What happens when flood plains wet themselves: vegetation response to inundation on the lower Balonne flood plain

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Abstract The distribution of floodwaters and their average recurrence interval (ARI) on the lower Balonne flood plain in semiarid Queensland, Australia, was mapped using 13 Landsat thematic mapper (TM) images. The vigour of vegetation growth was also mapped from a normalized difference vegetation index (NDVI) transformed “reference image” showing average pixel value between images captured over a period of nearly 10 years. The area of each NDVI class in each ARI zone was calculated. The largest proportion of vigorous vegetation occurred where flood frequency was between 1.25 and 1.75 years. The smallest proportion of vigorous vegetation occurred where flood frequency was low. Vegetation with very low growth vigour was common only where flooding occurred more frequently than once per year. Possible explanations for this relationship include reduced plant vigour due to soil anoxia, the impact of disturbance frequency on plant productivity, and pixel mixing at the vegetation/water boundary.

Key words flood plain vegetation; inundation; satellite remote sensing; Australia

INTRODUCTION

Inundation of flood plain areas has been associated with increased vigour of plant growth (Junk *et al.*, 1989). The majority of studies that examine this relationship have either been macroscale analyses using remote sensing technology to examine vegetation responses to climatic conditions (e.g. Foody & Curran, 1993) or conventional experimental studies at the microscale or plot scale (Robertson *et al.*, 2001). It appears that increased soil moisture status can cause an increase in plant growth vigour over large areas but reduced growth vigour and plant mortality can occur in very high flood frequency areas or with prolonged inundation (Lichtenthaler, 1998). Differential responses of individual plant species to wetting can also occur (Davenport & Nicholson, 1993) and the distribution of disturbance effects creates a spatially complex mosaic of plant growth conditions at larger scales (Kogan, 1990).

Increased plant growth in response to flooding is one of the most important processes controlling carbon and nutrient dynamics on flood plains and in the adjacent terrestrial and aquatic ecosystems. However, little is known about the spatial distribution of plant growth vigour on flood plains. This paper uses satellite remote sensing to examine the relationship between flood frequency and plant growth vigour at the mesoscale across a large flood plain complex in Queensland, Australia.

