarpe, 1991). Second, invasions of exotic shrubs in open grasslands and savannas have the potential to drastically alter both economic and ecological function (Grice & Brown, 1996*b*).

While the development and application of technologies to kill individual plants has been relatively successful, there has been little success in preventing establishment of new populations, reducing the impact of populations on landscape scale functions or preventing re-infestation after application of control technologies. This failure has largely been due to the inability of land managers to institute timely, well directed landscape restoration projects (Grice & Brown, 1996*a*). Apart from adequate economic incentives, the implementation of successful large-scale restoration projects has three fundamental information needs: (1) an accurate description of rates and patterns of the degrading process (in this case, shrub invasion); (2) reliable inferences about proximate causes of degrading processes; and (3) a means of prioritizing management actions and targeting control technologies at subpopulations critical to the maintenance of the larger population. We have chosen to test our methodology using *Acacia nilotica* (L) Delile invasion in an open tropical grassland because it has commenced relatively recently and is still underway, land use and management patterns are largely unchanged over the past half-century and native tree cover is virtually non-existent (Brown & Carter, in press).

Acacia nilotica subsp. *indica* (Benth.) Brenan is a leguminous shrub or small tree native to the arid and semi-arid regions of Africa and western Asia. It was introduced to the predominantly sheep-grazed Mitchellgrass Downs in the late 1800s as a source of shade to improve lambing and emergency fodder (Carter & Cowan, 1993). Early concern about the plant's undesirable spread has proved to be well-founded and large increases in *A. nilotica* populations have occurred since the 1970s when cattle, a more effective dispersal vector, replaced sheep as the dominant domestic grazer (Brown & Carter, in press). Approximately 7 million ha of the 21·5 million ha Mitchellgrass Downs are currently infested by *A. nilotica* and the potential for increase is great (Mackey, 1996).

Although control has been recommended for several decades, a concerted control strategy is still lacking. Active control programmes are instigated on a property-by-property basis and are typically constrained by the ability of individual property managers to devote financial and time resources to control activity and fluctuate with resource availability. Mechanical removal of trees from the most obvious and severe infestations is the usual large-scale control activity (Mackey, 1996). Chemical control is less frequently employed, since it is expensive, labour intensive and time-consuming. Attempts at biological control, involving the release of two potential control agents, have not been successful.

It is clear that essentially random (in space and time) control actions undertaken at small scales will not be adequate to control the spread of *A. nilotica* throughout the landscape. The problem would be better addressed by a regional programme of co-ordinated control activities by property managers, in order to address those outbreaks with the greatest potential for further spread in the most efficient manner possible. The most basic requirement for such a regional control strategy is an effective and inexpensive method of conducting surveys of weed populations over large areas.

This paper describes our evaluation of a method of analysis of aerial photographs designed to provide reliable information over large areas at low cost. This type of information is important in determining current levels of shrub invasion to aid in the design and implementation of control programmes. Additionally, chronosequential descriptions of population dynamics can be useful in determining proximate causes of invasion and in developing strategies, tactics and practices to reduce the likelihood of invasion in susceptible, but currently unoccupied areas.

Methods

We designed the methodology to assess the efficacy of the technique with regard to providing information to land managers in three different areas: (1) broad categorical analysis of tree density; (2) identification of individual objects; and (3) size of individual objects.

Study site

The study site was located on a cattle property, 'Wyangerie,' 20 km west of the township of Richmond (20° 31' S, 142° 54' E) in the Mitchell grasslands of north-central Queensland (Fig. 1). The area is topographically and edaphically simple, consisting of rolling downs, with slopes of less than 2%, and self-mulching, alkaline, clay soil. The climate is semi-arid. Average annual rainfall is 470 mm mostly occuring in the summer months, from November to March. Natural vegetation is dominated by Mitchell grasses, *Astrebla* spp. These perennial tussock grasses form well-spaced tussocks up to 0·5 m high and 0·3 m in diameter, but with average basal cover of less than 5%. The interstices contain various annual grasses and forbs. Native woody vegetation is usually confined to the boundaries of watercourses.

