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Remote sensing for assessing the zone of benefit where deep drains improve productivity of land affected by shallow saline groundwater

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ABSTRACT

The installation of deep drains is an engineering approach to remediate land salinised by the influence of shallow groundwater. It is a costly treatment and its economic viability is, in part, dependent on the lateral extent to which the drain increases biological productivity by lowering water tables and soil salinity (referred to as the drains' zone of benefit). Such zones may be determined by assessing the biological productivity response of adjacent vegetation over time. We tested a multi-temporal satellite remote sensing method to analyse temporal and spatial changes in vegetation condition surrounding deep drainage sites at five locations in the Western Australian wheatbelt affected by dryland salinity-Morawa, Pithara, Beacon, Narembeen and Dumbleyung. Vegetation condition as a surrogate for biological productivity was assessed by Normalised Difference Vegetation Index (NDVI) during the peak growing season. Analysis was at the site scale within a 1000 m buffer zone from the drains. There was clear evidence of NDVI increasing with elevation, slope and distance from the drain. After accounting for elevation, slope and distance from the drain, there was a significant increase in NDVI across the five locations after installation of deep drains. Changes in NDVI after drainage were broadly consistent with measured changes at each site in groundwater levels after installation of the deep drains. However, this study assessed the lateral extent of benefit for biological productivity and gave a measure of the area of benefit along the entire length of the drain. The method demonstrated the utility of spring NDVI images for rapid and relatively simple assessment of the change in site condition after implementation of drainage, but approaches for further improvement of the procedure were identified.

1. Introduction

Dryland salinity is a world-wide concern with distinct differences from irrigation salinity but both share saline shallow watertables as the prime cause of soil salinity in the root zone (Rengasamy, 2006). In the south-west of Australia (area known as the 'wheatbelt') dryland salinity is caused by increased recharge of water into the semi-confined aquifer bringing saline groundwater close to the surface (Clarke et al., 2002; George, 2004). As groundwater reaches within 2 m of the soil surface, capillary rise of salts causes salinisation of root zones and general decline in plant productivity (Nulsen, 1981), damage to buildings and infrastructure (Beresford et al., 2001) and has negative effects on natural ecosystems (Cale et al., 2004; Cramer and Hobbs, 2002; Jones et al., 2009). In this region almost one million hectares of land were mapped as saline in 1996 and a further 5.4 million hectares are at risk of future salinisation (Caccetta et al., 2010; McFarlane et al., 2004, 1992a). Globally, the area affected by salt-affected soils is 831 million hectares (Rengasamy, 2006). In India alone, irrigated saline-waterlogged soils cover 5 million hectares (Ritzema et al., 2008). Drainage to lower water tables is a necessary management tool in salt-affected areas.

Some techniques to lower the water table and alleviate the effects of dryland salinity include revegetation, growing high water use perennial crops and the installation of deep drains (Ali et al., 2012; Bell and Mann, 2004; Graham et al., 2010; Pannell and Ewing, 2006). Deep drains, an engineering approach to salt-land remediation, were initiated in Western Australia in the late 1970s and are increasingly seen by farmers and catchment groups as a viable option to manage salinity, though questions remain about their efficacy (Robertson et al., 2009a, 2009b).

Deep drains (2–3 m deep) are intended to cause the water table to drop by increasing groundwater discharge to surface drainage

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(EPA, 2007; NDSP, 2001) and to increase salt leaching from the root zone of plants (Dogramaci and Degens, 2003). This allows cropping in areas threatened by rising water tables and salinity and reclamation of waterlogged or saline areas. However, installation and maintenance of deep drains is costly, and economic viability is in part dependent on the drains' zone of benefit. The area of benefit is a measure of the drain's efficiency. It is generally expressed as the lateral extent of the drain's influence on the water table and vegetation and is dependent on soil and regolith parameters such as hydraulic conductivity (Ali et al., 2004). Previous studies at a deep drainage site at Narembeen in the Western Australian wheatbelt, reported that one year after the drain was installed, groundwater levels dropped to below 1.5 m for a distance of 200–300 m from the drain and root zone salinity decreased for a distance up to 100 m from the drain (Ali et al., 2004).

Lowering the water table and decreasing root zone salinity may not translate to improved crop growth unless levels of both constraints fall below biological thresholds. In addition, a decrease in the level of salt in the soil may cause clay dispersion (Bell and Mann, 2004). The recovery of soil structure and soil organic matter levels will also have a significant bearing on soil productivity after draining. The time over which such improvements in soil conditions, and therefore in biological productivity, occur following deep drainage remain unclear.

While the regional scale assessment of salinity is useful for natural resource managers (Measham, 2009), mapping at a farm or field scale is particularly valuable to individual farmers as it informs their management decisions. The State Salinity Council recommended that monitoring and evaluation of deep drainage should be carried out at the property, catchment and regional scales (Short and McConnell, 2000). Such monitoring would help to develop guidelines to ensure the appropriate and most effective application of deep drains. Ali et al. (2004) concluded that, despite increasing use of deep drainage, there was lack of detailed evaluation of their effectiveness.