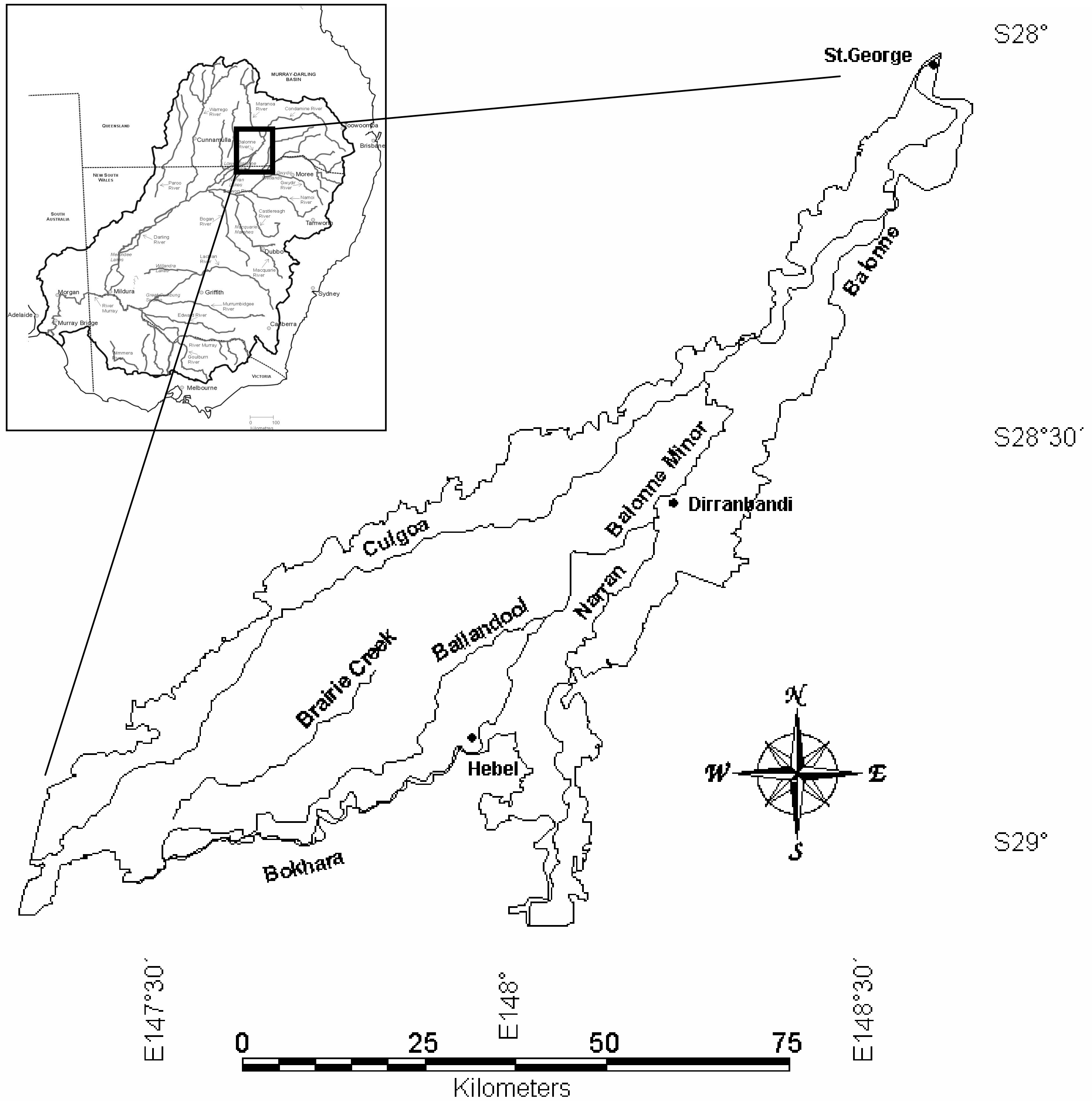

Fig. 1 The lower Balonne flood plain.

There are a number of probable patterns of plant growth vigour in relation to flood frequency that may occur on the lower Balonne flood plain. The subsidy–stress hypothesis (Odum *et al.*, 1979) predicts that plant productivity will be highest at moderate flood frequencies because very high or very low flood frequency places stresses on plants that reduces their growth vigour. However, due to the aridity of this semiarid region, we predict that the most vigorous plant growth will occur in areas that are most frequently flooded or that have permanent water, and that the least vigorous vegetation will occur in the driest parts of the flood plain.

STUDY AREA

The lower Balonne flood plain straddles the New South Wales and Queensland border in southeast Australia (Fig. 1). It covers an area of approximately 19 880 km^2 and is typical of many flood plains in the Murray–Darling basin. Flows travel onto the flood plain via the Balonne River at St George. Three bifurcations downstream of Dirranbandi divide the Balonne into five separate channels. From west to east, they are the Culgoa, Brairie, Bokhara, Ballandool and Narran and are surrounded by large areas of flood plain. The Culgoa and Narran carry most of the flow, conveying 55% and 35% of the long-term mean annual discharge at St George respectively.

The climate of the region is semiarid. Annual evaporation is approximately 2000 mm, and rainfall averages 400–450 mm $year^{-1}$. Approximately 40% of total annual rain falls in winter, but the higher summer evaporation rates mean that crop potential is similar in winter and summer (Wylie, 1993).

Vegetation community composition varies markedly across the flood plain and there are distinct associations between groundcover plants and flood frequency (Ogden & Thoms, 2001). Vegetation communities are dominated by river red gum (*Eucalyptus camaldulensis*), coolibah (*E. coolabah*) and lignum (*Muehlenbeckia florulenta*) in high flood frequency areas, with grasslands and *Bassia* spp. dominant in less frequently flooded areas.