The field survey of shrub density, canopy cover and shrub location was conducted along a 151 m × 30 m belt transect running north–south. The terrain was flat and

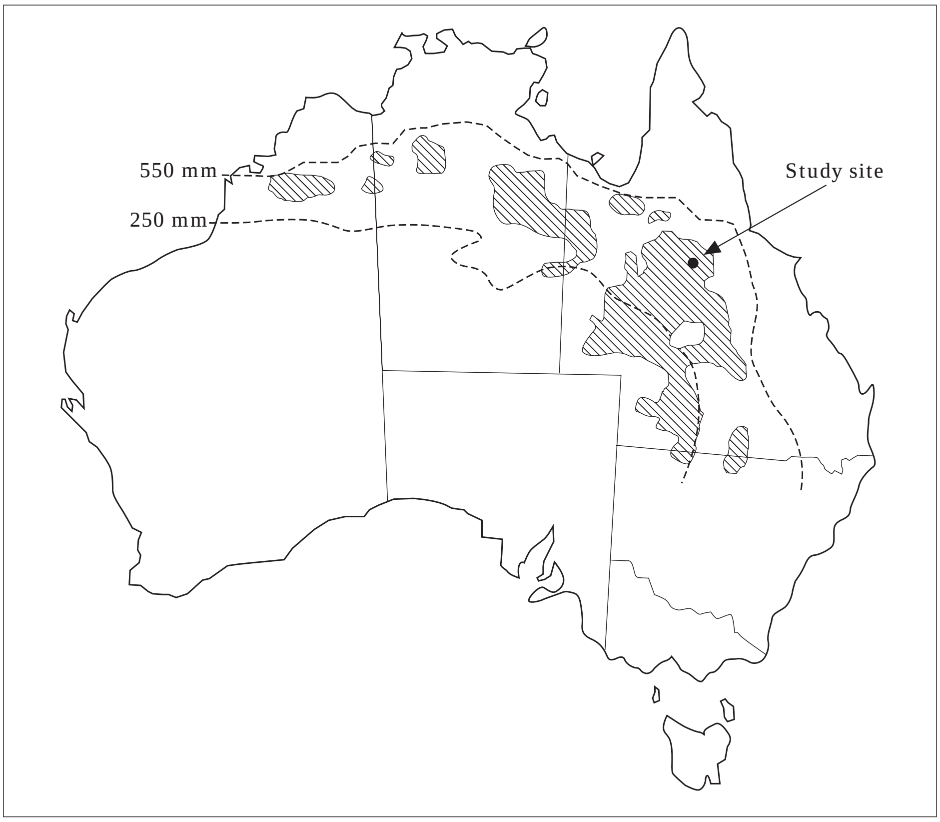

Figure 1. Location of the study site within Queensland's Mitchell grasslands. Isohyets show general relationship of average annual precipitation (mm) and *Acacia nilotica* distribution (hatched area).

uniform, with a moderately high infestation of well-established *A. nilotica*, but no other woody vegetation.

Aerial photograph analysis

The image used in the study was a colour aerial photograph taken in October 1994. At that time, the contrast between dormant grasses and shrubs was greatest. The scale of the image was approximately 1:12,000. A selected scene of apparently moderate to high *A. nilotica* infestation was digitized as a greyscale image (GIF format). Conversion to a greyscale image was performed because much of the historical aerial photography is monochrome and our objective was to develop a robust procedure that could use existing data sources.

The scanning resolution was set at 200 dots cm^{-1}, with 1:1 ratio of original to scanned image size, thus each pixel corresponded to a square with sides of approximately 0·6 m. Each pixel in the digitized image had an integer 'brightness value' from 0 (darkest value) to 255 (brightest value). The scanning resolution was chosen to maximize plant detection while minimizing computer processing times. A previous survey of nearby areas (Carter, 1994) found that only 1·5% of plants had canopy diameters less than 0·6 m while 94·1% had diameters of at least 1 m. The scanned image was imported into the Geographic Information System ARC/INFO (ESRI, 1995) as a grid coverage for analysis.

Image analysis

The purposes of image analyses were (1) to identify objects in the images which could be related to trees in the landscape and (2) to characterize these objects with measures of location and size. Development of a computer procedure for recognition of objects in the digitized aerial photographs was based upon three simple propositions about the appearance of tree and non-tree objects in the images: (i) shrubs appear darker than either soil or grass. This was apparent from inspection of the aerial photographs used, and accords with the description of the spectral properties of the elements of Australian rangeland scenery of Graetz & Gentle (1982); (ii) shrubs appear darker towards their centre than on their edges, due to greater foliage density and self-shading; and (iii) shrub canopies do not overlap significantly (Smith & Goodman, 1987; Ben-Shahar, 1991).

Computer analysis began with a 'density slicing' procedure to remove from the image all elements which were too bright to be considered shrubs. The best boundary brightness value separating tree and background elements across the area of analysis was subjectively chosen after sampling the brightness values at the edges of objects considered to be shrubs. All pixels brighter than this value were removed from the grid coverage, to produce a new grid coverage consisting of many disjoint areas which could represent either single trees or groups of shrubs.

Figure 2(a) is a stylized representation of an unprocessed grid coverage with three groups of objects on a relatively bright background. The bands of different brightness within the groups represent ranges of brightness, but are depicted as discrete values for clarity. Density slicing assigns a null value to the bright background pixels of Fig. 2(a) to produce Fig. 2(b).

