Kobryn, H.T., Lantzke, R., Bell, R. and Admiraal, R. (2015) Remote sensing for assessing the zone of benefit where deep drains improve productivity of land affected by shallow saline groundwater. Journal of Environmental Management, 150. pp. 138-148.

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.

Keywords

Agricultural productivity, deep drainage, dryland salinity, monitoring, remote sensing, vegetation indices

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; McFarlane et al., 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; Robertson et al., 2009b).

Deep drains (2-3 m deep) are intended to cause the water table to drop by increasing groundwater discharge to surface drainage (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 modeling 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 to 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 to 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; Metternicht and Zinck, 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 cool, wet winters (Gentilli, 1972). Description of these sites is presented in geographical order from south to north and along a decreasing rainfall gradient. Dumbleyung is in the south central, medium rainfall agroclimatic zone, Narembeen is on the border of the central, medium to low rainfall agroclimatic zones, Beacon and Pithara lie in the north central, low rainfall agroclimatic zone and Morawa is located in the northern region (Figures 1 and 3) (Moore, 2001). Long term annual rainfall was the highest at Dumbleyung (434 mm) and lowest in Morawa (277 mm) (Figure 3) (BoM, 2012).

Deep drains were constructed at different times at each site between 1999 and late 2005. Field validation data on groundwater levels and plant productivity for four of the sites were available (except Narembeen) (Bell et al. 2010).

2.1.1. Dumbleyung

This was the most southern of all sites, located 11 km north-east of Dumbleyung (225 km south east of Perth) (Figure 1). The soil profile of the Dumbleyung site consisted of a thin layer of dark grey sandy topsoil with an abrupt boundary to a clay subsoil which becomes heavier with depth (Percy, 2000). Bedrock of weathered granite was located at a depth of 4 to 6 m (Cox 2002). Groundwater levels at the Dumbleyung site prior to installation of the deep drain fluctuated between 0.70 and 1.1 m below the surface (Cox, 2002). Cereal crops were the dominant land use. However, saltbush and tree planting have been undertaken on salinised land in recent years.

The drain was installed in December 2002 and ranged from 3.0 to 1.62 m deep. It consisted of a collector drain running approximately north-west, and four lateral drains branching to the west (Figure 1). The drain discharged into a tributary of Lake Dumbleyung.

2.1.2. Narembeen

The study site was 40 km east of Narembeen (approximately 280 km east of Perth) (Figure 1). Soils within the drainage area were described by Ali et al. (2004) as duplex with loamy sand underlain by sandy clay. Permeability was high in the top sandy layer and low in the underlying clay. A ferricrete layer was 2.0 m below the surface.

This study focused on a small, western section of the drain (Figure 1) installed in July 1999 to a depth of 2.5 m and de-silted in August 2001. The general flow direction was from southeast to northwest.

2.1.3. Beacon

The Beacon site was approximately 250 km north-east of Perth (Figure 1). The soil profile consisted of sandy loam topsoil, which at a depth greater than 80 cm graded to red clay subsoil. Alkalinity was moderate at the surface, and soils were slightly salt-affected. Large portions of the land became saline after the water table rose due to above-average rainfall in 1999 (G. Kirby, pers. comm.). The drain, completed in October 2005, consisted of the main trunk flowing southwards and two short subsidiary drains (Figure 1).

2.1.4. Pithara

The site was located 23 km east of Pithara (approximately 200 km north/north-east of Perth) (Figure 1). The drain was installed in August 2004 and flowed in a north-westerly direction for 21.5 km. Several tributaries were added to the central drain as it progressed down the catchment (Figure 1). The south-eastern segment was classified as the deep drain zone while the north-east zone consisted only of shallow drains. Soil associations present within the study area included mainly saline soils plus loamy duplex, sandy earth and alkaline, red, shallow and deep loamy duplex (Department of Agriculture, pers. comm.).

2.1.5. Morawa

Located on the eastern edge of the wheatbelt, this site was the most northern of all study areas, some 370 km north of Perth (Figure 1). The deep drain, nearly 7 km long, followed natural drainage from the north-east to the south-east (Figure1) and was completed in January 2005. Two small sections were added to the starting section of the drain, adding another 600 m to its length.