MATERIALS AND METHODS

Thirteen Landsat TM images were used in this project and each was processed using ER Mapper image processing software version 6.1. Six of the images (March 1994, January 1996, March 1997, September 1998 and 9 and 25 March 1999) show the flood plain during different stages of inundation. The remaining seven images show a dry flood plain (January 1993, November 1994, August 1997 and February 1999) or many days after flooding (September 1989, July 1996, April 1999). Geometric rectification was performed by registering a base image (19 January 1993) to a map grid and co-registering the other images to it using 40 ground control points per image. Sun angle correction and dark pixel subtraction algorithms were used for radiometric correction of the base image, and pseudo-invariant calibration was used to equalize pixel brightness in all remaining images to the base image. The outer boundary of the flood plain was defined by the spatial extent of inundation in the satellite image showing the largest flood (28 January 1996; 160 512 Ml day^{-1} at St George). This was modified to encompass the extent of alluvial soils visible in false colour images where this was obvious. All pixels outside this boundary were eliminated from each image. Areas of agricultural land use, including irrigated fields and water storages, were also eliminated.

Flood plain inundation was mapped in two steps. First, a ratio of Band 1 (visible blue; 0.45–0.52 μm) to Band 7 (middle infrared; 2.08–2.35 μm) was used to map deep open water. This transformation was readily applied to each date of imagery and efficiently identified inundation with a minimum of user input. Second, a change detection comparison between Band 5 in the flood image, and Band 5 in the nearest date of dry imagery was used to identify areas of shallow water. These areas typically showed subtle pixel darkening, or high vegetation growth vigour adjacent to obviously inundated areas. The total area of inundation was calculated as the sum of the open and shallow water in each image.

An unsupervised classification of an overlay of the 13 inundation maps was used to identify areas within the flood plain based on their flood characteristics. Previous analyses (Sims *et al.*, 1999) showed that the spatial extent of inundation in the flood maps was most significantly correlated with maximum total daily Balonne River discharge at St George in the 14 days prior to image capture (*Qp14).* Inundated area = *Qp14* × 1.50 – 4143.58 ha ($r^2 = 0.968$; $F = 328.2$; $df = 12$; $P < 0.001$). The average recurrence interval (ARI) in years for each *Qp14* volume was calculated from total daily discharge recorded at St George from August 1965 to August 1999. The flood frequency map was created by labelling each region with the minimum *Qp14* at which it was inundated and the ARI for that *Qp14* volume.

Plant growth vigour was mapped using the normalized difference vegetation index (NDVI). A reference image depicting average plant growth vigour for the 13 images was created. This was done by calculating the average pixel value, on a pixel-by-pixel basis, for each image band in each of the seven images showing the flood plain dry. The transformed bands were then re-combined into a single data set. The averaging process minimizes the influence of seasonal or climatic variations on the representation of plant growth condition over time, and shows, on average, where one would encounter particular growth conditions over the period of image capture. Recombining the image bands in this way maintains the full image processing flexibility of the original image data set, including the capability to perform multispectral image classification. Pixel values in an NDVI transformation of the reference image were divided into five classes based on their standard deviation from the mean. The five classes were: LOW (< mean – 2SD); MODERATELY LOW (> mean – 2SD and < mean – 1SD); MODERATE (mean ± 1SD); MODERATELY HIGH (> mean + 1SD and < mean + 2SD); and HIGH (> mean + 2SD). Areas of open water were eliminated from the reference image and the proportion of each flood frequency zone occupied by each NDVI class was calculated.

RESULTS

The pattern of flood plain inundation across the Lower Balonne is complex (Fig. 2). Inundation commences when flows exceed 26 450 Ml day^{-1} (ARI of 1.5 years). Flood waters remain confined to the central region of the flood plain at flows up to 58 821 Ml day^{-1} (ARI of 2.5 years) when they re-enter the Culgoa River approximately 30 km downstream. At flows around 65 176 Ml day^{-1} (ARI of 3 years) a larger proportion of the flood plain becomes inundated including the lower reaches of the Culgoa River (Fig. 2). Over 246 000 ha of the flood plain are inundated at flows in excess of 160 512 Ml day^{-1} (ARI of 10.5 years). Overall, the western and central regions of the flood plain are flooded more frequently than the eastern regions (Fig. 2) and there are several small regions that remain dry, even during a flood event with a return period of 10.5 years. Hence distinct zones of flooding can be recognized in this large flood plain complex and the high flood frequency areas are not necessarily located adjacent to the main river channels.