Further density slicing was then performed to separate multiple trees within the remaining areas of the image; this eliminated bright 'background objects' from 'dark objects' and was determined by the properties of each connected group of pixels in the grid coverage, rather than being a single value applied to the entire scene. This iterative process was controlled by a macro we developed called REDUCE (code available from authors) designed to: (1) identify in the input grid coverage groups of connected cells which were then treated as individual objects; (2) determine the range of brightness values of the cells within each object; (3) remove from each object the cells with values in the brightest 10% of its range; (4) discriminate between objects which had merely become smaller, and those which had been split into two or more new objects; (5) create a new grid coverage consisting of the new objects resulting from splitting; and (6) display the remaining objects, and offer the operator the option of using those objects as input to another run, or saving the remaining objects in another grid coverage.

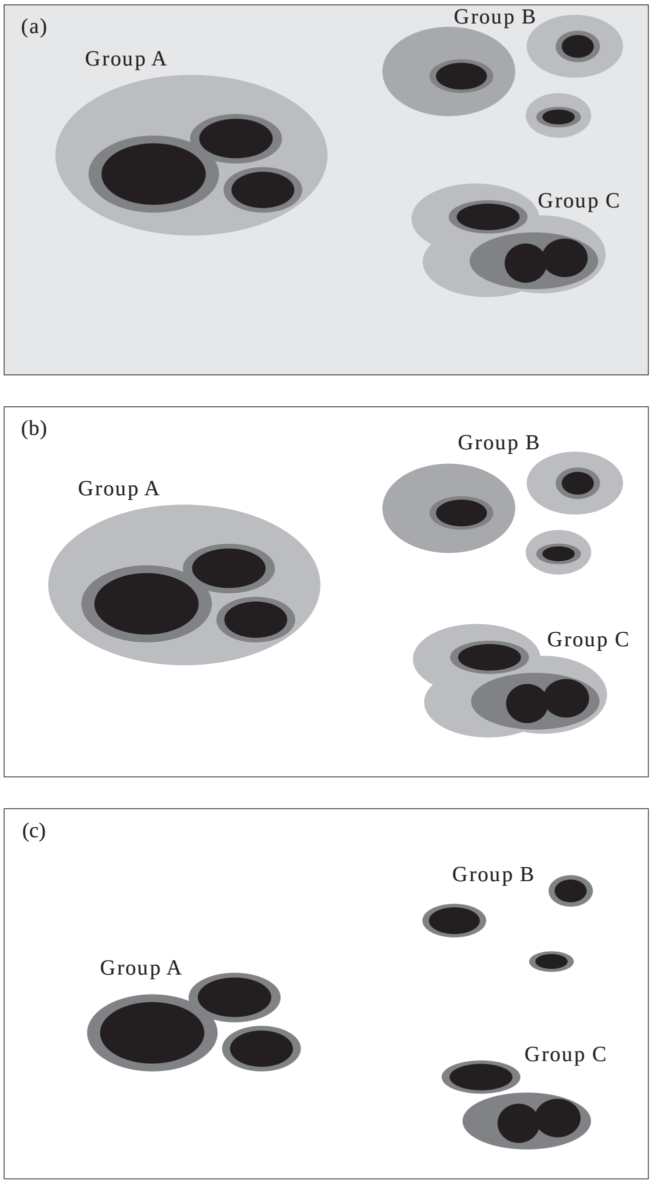

Figure 2. The interactive density-slicing procedure: (a) an unprocessed grid image; (b) a grid coverage after density slicing; and (c) the effect of REDUCE on density-sliced image.

The result of each series of passes through the program was at least two new grid coverages containing the products of splitting objects from the input grid coverage. Only the final grid coverage produced by this process was necessarily considered to be completely resolved into objects representing individual shrubs. Any of the objects in the other new coverages could still require further splitting before each object represented only one tree. Therefore, each of those grid coverages was inspected and all coverages containing objects considered to require further splitting were merged and used as input to another sequence of analysis.

The effect of removing the brightest pixels of Fig. 2(b) is shown in Fig. 2(c). In Groups A and C a single object has been split into two new objects. At stage 5 these groups would be saved in a separate grid coverage, and the operator would then be presented with the remaining Group B and the option of further reduction. If necessary, the technique could be applied to the grid coverage containing Groups A and C, to create three objects in Group A and two objects in Group C.

Each set of grid coverages was considered a 'generation' of objects, since each contained objects derived from objects in the input grid coverage. Accordingly, the first grid from which all others were derived (e.g. the groups in Fig. 2(b)) was termed 'P,' and the merged groups of grids produced after each cycle of reduction and splitting were termed 'F1,' 'F2,' and so on. The importance of this identification of the generation in which each object emerged will be explained below.

