International Journal of Remote Sensing
Vol. 27, No. 10, 20 May 2006, 2049–2054

Wavelet estimation of plant spatial patterns in multitemporal aerial photography

EVA K. STRAND*†, ALISTAIR M. S. SMITH§, STEPHEN C. BUNTING†, LEE A. VIERLING†, DAVID B. HANN‡ and PAUL E. GESSLER§

†Department of Rangeland Ecology and Management, University of Idaho, Moscow, ID 83844, USA

‡Department of Mechanical and Manufacturing Engineering, Trinity College, Dublin, Ireland

§Department of Forest Resources, University of Idaho, Moscow, ID 83844, USA

(*Received 4 June 2005; in final form 21 October 2005*)

Wavelet analysis represents a powerful set of image processing techniques that have considerable potential to quantify ecologically relevant patterns at multiple scales. This paper provides a preliminary assessment of whether two-dimensional wavelets convolved with 1 m panchromatic aerial photography can be used to detect automatically the location and crown diameters of western juniper (*Juniperus occidentalis*) plants as they encroach upon a sagebrush (*Artemisia* spp.) steppe landscape. The juniper crown diameters derived from wavelet analysis produced a strong correlation with crown diameters measured via comparable hand-digitizing in a geographic information system ($r=0.96$, $n=69$) with a 5% commission and an 8% omission error. Through comparison with historical photography, we found that juniper plant cover increased 2.7 fold (from 2.7% to 7.3% total cover) during the period from 1939 to 1998 within the 15 ha study area. This approach has considerable potential for the long-term monitoring of vegetation change via aerial photograph and other remotely sensed imagery.

1. Introduction

Woody plant encroachment upon lands formerly dominated by grasses and forbs is an ecological phenomenon of global concern (Archer *et al*. 1995, Asner *et al*. 2003). Woody species (e.g. *Quercus, Juniperus, Larrea, Prosopis*, and *Acacia*) are increasing in density in response to changes in environmental conditions such as fire suppression, excessive herbivory, and climate change (Archer *et al*. 1995), resulting in forage reduction, decreased biodiversity, and at its extreme, desertification (Asner *et al*. 2003). This process is exemplified by western juniper, which over the past 100 years has been expanding into western US sagebrush steppe (Miller and Rose 1995).

Previous methods for the remote identification of location and size of individual plants within imagery have applied hand-digitizing within geographic information systems (e.g. Ansley *et al*. 2001), user-defined grey-scale partitioning (e.g. Lahva-Giott *et al.* 2001), or textural analysis techniques (e.g. Asner *et al*. 2003). Although grey-scale partitioning and textural analysis can allow separate objects to be visually isolated within imagery, they, in general, only provide information for an entire collection of objects (e.g. a cover map), rather than providing data on each object separately.

Up to March 2005, approximately one hundred peer-reviewed publications have incorporated wavelets in various aspects of remote sensing, with nearly

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160500444764

three-quarters of these publications focusing on image filtering, hyperspectral pixel analysis, image reconstruction, image registration, texture analysis, data fusion, and feature matching (e.g. Le Moigne *et al.* 2002, Ulfarsson *et al*. 2003). Although, in the remote sensing community, wavelets have been used in the multiscale assessment of urban areas (Myint *et al.* 2004), the full potential of these methods remains under-researched. In particular, 'ecological' feature recognition (i.e. plant location and sizes) at multiple scales is a promising application of wavelets to ecological problems, which have previously only used wavelet-based measures to identify potentially important analysis scales (Dale and Mah 1998).

In this preliminary study, we evaluate the potential of one form of wavelet analysis to identify and extract information on 'individual' juniper features from both historic and recently acquired high spatial resolution aerial photography.

2. Methods

2.1 *Study area and aerial photography*

This study is centred on the Owyhee Plateau in south-western Idaho (116° W Long, 43° N Lat), an area characterized by western juniper in a sagebrush steppe landscape. Western juniper (*Juniperus occidentalis*) occurs mainly as open savanna-like woodlands dissected by rocky canyons and riparian areas. Elevation ranges from 850 to 2560 m, with an annual average precipitation ranging from 250 mm at lower elevations to 1000 mm at the crest of the mountain range. High spatial resolution ($<$ 1 m) panchromatic aerial photography was acquired for this area in 1939 (figure 1(*a*)) and 1998 (figure 1(*b*)), and serves as the basis for wavelet analysis. These images are composed of dark juniper plants against a matrix of sagebrush steppe in multiple shades of grey for an area 15 ha in size. Prior to analysis in MatLab (2004), the sample image was converted to an ASCII matrix (390 x 390 pixels) with a 1 m pixel size.