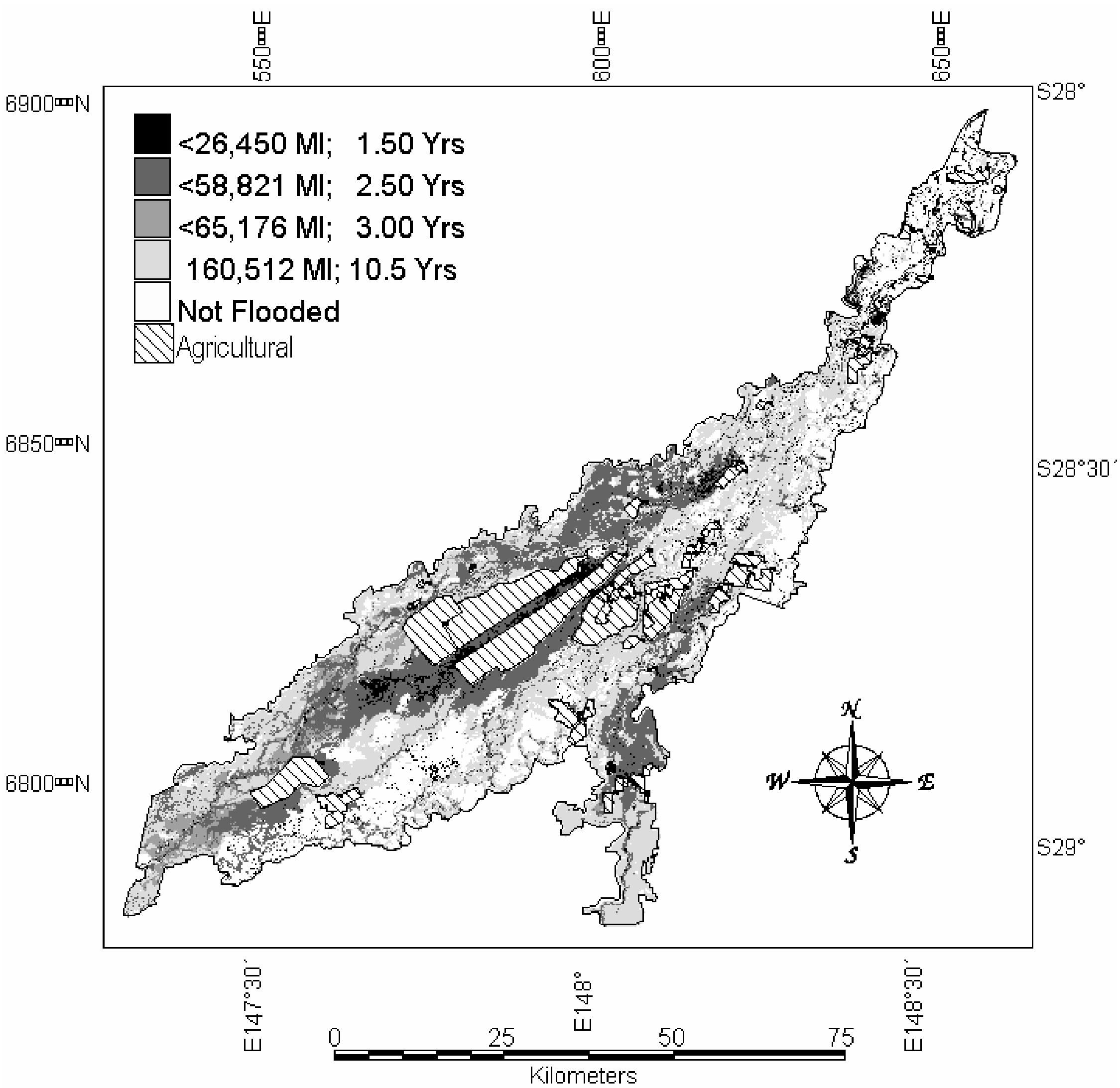

Fig. 2 Flood plain inundation in the lower Balonne. Flood frequency classes are shown as the *Qp14* discharge for each inundation area and the average recurrence interval of flooding. ARI zones have been grouped for display purposes.