Figure 3 outlines the process of repeated analyses leading to the creation of three 'generations' of objects from a 'parent' grid coverage. The number of runs and the number of generations produced during the analysis are purely illustrative.

Canopy size analysis

The preceding process of object recognition could not be expected to yield objects with sizes corresponding directly to the sizes of trees in the landscape. The process of object extraction decreased object size each time REDUCE was run. Additionally, the extent of decrease could not be deduced from the number of times the area giving rise to an object had been affected by REDUCE, since the program removed part of the range of values in an area rather than a fixed proportion of the number of cells constituting it.

The approach taken to size estimation was to assume that the area retained after the initial density slicing was correlated with the sum of the canopy areas of the shrubs in the image. Additionally, it was assumed that the relationship between image area and shrub canopy areas was both linear and constant across the scene and that the frequency distribution of the brightness values of joined objects was sufficiently similar that REDUCE affected each to the same degree. Given these assumptions it was then possible to apportion the area of a parent object among its daughter objects in accordance with the relative sizes of these daughter objects. For instance, if an object of area 100 grid cells produced two daughter objects, with areas of 60 and 20 grid cells, then those daughter objects were assigned 'virtual areas' of 75 and 25 grid cells, respectively. This process was then repeated for groups of objects arising from each daughter object, with the 'virtual areas' being continually re-apportioned down through the generations.

The containment relationships of objects necessary for this apportioning of area was determined using ARC/INFO vector coverages. Each 'generation' of objects in a grid coverage was converted to an ARC vector coverage. The POLYREGION function was then used to define a single, albeit discontiguous, region consisting of all the polygons in a particular vector coverage. All vector coverages were then combined into a single vector coverage within which each 'generation' of objects constituted a separate region or subclass. Thus, the analysis illustrated in Fig. 3 would yield an ARC polygon coverage with four subclasses corresponding to P, F1, F2 and F3.

The inbuilt macro REGIONXAREA, a macro supplied with the ATC/INFO software, was then used to generate an INFO database table describing all the containment relationships of the polygons in each region. This INFO table specified, for every pair of intersecting polygons, the subclass and id number of the first polygon, the subclass and id number of the second polygon, the size of the area of overlap and the percentage of the first polygon contained within the overlap. Given the nature of