Insert Fig 1

2.2. Data processing

Temporal comparisons of vegetation index data were undertaken within the deep drain buffer zones (500 m buffers) and with a second “control” buffer zone from 700-1000 m. Extracted satellite vegetation index data were compared to the distance from the drain over time.

In addition, pairs of spring NDVI images of before- and after- drain construction were analysed for spatial patterns within and outside the 500 m buffer. The data sets used in this project were satellite imagery (Landsat Thematic Mapper); digital elevation model (DEM) and slope data, vector GIS data for drains, roads and town locations and aerial photography. All image analysis was undertaken using IDRISI software (v16.05) (Eastman, 2010). Data processing included data extraction and georeferencing, creating buffer polygons around the drains and masking undesirable features such as drains and roads and native vegetation patches. NDVI values over time, slope, elevation and distance from the drain were extracted for each site (one point per pixel of the image) and exported for statistical analysis.

2.2.1. Pre-processing

Landsat TM satellite data acquired during spring were sourced from the Land Monitor and AgImage projects (www.landgate.wa.gov.au) with atmospheric and geometric corrections already implemented and data resampled to 25 m. Additional image georeferencing was performed within the extent of the individual sites to ± ¼ pixel accuracy. Images were spatially subset into multi-temporal data cubes.

2.2.2. Buffers and masking of image data

To facilitate extraction of NDVI data, buffers were created for all the drains. The 500 m buffer width was used as previous work established that the zone of drain influence was unlikely to extend beyond that distance and the choice of 500 m was to provide a conservative estimate of drains' impacts (Ali et al., 2004; Van Dongen, 2005). Only deep sections of the drains were investigated as Ali et al. (2004) showed that shallow drains did not result in lowering of the groundwater table. Areas not available for cropping were masked using existing data such as roads and further refined by visual interpretation of high resolution aerial images.

As the drains did not neatly fit into the centre of each 25 x 25 m Landsat pixel, an additional mask buffer of 36 m was used. Point vector files (one point per pixel centre) within the buffer area were created for data extraction. Distance from drain was calculated and assigned to each extracted data point.

Digital elevation model (DEM) at 30 m horizontal and 0.5 m vertical resolution was used to calculate slope and aspect and analysed in the context of the zone of influence for the drains.

2.2.3. Vegetation index data

NDVI images for drain sites were created from two sources of pre-processed Landsat data, Land Monitor and AgImage projects, using standard formulae (Elvidge and Chen, 1995). Spring (August-September) NDVI values were extracted from the data series using unique identifiers within the 500 m and 700-1000 m buffers (Eastman, 2010). The orthogonal distance from each pixel to the drain was also calculated and included in analyses to determine the zones of benefit of the drains.

To help visualize spatial variability across and along the drains, NDVI difference between selected spring Landsat images were calculated for pre- and post-drain construction. These comparisons were limited to paired years with comparable spring rainfall. As an example, we provide results for one of the sites, Dumbleyung (2003 and 2007). Image differencing produced data of the standardized difference and standardized classes (mean ± 3-4 standard deviations).

2.2.4. Linear mixed effect model

We used statistical modeling to investigate the relationship between NDVI, distance from the drain and presence of a drain. The general model considered was a linear mixed effects model of NDVI on ground elevation, ground slope, distance from the drain, whether the area was in the zone of influence (i.e. <500 m from the drain) or not (i.e. 700-1000 m from the drain), site, whether or not the drain had been installed, and all possible interactions among the distance from the drain, site and whether or not the drain had been installed. These variables were fixed effects in the model. Random effects were included for individual pixels.