High plant growth vigour tends to occur in three main areas of the flood plain; the central region of the flood plain; adjacent to the main river channels; and, in the upstream parts of the flood plain (Fig. 3). LOW and MODERATELY LOW plant growth vigour occurs to the west of the Culgoa River, and in small patches throughout the eastern parts of the flood plain downstream of the large agricultural developments.

At a regional scale there appears to be a high association between plant growth vigour and flood frequency in the lower Balonne flood plain. However, the composition of the various plant growth vigour classes within each flood frequency zone (Fig. 4) shows that the relationship between flood frequency and plant growth vigour is nonlinear. The combined proportion of MODERATELY HIGH and HIGH vigour vegetation is largest where flooding occurs at an intermediate frequency between 1.25 and 1.50 years. The proportion of highly vigorous vegetation in each ARI zone then tends to decrease with decreasing flood frequency. Low growth vigour is common

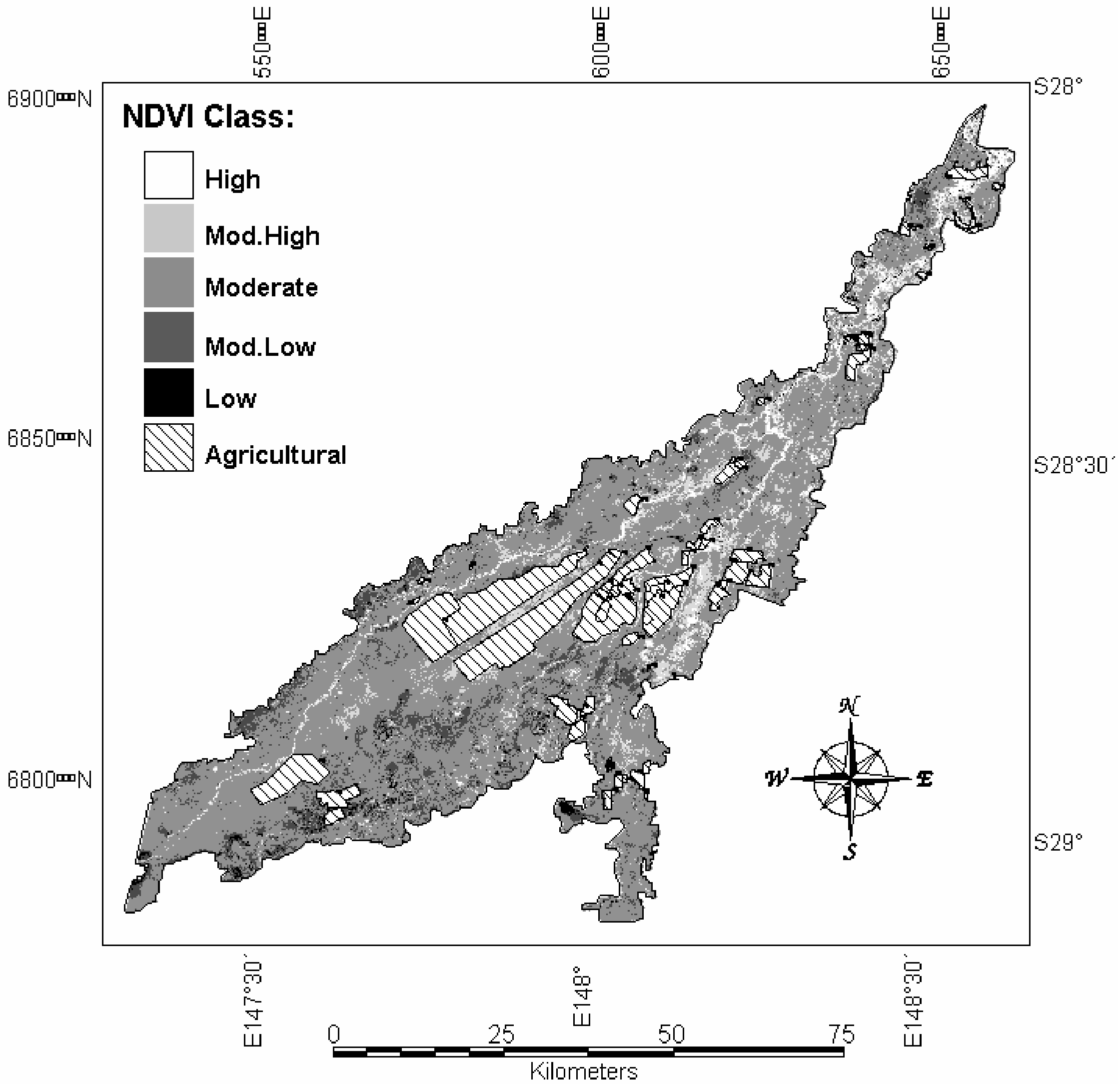