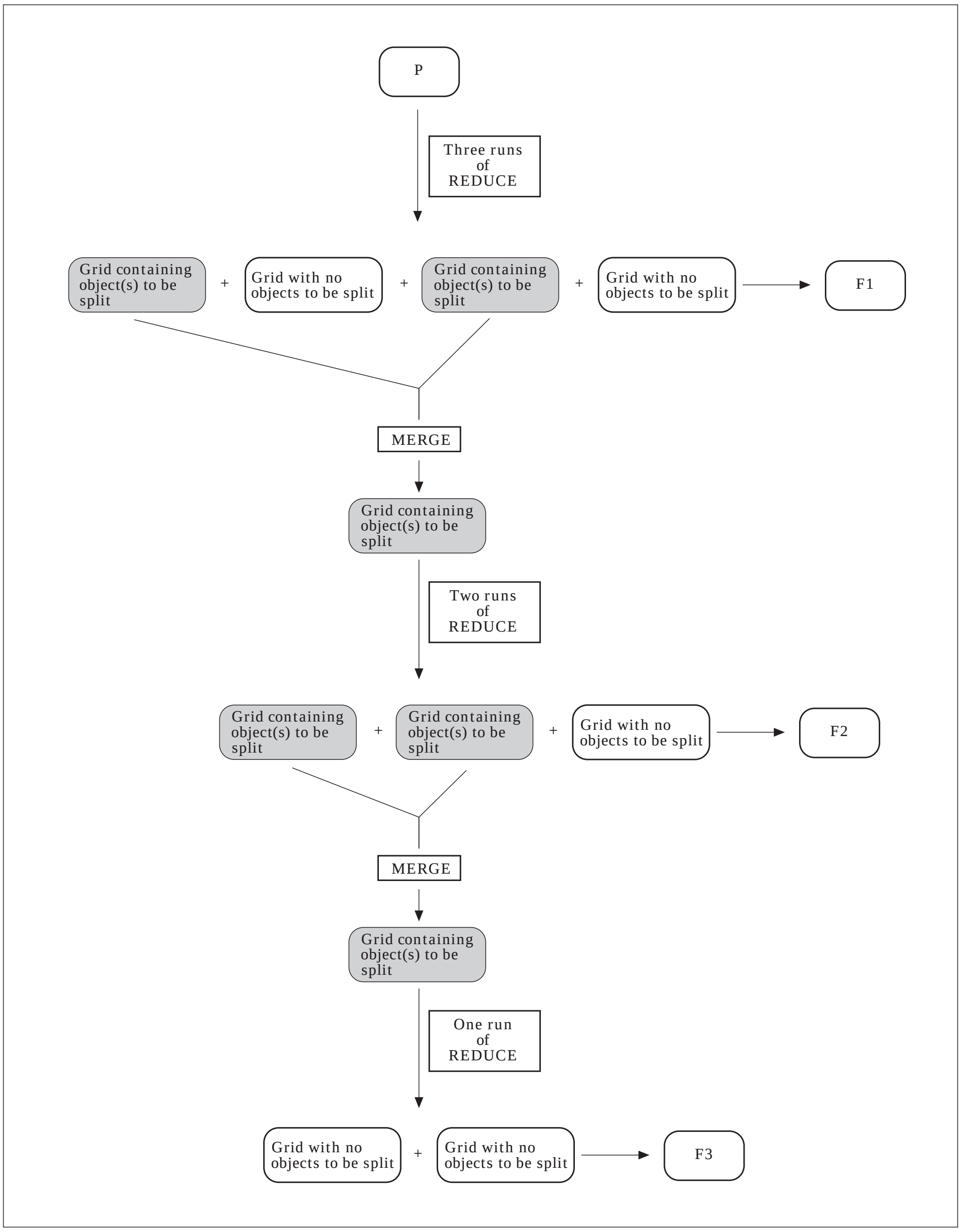

Figure 3. Flow diagram of object isolation procedure using REDUCE.

the process which generated the polygons, it is clear that each daughter polygon must be entirely contained within the area of overlap with its parent polygon, i.e. 100% overlap, and that each area of overlap only contains one daughter polygon. It is also clear that each polygon must be traceable back to a polygon in the ‘P’ subclass, through each intermediate subclass.

On the basis of these containment relationships, areas were allocated from polygons of the ‘P’ subclass to the ‘F1’ subclass, then from ‘F1’ to ‘F2’ and so on to the last generation of polygons.

Results

It should be noted that the operator decisions made during image interpretation process of REDUCE were not guided by the ground survey of the area, since such data would not be available for the analysis of archival images. A ground survey was only conducted after the image analysis and used to assess the accuracy of the process. The use of such survey data to guide the decisions made while running REDUCE would greatly improve the results of the analysis. Such a preliminary survey would obviously be the preferred option for a large-scale survey of present-day vegetation, where the image analysis could be ‘calibrated’ on a surveyed representative area before being applied to the entire study area.

Density determination

The field survey located 95 shrubs, while computer analysis identified 99 objects. Comparison of the survey and analysis mapping indicates that in 50 instances there is a 1:1 correspondence between surveyed shrubs and computer objects, in nine cases the computer generated multiple objects from a single surveyed shrub, in 20 cases the computer interpreted several shrubs as a single object, and in the remaining 16 cases a surveyed shrub had no corresponding object in the computer analysis. The undetected shrubs were significantly smaller than the detected trees ($t_{93} = 3{\cdot}60$, $p < 0{\cdot}01$), with mean areas of $2{\cdot}6\,m^2$ and $9{\cdot}1\,m^2$, respectively.

Location of individual objects

The surveyed shrub locations and computer object locations are plotted (in the co-ordinates of the digitized image) in Fig. 4. One unit in the grid coverage corresponds to 0·54 m. The mean distance from each of the 50 surveyed shrubs for which a single, corresponding object could be identified to that corresponding object was 1·3 m. The mean distance from any shrub which was detected by the computer analysis, even if not in a 1:1 relationship, to the nearest computer object was only marginally larger, at 1·4 m. The average distance for all 95 shrubs was 1·7 m.

Canopy size

Thirty-eight pairings of computer object and surveyed shrubs were used to test the reliability of computer object size as an indicator of plant canopy size. The 38 chosen pairs represented the best positional matches between the two data sets, and were usually computer objects which were defined in the early stages of analysis, and therefore were the most direct measures of object size within the image. They would consequently be expected to give the most favourable measure of reliability. Figure 5 is a plot of computer generated canopy area, c, against field survey area, f, for the 38 pairs with a linear regression line (forced through the origin) added. The equation of the regression line is $c = 1{\cdot}97 \times f$. The regression is significant ($F_{(1,36)} = 34{\cdot}92$, $p < 0{\cdot}001$), with moderate fit of the data ($r^2 = 0{\cdot}49$).