2.2 *Wavelet-based image feature analysis*

Following Ulfarsson *et al*. (2003), we employ discrete wavelet transformation (DWT) to identify individual features within multitemporal aerial photography. DWT is performed by convolving ever-increasing sizes (i.e. dilation scales) of the wavelet shape, termed the basis function, with the imagery. DWT differs from continuous wavelet transformation (CWT) in that only discrete sets of dilation sizes are assessed, rather than a continuous distribution of possible sizes (Addison 2002). In wavelet analysis, the wavelet basis function, $\Psi(\mathbf{x})$, must meet certain mathematical criteria, including a finite energy (equation (1)) and a mean of zero (equation (2)):

$$\textit{Wavelet Energy Criterion}: \int_{-\infty}^{\infty} |\Psi(x)|^2 dx < \infty \tag{1}$$

$$\textit{Wavelet Mean Criterion}: \int_{-\infty}^{\infty} \Psi(x) dx = 0 \tag{2}$$

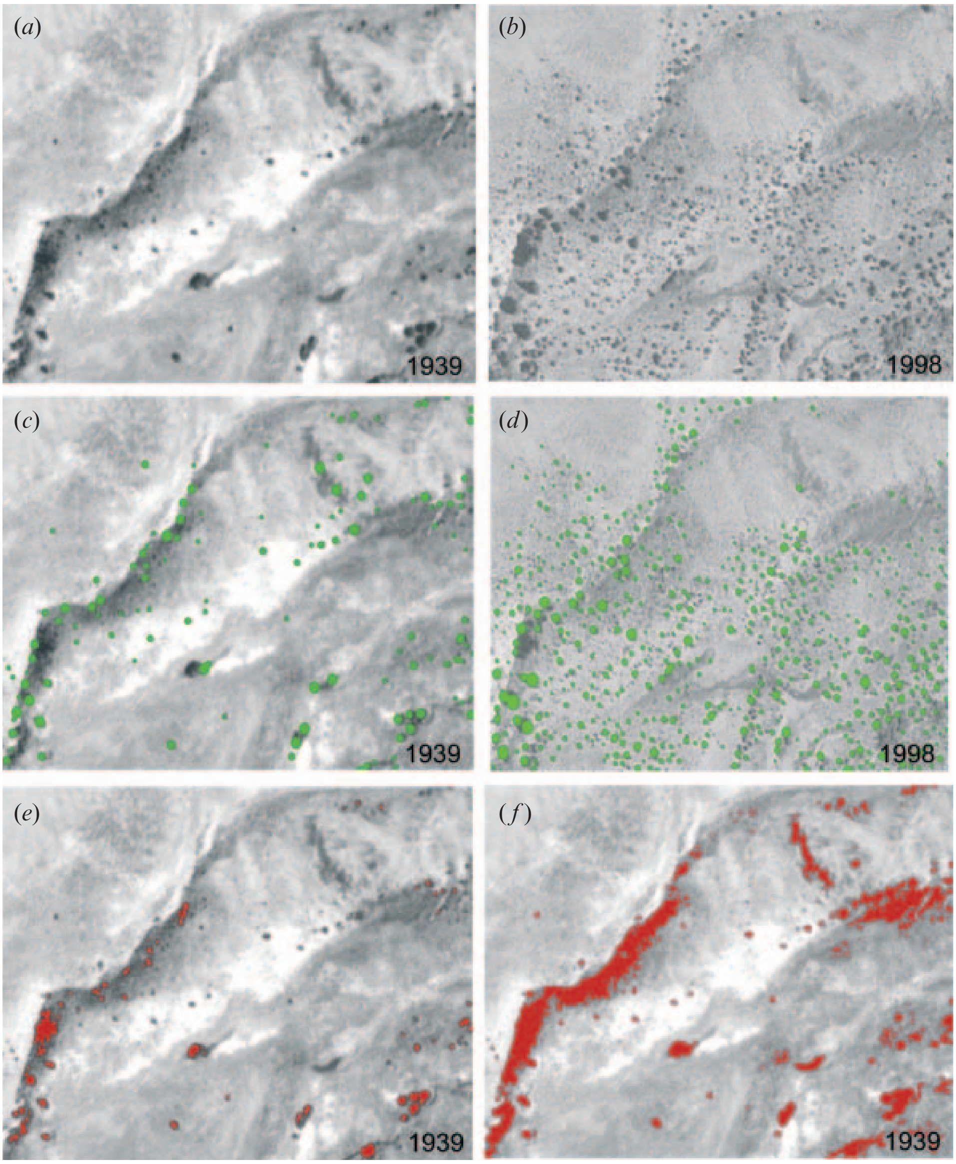

Figure 1. Aerial photograph of a western juniper/sagebrush steppe landscape (15 ha). (*a*) Original aerial photograph, 1939. (*b*) Original aerial photograph, 1998. (*c*) and (*d*) Projected juniper plant radii derived from wavelet analysis for the 1939 and 1998 photographs. (*e*) and (*f*) Projected juniper cover, 1939, from grey-scale partitioning using thresholds of 90 and 140. The juniper cover estimated from the 1939 photograph is 2.7% using wavelet analysis, 1.0% using the grey-scale threshold 90, and 7.3% using the grey-scale threshold 140. The juniper cover in 1998 is estimated at 7.3% using the wavelet technique. Source: The 1939 aerial photograph: USDA-SCS. The 1998 image: USGS (http://inside.uidaho.edu/geodata/USGS/DOQ.htm).