Ground elevation and slope were included in our model, as they serve as surrogates for depth to groundwater and rate of drainage respectively. Distance from the drain serves as a surrogate for soil salinity and the magnitude of the drains effect on groundwater level. Positive effects correspond to increased NDVI with increased ground elevation, slope, or distance (up to a certain point). An indicator for whether an observation fell in the zone of influence was included to allow for comparisons of NDVI outside and inside the expected zone of influence for the drain, and an indicator for whether or not the drain had been installed was included to allow us to assess the impact of the drain on NDVI. A positive effect for the zone of influence indicator is indicative of higher NDVI outside the zone of influence, while a positive effect for the indicator for drain installation reflects higher NDVI after installing the drain. Finally, a factor for site was included to allow for comparisons across sites. In this case, Beacon served as a reference, and coefficients for other sites reflected comparisons of NDVI of that site with Beacon. Inclusion of interactions among distance from the drain, site, and whether or not the drain had been installed allowed for the modelling of differential effects of distance from the drain on NDVI depending on site and whether or not measurements were taken pre- or post-installation of a deep drain.

While it would have been appropriate to account for spatial dependence in NDVI measurements based on pixel location, standard isotropic variogram models (exponential, Gaussian, linear) could not be fit due to the dataset size. This was still the case after subsampling less than 10% of available data points. This subsampling was done through systematically sampling the data by including pixels that were a distance of 100 m apart from each other based on a randomly selected starting pixel, as illustrated in Figure 2 for Dumbleyung. Although we could not account for spatial correlation in our model and, consequently, treated subsampled pixels as independent of each other, the subsampling of pixels through systematic sampling provided the best alternative in terms of effectively reducing spatial correlation. Our model was fit using the “nlme” package (Pinheiro et al., 2013) in R version 3.0.1 (R Development Core Team 2013). This model was subsequently compared to reduced models, none of which produced reductions in Akaike information criterion (AIC) or Bayesian information criterion (BIC).

Insert Fig 2

3. Results

All sites experienced lower than long-term average rainfall during the period 1997-2009 (Figure 3). Dumbleyung, the southern-most site had the highest average rainfall and Morawa, the most northern site, the lowest (Figure 3).

Pithara and Beacon had the longest network of drains and hence the largest areas within designated buffers. While approximately one third of the areas at all sites within 500 m buffers were masked out, at Morawa about 70% had to be masked out as much of the land was not used for cropping or grazing. Areas identified as suitable for control (700-1000 m from the drain) varied from 150-470 ha (Table 1).

Insert Fig 3

Figure 4 shows a plot of NDVI vs. distance from the drain for each of the five sites for each year for which measurements are used for that site. Raw data are plotted in gray, and means for a given distance for a specific year are plotted in black. Solid symbols denote measurements corresponding to years after installation of the drain. Initial inspection suggests a positive association between NDVI and distance from the drain, so the drain appears to be least effective for areas closer to the drain. The immediate impact of the drain itself is not clear, as we do not notice a wholesale shift in NDVI values corresponding to those years after installation of the drain. For instance, the two available years post-implementation of the drain for Morawa overlap the pre-implementation years in terms of average NDVIs by distance.

Insert Fig 4

3.3.1. Dumbleyung

For the sake of brevity only the Dumbleyung site is used to illustrate in full the data analysis conducted at each site.

Over the period of study, lowest annual rainfall was measured in 2002 and 2007 while the highest values were in 1998 and 2008 (Figure 3). Total area covered by deep drainage within 500 m of the drain was 327 ha, the smallest of all sites. The drain was also the shortest (< 2 km) (Table 1).

There was not much difference in NDVI image sequence over time between years with average rainfall (1999) and a year with below-average rain (2007), after the drain was constructed. However, NDVI values were very low in 2009 when the rainfall was well below the long term average. Pairwise comparisons of spring images for NDVI between 2003 and 2007 showed considerable increase in the NDVI, mostly in the upper and middle part of the drain and a marked decrease in the NW section. Difference analysis also demonstrated high variability in the area of benefit for each drain, suggesting some portions of the drain sections were performing better compared to others (Figure 5).

3.3.2. Narembeen

Annual rainfall at the site was quite variable over the period of 1997 to 2009. Highest rainfall was measured in 2008 and 1999 while the lowest in 2002 and 2007 (Figure 3).