Discussion

Differences between field survey and computer positions were approximately triple the level which could be attributed to error in the field survey, and the degree of 1:1 correspondence between shrubs and computer objects was not as high as might be desired. Some positional error must arise from the modelling assumption that the shrub could be considered to be located at the centroid of the computer object. The

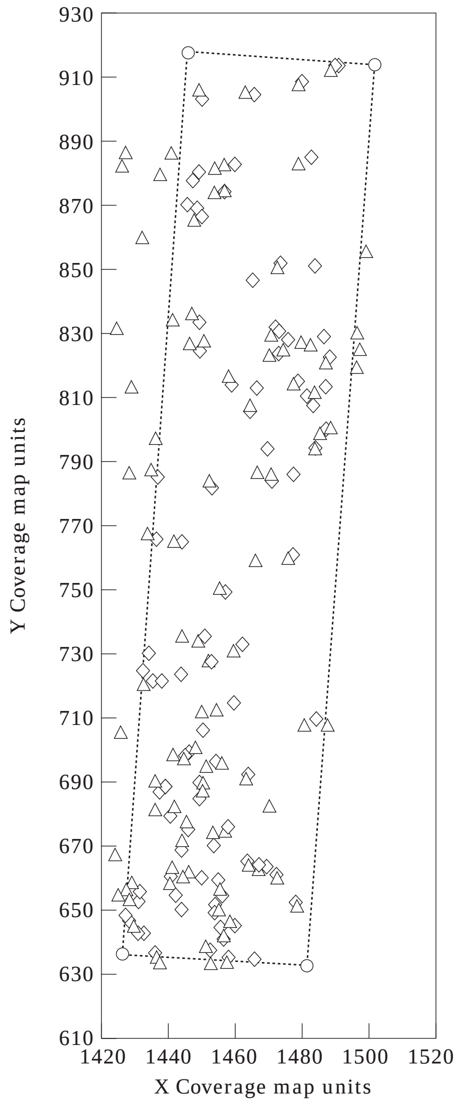

Figure 4. Plot of surveyed tree (◇) computer object (△) locations. Dotted line indicates survey area boundary.

computer objects could not be expected to perfectly reflect the shape of the corresponding shrubs and, even if they did, it is not necessarily true that the trunk would be located at the centroid of that shape.

The photographs used in this study were taken at close to 0830h in October, so the solar elevation would be approximately 40°. The model used for image analysis assumed that trees would appear brightest around the edges and become darker towards the centre of the crown due to the darkness of the foliage and to self-shading. Shadow in the intervening spaces would not necessarily be a major drawback if such shadow only resulted in an increase in the apparent size of the trees, and if the effect were constant across the entire scene. It would only affect the scaling between calculated and actual tree sizes. Even a non-linear effect over the range of plant sizes could be accommodated relatively easily.

Unfortunately, the impacts of extensive shadow can be less tractable than a simple increase in apparent size. The consequences of the low (e.g. morning) solar elevation can be understood by considering each shrub to have two shadow elements, the self-shaded canopy, and the ground shadow to the west of the tree. Figure 6 shows the effect of this 'extra' ground shadow on two shrubs, A and B. The difference between the true positions (a or b) and the calculated positions (a' or b') is clearly greater for the larger tree, and, since both positions are displaced in the same direction, the apparent separation of the two shrubs is decreased. Thus, the apparent positions of shrubs would also need to be adjusted for solar elevation in accordance with the sizes of the shrubs, adding adjustment to adjustment and compounding the effects of error.

Effects not amenable to simple calibration could also be induced. If the two shrubs were sufficiently close, the round shadow from shrub B would merge with the canopy shadow of shrub A, as shown in Fig. 7. If the total shadow were not split by REDUCE, the analysis would create one object, located between a and b, but larger than both. One of several other possibilities is that REDUCE might split the canopy shadow of shrub B into one object and treat the other three shadow elements as a separate object. In this case, position a' would be between positions a and b, and position b' would be at or near position b.

Comparison of the survey and analysis mapping reveals an instance which could be explained by this mechanism. The survey contains a pair of shrubs lying on a roughly

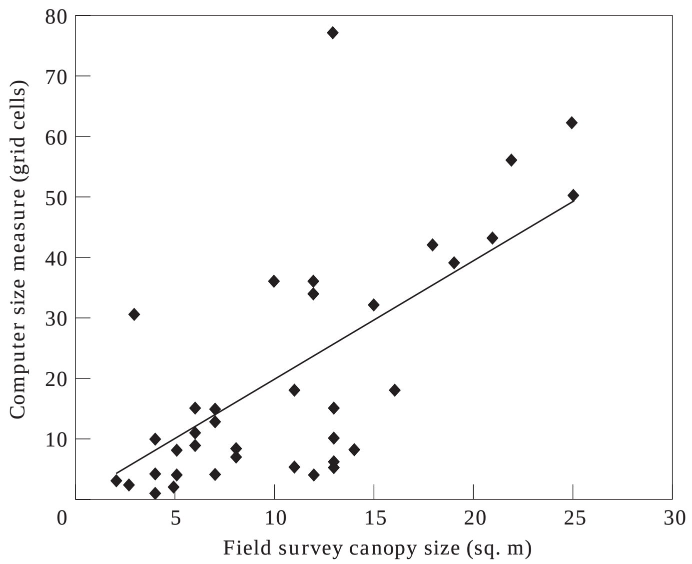

Figure 5. Regression of computer size measure against surveyed canopy area.