Fig. 3 The distribution of plant growth vigour mapped using the NDVI transformed reference image.

only where flooding occurs more frequently than once in 1.25 years (Fig. 4). The least frequently flooded areas (ARI 10.5 years) have the largest proportion of MODERATELY LOW vigour vegetation, but this proportion is also large where flooding occurs more frequently than once in 1.25 years (Fig. 4).

DISCUSSION

Inundation of the lower Balonne flood plain occurs in three phases. Inundation commences when flows exceed about 20 000 Ml day^{-1}, but remains confined within the main flow path along the central region of the flood plain. The area of inundation expands from this central region to adjacent areas when the flow exceeds 60 000 Ml day^{-1}. Flows in excess of 100 000 Ml day^{-1} inundate more remote parts of the flood plain, especially along the Culgoa River channel. Hence, this flood plain wets

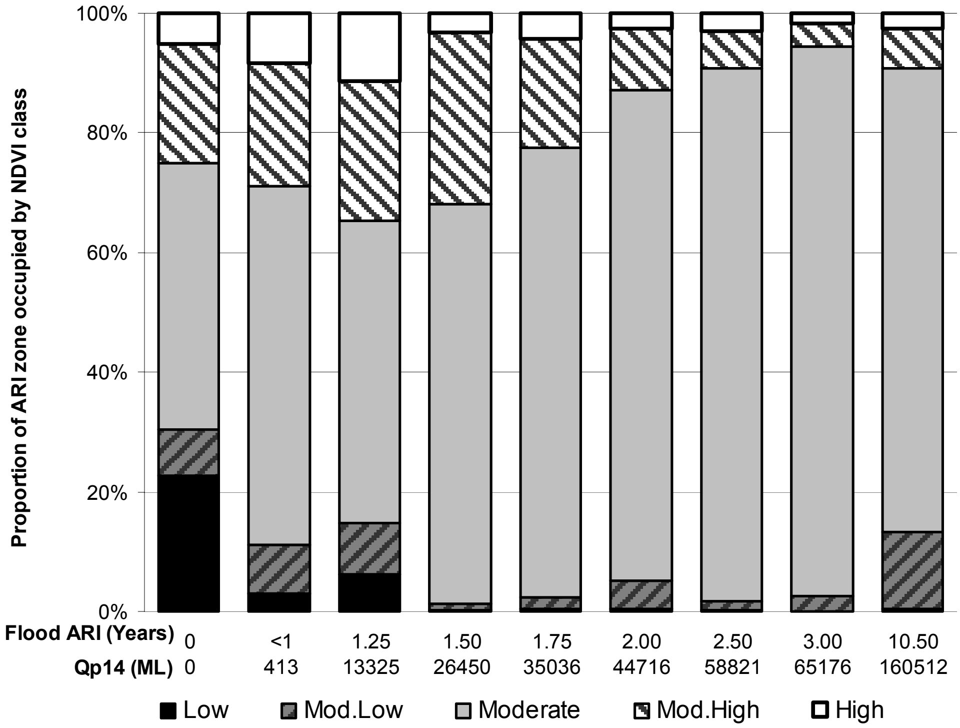

Fig. 4 Plant growth vigour class composition of ARI zones.

itself from inside to out rather than displaying a gradual wetting from a main channel to more distal areas as commonly recorded in the literature (e.g. Anderson *et al*., 1996).