To determine whether the drains are effective, an accurate measure of pre-drainage land productivity must be acquired and used as a benchmark. Monitoring is required to assess the efficacy of the drains and any improvements in agricultural productivity. Some early surveys in Western Australia used stereo aerial photography combined with extensive fieldwork (Nulsen, 1981; Salama et al., 2007). Others studied groundwater levels, root zone salinity and soil properties (Ali et al., 2004).

Field-based assessment of dryland salinity is very costly, hence satellite remote sensing has been investigated for responses of soils and vegetation over time (Gao and Liu, 2008; Metternicht and Zinck, 1996; Mougenot et al., 1993; Verma et al., 1994). Geographic Information Systems (GIS) and other spatial modelling tools have been used to map current extent and predict risk and future extent of saline areas (Caccetta et al., 2010). Airborne hyperspectral and field spectroscopy methods have been shown to provide good discrimination of salt-affected areas (Dutkiewicz et al., 2009; Farifteh et al., 2007).

Routine methods have been developed to assess crop biomass and yield on a large spatial scale (Metternicht and Zinck, 2003; Smith et al., 1995; Doraiswamy et al., 2003). With the growing availability of satellite archives, these applications are increasing (Pettorelli et al., 2005). However, uptake by operational programs has been slow (Apan et al., 2007). Salinity in the landscape can be detected and mapped as either direct signals from salt crystals or the salt crust or as an indirect signal expressed through the types and density of the vegetation cover (Mougenot et al., 1993; Verma et al., 1994). Spectral responses of vegetation to salinity, whether positive or negative, can act as an indicator of the impact of the drains. The major limitation, however, is if the salt-affected (or naturally saline) land is covered with salt tolerant plants (Dutkiewicz et al., 2009; Metternicht, 1996). The spatial and temporal characteristics of salt-affected land can also be used to distinguish it from other areas. This approach was adopted by the Land Monitor Project to map salinity in the south-west region of Western Australia (Caccetta et al., 2010).

A pilot study (Van Dongen, 2005), which included four out of the five current study sites, examined the relationship between field soil conductivity and satellite-measured vegetation indices. The spatial and temporal changes in the area of saline land were assessed using Normalised Difference Vegetation Index (NDVI) derived from Landsat TM data acquired between 1987 and 2004. NDVI and soil conductivity (EC_{ah}), measured with an EM38 instrument, were analysed through linear regression. A strong relationship between NDVI and EC_{ah} was found at three of the four sites ($R^2 = 0.5–0.7$) (Van Dongen, 2005). At Dumbleyung, Beacon and Pithara, the salinity maps showed that, from 1988 to 2003/4 before the installation of deep drains, the area of saline land increased. At Narembeen, between 1996 and 2003 (the period before and after the deep drain was installed), the mapped area of saline land declined by 11.2%. The 2003/4 salinity maps explained 87–93 % of variation in field EC_{ah} data and were comparable to salinity maps produced in 2000 by the Land Monitor Project (Van Dongen, 2005). However, this study lacked sufficient replication of sites and time series to draw firm conclusions about the efficacy of the deep drains in alleviating the effects of dryland salinity.

In this study, vegetation indices were used to analyse multispectral imagery for multiple years to determine if there were any changes in vegetation cover in areas surrounding deep drains, and to assess evidence for a zone of benefit from deep drainage. Vegetation indices can be used to provide a quantitative assessment of vegetation condition, in the form of density and vigour. Many studies showed that red and near-infrared (NIR) wavelengths were the best two-band combination for identifying saline agricultural land (e.g. see Mougenot et al., 1993; Verma et al., 1994; Metternicht, 1996; Metternicht and Zinck, 1996, 2003). The simple ratio of NIR to red can also be correlated with the photosynthetic activity of plants but is affected by changing illumination conditions such as surface slope and aspect. Due to this, the NDVI has been used extensively as a standard index for crop canopy assessment (Hatfield et al., 2004) and phenological studies (Reed et al., 1994). Landsat-derived NDVI data of the south-west region of Western Australia are accessible through archives such as the West Australian Department of Land Information (DLI) and are available at property scale via an online web delivery service.

Objectives of this study were to analyse the changes over time in vegetation cover using historical remote sensing data in land surrounding deep drains, and to assess evidence for a zone of benefit from deep drainage at selected sites.

2. Materials and methods

Historical, free satellite remote sensing data and relatively simple data processing methods were chosen to provide a synoptic view of the deep drainage sites and their surroundings using operational sensors suitable for monitoring. Techniques used did not aim to create maps of saline land. In this study, through analysis of greenness of the landscape we aimed to assess if deep drainage was making any difference in the vegetation response that could be attributed to lowering of the groundwater.

2.1. Study sites

The five sites were located in the south-west region of Western Australia. The climate is Mediterranean with hot, dry summers and