east–west axis, centred at co-ordinates (1468,664) in Fig. 4. The field survey located a shrub of area 13 m^2 3 m east of a tree of area 3 m^2, but the computer analysis assigns areas of 5·3 grid cells to the larger eastern tree and 32 grid cells to the smaller western shrub. Additionally, the computer position of the smaller shrub is 1·4 m east of its surveyed position while the larger shrub is displaced 3 m to the west.

This brief examination of the role of shadow shows how it can potentially induce errors in all three characteristics being investigated: size, number and position of objects. The enormous number of potential permutations of tree size, shape and grouping geometry could produce far more complex situations than those considered here, and defeat far more complex analytic procedures than those developed in this study.

The best way to reduce these problems is to avoid them by using images taken when solar elevation is as close to directly overhead as possible rather than to attempt to adjust analyses to correct a vast array of potential errors induced by shadows. In many cases, especially those involving use of archival material, researchers may have no

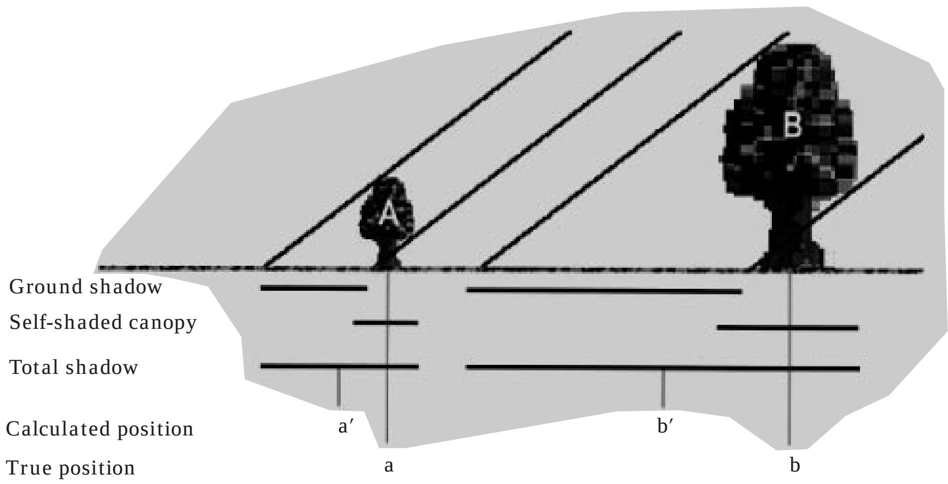

Figure 6. The effect of low solar elevation on tree shadow.

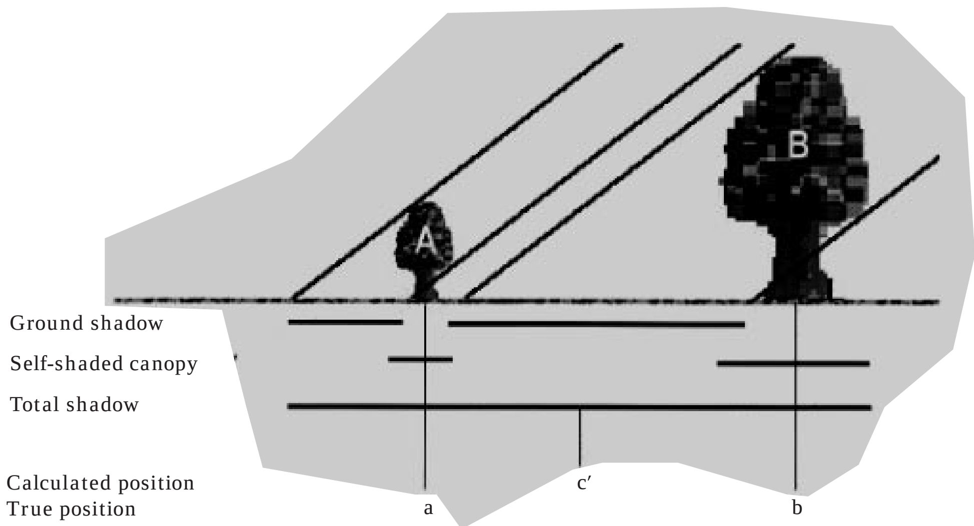

Figure 7. The effect of low solar elevation on the shadows of closely-spaced trees.

option but to use images taken at sub-optimal times, so some more detailed consideration of the effects of solar elevation on the landscape under investigation would be required in order to determine the severity of the constraints imposed by different solar elevations.