Compared to other sites, deep drains at Narembeen were quite complex in their spatial layout with several smaller drains joining the main trunk (8.7 km long) (Fig 1). Total area within the 500 m buffer was the third largest amongst the sites and this site had relatively low proportion of areas not cropped (Table 1).

There was a considerable spatial variability in NDVI before and after the drain construction. NDVI data for 1997 and 2007 selected for the pairwise comparisons showed that over 50 % of the buffer area had noticeable improvement in the greenness values. Most areas which responded positively were to the west and to the south of the main trunk of the drain.

Average NDVI values over time were highest for data sets during years of higher rainfall and mostly post 2001 when the drain was constructed. There was general increase in NDVI with the distance from the drain, except for September 2002 and 2004. August 2009 data also showed very low average NDVI values. Highest NDVI values were post-drainage in August 2003 (above average rainfall) and August 2007 (below average rainfall). In this particular study, site average NDVI values extracted were very similar and NDVI was leveling at the distance of about 200 m from the drain.

3.3.3. Beacon

This site had consistently declining annual rainfall between 1997 and 2009 (Figure 3). Similar to Pithara, the highest rainfall was in 1999, while the lowest was in 2007 and 2002. Compared to the long-term average rainfall of 332 mm (BoM 2012), only three years in the period studied exceeded that value. Of all the study sites, the Beacon deep drain was the longest (20.8 km). This site had the second largest area within the 500 m buffer and the largest area covered by native vegetation (Table 1, Figure 1).

Of the five NDVI images for the period before the drain, two (1987 and 1992) had very low NDVI values, while the other two (1998 and 2003) were relatively high. Areas along the drain had consistently low NDVI before 2005 when drainage was constructed. Of the three post- drainage spring NDVI images, the 2009 data set showed the highest NDVI across the landscape including areas close to the drain.

Average spring NDVI values plotted against distance from the drain showed the 1987 data with the lowest rainfall had the lowest NDVI values. The fitted line for 2009 had the highest values despite that year being below the average rainfall.

Difference between the pre- and post- drainage spring NDVI showed that while there was more improvement measured through increase in NDVI in the southern most area, most of the change was at paddock-scale. Some of the differences were up to two standard deviations from the mean for the whole image area, suggesting it is possible to achieve relatively high greenness in areas which previously had quite low productivity.

3.3.4. Pithara

This site had the largest surface area within the 500 m buffer and the second longest drain (Table 1). Annual rainfall pattern was similar to Morawa, with 1997, 2002 and 2007 having the lowest rainfall. Highest rainfall was in 2000 and 2009 (Figure 3).

Large seasonal and annual variability in rainfall as well as local conditions including cropping regime and impacts of salinity resulted in highly variable NDVI datasets. Some of the lowest NDVI values were measured in 1987, 2003 and 2007, while 1998 and 2004 NDVI values were relatively high across the study area. Data for 2004 and 2009 were used to calculate image differences including standardised difference. Most of the spatial variability in NDVI between 1987-2009 was confined to areas near the drains.

The pattern of change in NDVI over time highlighted the general trend of NDVI increase with the distance away from the drain. Generally, years with lower rainfall had lower NDVI. In 2004, NDVI values were the highest in the series examined here by contrast with 2009 which had similarly high rainfall. Comparisons between areas with shallower (north-east) and deeper (south) drains at Pithara showed that deeper drains had slightly more effect than shallower drains (data not shown).

Comparisons of NDVI data before and after drain construction showed large spatial variability within and outside the 500 m buffer (up to 2 standard deviations frome the mean), most notably in the upper reaches of the drain.

3.3.5. Morawa

Compared to other sites, at Morawa there was relatively small area within the 500 m buffer cropped in recent years (Table 1) (Fig 1). The site had some of the lowest NDVI values. Large inter-annual variability in spring data was observed both before and after the drain was constructed.

The NDVI values gradually increased with distance from the drain and were lower for the period before the drain was installed (2005) compared to after the drain was commissioned, except for 2007, one of the driest years on record for that area (Figure 3). There was a noticeable increase in the mean NDVI values about 100 m from the drain.