The spatial distribution of vegetation growth vigour is, in general, associated with the frequency of inundation. However, the highest plant growth vigour occurs in areas flooded every 1–2 years (Fig. 4). Areas that are flooded more frequently than this contain vegetation with the lowest growth vigour observed on the flood plain. Consequently, our initial prediction, that there would be a direct correlation between plant growth vigour and flood frequency, is not supported by these results. These results support the subsidy–stress hypothesis by showing that a unimodal distribution of plant productivity, peaking at moderate flood frequencies, occurs in relation to flood frequency on the lower Balonne flood plain. This distribution may be caused by the effects of soil anoxia (Ogden & Thoms, 2001). Large-scale agricultural developments have recently changed the frequency and permanence of inundation by restricting the central flow path to a narrow floodway between levee banks (Fig. 2). These new inundation conditions may be intolerable to plant species that became established under the former inundation regime.

The interpretation of plant growth vigour may have been affected by nonlinear spectral mixing. The reference image may contain a large number of mixed water/vegetation pixels because differences in moisture conditions prior to image capture could change the surface area of water bodies between the images from which it is made. Differences in plant biomass or canopy cover characteristics between flood frequency zones may also impact upon the interpretation of growth vigour. In general, however, the reference image is a useful tool for showing longer-term landcover characteristics in highly dynamic environments.

CONCLUSIONS

This paper addresses ecological and technical issues for remote sensing studies of flood plain landscapes. The pattern of inundation across on the lower Balonne flood plain and plant growth vigour in response to this wetting is complex. However, plant growth vigour is lowest in areas flooded more frequently than once per year. This distribution is contrary to that expected in this semiarid region where vegetation growth has previously been correlated with watering. Instead, this study supports the subsidy–stress hypothesis by showing that plant productivity peaks at moderate flood frequencies. Plant growth vigour was mapped using an NDVI transformed reference image that shows average pixel values over a period of almost 10 years. This type of averaging transformation is highly suitable for mapping landcover in dynamic landscapes and we recommend that it be applied and developed further.

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REFERENCES

Anderson, M. G., Walling, D. E. & Bates, P. D (eds) (1996) *Floodplain Processes*. John Wiley, Chichester, UK.

Davenport, M. L. & Nicholson, S. E. (1993) On the relationship between rainfall and the normalized difference vegetation index for diverse vegetation types in East Africa. *Int. J. Remote Sens.* **14**(12), 2369–2389.

Foody, G. & Curran, P. (eds) (1993) *Environmental Remote Sensing from Regional to Global Scales*. John Wiley, Chichester, UK.

Junk, W. J., Bayley, P. B. & Sparks, R. E. (1989) The flood pulse concept in river–floodplain systems. *Can. Spec. Publ. Fish. Aquat. Sci. 106*, 110–127. NRC Research Press, Ottawa.

Kogan, F. N. (1990) Remote sensing of weather impacts on vegetation in non-homogeneous areas. *Int. J. Remote Sens.* **11**(8), 1405–1419.

Lichtenthaler, H. K. (1998) The stress concept in plants: an introduction. *Ann. NY Acad. Sci.* **851**,187–198.

Odum, E. P., Finn, J. T. & Franz, E. H. (1979) Perturbation theory and the subsidy–stress gradient. *BioScience* **29**(6), 349–352.

Ogden, R. W. & Thoms, M. C. (2001) Effects of reduced flooding on the soils and plants of a lowland semi arid floodplain in south-east Queensland. In: *Proc. 3rd Australian Stream Management Conference* (Brisbane), 695–700.

Robertson, A. I., Bacon, P. & Heagney, G. (2001) The response of floodplain primary production to flood frequency and timing. *J. Appl. Ecol.* **38**, 126–136.

Sims, N. C., Thoms, M. C., Levings, P. F. & McGinness, H. M. (1999) Large scale vegetation response to wetting on the Lower Balonne Floodplain. *Tech. Report Lower Balonne Floodplain Advisory Committee, Cooperative Research Centre for Freshwater Ecology, Canberra.*

Wylie, P. B. (1993) Land use in the Condamine-Balonne-Culgoa catchment. In: *Water Quality Management in the Condamine-Balonne-Culgoa Catchment* (ed. by S. J. Kenway), 1–50. Condamine-Balonne-Water Committee, Dalby, Queensland.