The data collection, translation and manipulation processes are unavoidable sources of error. The resolution of digitized images, and therefore the grid cell size, sets the lower limit to precision. Conversion between coverage types in a Geographic Information System may also increase error (Howard *et al*., 1994). For example, translation of data from grid coverages into vector coverages could potentially add error of up to half the cell width (i.e. up to 0·27 m) since vector locations are derived from the centre of grid cells. This error would be greatest in the translation of small objects or points between coverage sites and could be compounded when the distance between two locations is measured. The errors in defining the boundaries of large objects would tend to offset each other. Errors of this sort can be reduced but not eliminated and are notoriously difficult to track and quantify within a GIS (Davis *et al*., 1991).

Errors arising from data manipulation are unlikely to have been the major source of error within this study. In any case, given the difficulty in quantifying them, it is better to concentrate on removing other sources of error, and then assess whether the error which remains threatens the validity of the conclusions drawn. The greatest source of error for this study, and therefore the most important one to address is the effect of shadows on image interpretation. The potentially dominant role of shadow as an element of Australian rangeland images has been demonstrated in a study of Landsat MSS images of South Australian rangelands (Graetz & Gentle, 1982). They demonstrated that, within an area having 30% shrub cover, a solar elevation of 35° could generate shadow over 22% of the intervening ground. The likely effects of such extensive shadow on the analytic method used here should be considered.

Several models have been usefully applied to satellite remote sensing data in order to estimate tree canopy cover in woodlands (Franklin *et al*., 1991). However, this type of analysis is most useful in interpretation of relatively low resolution imagery such as the 30 m × 30 m pixels found in Landsat TM images. Issues such as the contiguity or otherwise of a shrub and its ground shadow are not critical when using such data, as long as the generalized spectral behaviour can be modelled, but they are crucial to a study which attempts to resolve individual shrubs in high resolution monochrome images.

Remaining error types could be reduced by applying additional criteria for discriminating between shrub and non-shrub objects. For instance, excluding from the analysis the smallest range of the computer generated objects would improve the overall reliability of the classification since, as has been noted above, the objects which had no apparent connection with any shrub were significantly smaller than the average. Other potential criteria are shape, limiting the eccentricity of objects considered to be acceptable ellipses and the range of variation of brightness values within an object, since trees usually exhibit a greater range of brightness than, for instance, areas of deep shadow.

Implications of using this approach for management decisions

When dealing with phenomena such as shrub invasion, the first requirement for the development of a coherent management programme is a knowledge of the severity of the problem in terms of its areal extent and intensity. The lack of such information is a severe handicap which is bemoaned by both land managers and policy-makers. While the necessity for a comprehensive database on which to base management action is apparent, so is the fact that its acquisition from labour-intensive surveys will remain prohibitively expensive. This method of aerial photograph interpretation offers a relatively inexpensive means of gathering reliable data on the extent and density of invasions at an appropriate scale and in a format which facilitates its collation, dissemination and analysis within Geographic Information Systems. We suggest that the use of this technique for determining the level of invasion in broad density categories (i.e. open, low, moderate, high) is both reliable and cost effective. However, attempting to use this technique to track recruitment into the population or increases in size of individuals will require more careful design of criteria for acquisition of aerial photography, a much greater effort in the analysis and ground-truthing phase. If the objective of the study is to determine chronosequential changes in population attributes from the past to the present, the opportunities to improve the quality of aerial photography may not be available.

The ease and low cost of data collection and analysis permit surveys to be conducted at a frequency appropriate to the landscape being managed. Additionally, this method can exploit the existing archives of aerial photographs, allowing the temporal dynamics of processes to be studied over time frames which would otherwise be inaccessible to researchers.

As the temporal paradigm of rangeland management shifts from an equilibrium to a non-equilibrium view of vegetation dynamics (Westoby, 1980), our methodology becomes increasingly valuable for detecting and characterizing rates and patterns of shifts in dominant life-forms. If changes in climate, disturbance regimes or land management can be linked temporally with shifts in vegetation structure, a predictive model of the impact of future responses can be developed.

Spatially, this methodology can be used to identify focal points for monitoring change in areas subjected to similar disturbances. If proximate causes, patterns of change and relevant time frames are identified, management actions can be initiated.

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