Within this study, the Mexican hat wavelet (equation (3)) was selected due to its spherical shape and smooth edges approximating the appearance of a juniper plant in an aerial photograph.

$$\Psi(x,y) = \left(1 - x^2 - y^2\right) * \mathrm{e}^{-(x2+y2)/2} \qquad (3)$$

The 2-D Mexican hat wavelet basis function was successively convolved, over a range of dilation scales selected by the likely crown diameters of juniper trees (i.e. 1 to 10 m in increments of 0.1 m), with the aerial photograph to produce a wavelet intensity image corresponding to each dilation scale. This intensity image exhibited high values when features within the image, **I(x,y)**, were very similar to the size and shape of the wavelet function, **Ψ(x,y)**, at that particular dilation scale. When the wavelets and the image features are similar, a high intensity peak is created, while lower intensity values are produced when the wavelet function is not similar to the image feature.

In this study, we were solely interested in identifying juniper plants, which appear as dark objects against a lighter sagebrush background (figure 1). The wavelet analysis was coded in MatLab (2004), and the output of the analysis is a list of individual plant locations and estimated plant sizes (determined by dilation with the highest value for DWT). Although this output contains data on individual trees, the results of the wavelet analysis were displayed in a GIS environment and overlaid onto the original aerial photographs, which allowed the direct assessment of plant cover and density.

2.3 *Comparison to alternative measurement techniques*

We evaluate wavelet analysis to be directly comparable to hand-digitizing in a GIS and to grey-scale partitioning. We used GIS software (http://www.esri.com) to measure 69 juniper crown diameters in the x and y directions directly from the orthorectified aerial photograph. When implementing the grey-scale binary partitioning, we chose two thresholds, such that at the lower threshold (90), all juniper trees in the image were recorded as woody plants, but also part of the darker background was included in the 'woody plant' category. At the higher threshold (140), no background was recorded as 'woody plants'; however, many juniper plants were recorded as background.

3. Results

Figure 1 demonstrates that wavelet analysis identifies accurately the size and location of individual trees in both the 1939 and the 1998 imagery. The juniper crown diameters ranged from 2–9 m and were in good agreement with plant diameters directly measured in a GIS (figure 2, $r=0.96$). Figure 1(*e*) shows that a low grey-scale threshold (90) yields an under-prediction of juniper plants, while figure 1(*f*) illustrates that a high threshold (140) results in an over-prediction of juniper cover. These results demonstrate that in contrast to wavelet analysis, grey-scale partitioning is sensitive to the shade of the background.

Wavelet-derived juniper cover in the 1939 image was 2.7%, compared to 1.0 % for the low grey-scale threshold (90) and 7.3 % for the high grey-scale threshold (140). The juniper cover in 1998 is estimated as 7.3% using the wavelet technique (figure 1(*d*)). As such, it is apparent that grey-scale partitioning is sensitive to the selected threshold. Wavelet analysis of the 1998 photograph estimates 634 juniper

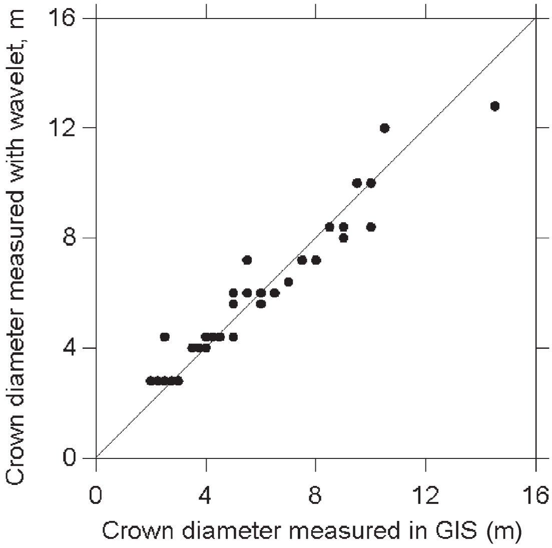

Figure 2. Plant size as determined by wavelet analysis compared to measurements in a GIS environment.

plants within the 15 ha analysis area. The commission error is estimated to be less than 5%, representing features such as rock outcrops and small circular, dense sagebrush patches that were misclassified as juniper plants. Occasional small juniper plants were not detected by the wavelet technique, yielding an 8% omission error. The omission error might be reduced by the use of imagery with a finer pixel size.

4. Discussion

The wavelet analysis approach presented in this study has the potential to become an important tool for the analysis of woody plant encroachment rates, and may shed light on relationships between landscape patterns and ecological processes. Furthermore, the accurate identification of plant size and location will enhance our understanding of ecotone dynamics and plant responses to climate variability.

Quantifying objects within an image using wavelet analysis depends on the minimum object size, the spatial resolution of the image, and the initial wavelet scale, as in general, the smallest applicable wavelet will be close to the cell size of the imagery. An advantage of the wavelet method is that it can be applied directly to images of any spatial resolution, and thus could be an important tool to analyse vegetation features over multiple scales and over multiple image sources. In addition, the output of this technique is a point pattern of plant size, rather than a cover map, which can be broadly assessed with spatial analysis techniques.

Limitations of this technique can be expected in closed canopy environments such as forests, where clusters of objects may be incorrectly defined as larger individuals. However, such misclassifications can be limited through selecting a sensible maximum feature size. Wavelet analysis does not discriminate between vegetative species, rocks, or other objects, unless they are unique in shape or size, and as such, this method does not directly provide a classified image. Furthermore, depending on the quality of the imagery, shadow effects may skew the size of objects as interpreted by the wavelet.

5. Conclusions

The wavelet analysis technique presented herein is a 'rapid, objective, repeatable, and background invariant' method for quantifying ecological patterns. Further research in plant ecology applications combining two-dimensional, multiscale wavelet analysis of fine-scale landscape images (e.g. aerial photography, IKONOS, or QuickBird) with spatial point pattern analysis techniques could yield important information about plant succession, biogeochemical properties, and landscape composition across large areas. This method is promising for the analysis of long-term ecological change because the earliest remotely sensed images of many areas are black and white aerial photography. Using such a technique to quantify vegetation change over decadal time periods stands to improve our understanding of how current environmental changes relating to climate, fire suppression, and invasive species are manifest at the landscape scale.

Acknowledgements

Pat Clark, USDA, Agricultural Research Service, Northwest Watershed Research Center, Boise, Idaho provided the 1939 historic aerial photograph.

References

ADDISON, P.S., 2002, *The Illustrated Wavelet Transform Handbook* (London: Institute of Physics).

ANSLEY, R.J., WU, X.B. and KRAMP, B.A., 2001, Observation: long-term increase in mesquite canopy cover in a north Texas savanna. *Journal of Range Management*, **54**, pp. 171–176.

ARCHER, S., SCHIMEL, D.S. and HOLLAND, E.A., 1995, Mechanisms of shrubland expansion: land use, climate, and CO_2? *Climatic Change*, **29**, pp. 91–99.

ASNER, G.P., ARCHER, S., HUGHES, R.F., ANSLEY, R.J. and WESSMAN, C.A., 2003, Net change in regional woody vegetation cover and carbon storage in Texas Drylands, 1937–1999. *Global Change Biology*, **9**, pp. 316–335.

DALE, M.R.T. and MAH, M., 1998, The use of wavelets for spatial pattern analysis in ecology. *Journal of Vegetation Science*, **9**, pp. 805–814.

LAHAV-GINOTT, S., KADMON, R. and GERSANI, M., 2001, Evaluating the viability of *Acacia* populations in the Negev Desert: a remote sensing approach. *Biological Conservation*, **98**, pp. 127–137.

LE MOIGNE, J., CAMPBELL, W.J. and CROMP, R.F., 2002, An automated parallel image registration technique based on the correlation of wavelet features. *IEEE Transactions on Geoscience and Remote Sensing*, **40**, pp. 1849–1864.

MATLAB®, 2004, Matlab and Simulink, Version 7.0.0.27 (R14). The MathWorks. Available online at: http://www.mathworks.com/products/matlab/ (accessed 1 December 2004).

MILLER, R.F. and ROSE, J.A., 1995, Historic expansion of *Juniperus occidentalis* (western juniper) in Southeastern Oregon. *Great Basin Naturalist*, **55**, pp. 37–45.

MYINT, S.W., LAM, N.S.N. and TYLER, J.M., 2004, Wavelets for urban spatial feature discrimination: Comparisons with fractal, spatial autocorrelation, and spatial co-occurrence approaches. *Photogrammetric Engineering and Remote Sensing*, **70**, pp. 803–812.

ULFARSSON, M.O., BENEDIKTSSON, J.A. and SVEINSSON, J.R., 2003, Data fusion and feature extraction in the wavelet domain. *International Journal of Remote Sensing*, **24**, pp. 3933–3945.