Plots of all data points for the period before the drain construction and after showed generally higher NDVI values in the post- drain period (Figure 4).

3.3.6 Mixed model for all sites

The above results showed that a range of variables affect NDVI so we used the mixed effect model to examine effects on NDVI of ground elevation, ground slope, distance from the drain, site, whether or not the drain had been installed, and all possible interactions among the distance from the drain, site and whether or not the drain had been installed.

The effect of the drain in the results of the linear mixed effects model presented in Table 2 indicates that both distance from the drain and whether or not a drain had been installed alter the response of NDVI after adjusting for ground elevation, ground slope, and site. The change in NDVI pre- and post-installation of the drain depends on site, as shown by the significance of drain-site interactions. Interpretation of main effects of interest (distance from the drain, whether or not the drain had been installed) cannot be done apart from these interactions. However, we note that the net effect of the main effects for distance and whether or not the drain had been installed and interactions involving these variables are positive for both, meaning that NDVI increases both after installation of the drain and with increasing distance from the drain. At the same time, the highly significant negative coefficient for the variable indicating whether the pixel is located in the 700-1000 m buffer from the drain (“Control”) suggests lower NDVI values outside of the zone of influence of the drain after adjusting for ground elevation, ground slope, site, distance from the drain and whether the drain had been installed.

Insert table 2

4. Discussion

4.1. Beneficial effects of deep drainage on biological productivity: assessment and validation

Our results from the linear mixed effects model showed that, for every site, NDVI increased with both distance and with installation of the drain after adjusting for relevant variables. While only limited ground truthing of this interpretation was undertaken in the present study, a number of lines of evidence suggest that these are valid conclusions for the respective sites and hence support the efficacy of the approach tested in the present study. Firstly, results from this study support the emerging trends of a previous work by Van Dongen (2005) for Narembeen and Dumbleyung sites. Secondly, Bell et al. (2010) reported that crop yields within 120 m of the drain showed a positive response to deep drainage at Dumbleyung and Beacon within 3-5 years after the deep drain was installed. The crop productivity trials at Beacon and Dumbleyung suggest that crop yields are restored to levels that are comparable to non-saline land and hence this would be reflected as increased NDVI for pixels in the zone of benefit. The present conclusions for Narembeen are also consistent with studies by Ali et al. (Ali et al., 2004; Ali et al., 2012) who demonstrated through fieldwork and modeling that at selected deep drainage sites decreases in groundwater levels occurred for distances up to 150 m from the drain and it is in this area where increased NDVI is expected. Limited change in NDVI at Morawa and Pithara sites is consistent with groundwater results which showed water levels remained within 1 m of the soil surface for these sites after deep drains were installed (Bell et al., 2010). Hence at these sites any changes in water levels following deep drainage were insufficient to prevent surface soil salinity from the evaporation of shallow saline groundwater (Nulsen

1981). The apparent increase in NDVI values at Pithara and Morawa sites following the installation of deep drainage may reflect alleviation of waterlogging in the root zone and improved plant growth but alleviation of salinity at this site in the long term seems unlikely given that the new water table depth is still < 2 m.

Changes in crop productivity were consistent with groundwater levels responding very quickly post-contruction of the deep drains. Sites with lowest or no effect on groundwater table did not experience consistent increase in crop productivity (Morawa and Pithara).

Five sites selected for this study were (except for Morawa) previously investigated by Van Dongen (2005). Some of the data investigated by Van Dongen were collected too soon after drainage to deduce clear results. As discussed above, Bell et al. (2010) reported that recovery of crop yields after deep drainage to levels comparable to those in non-salinised soil took 3-5 years. Hence any assessment of the improvement in NDVI within the 500 m buffer up to 5 years after installation of the drain may give inconclusive results. Therefore, a re-assessment of NDVI at the deep drainage sites of the present study may show more distinctive increases if assessed in 3-5 years when all the drains have been in effect for longer than 5 years. Nevertheless, the present study analysed data from a much longer time period before and after the drains were constructed than Van Dongen (2005). The benefit of additional data and expansion of the sampling framework over all data points within the whole 500 m buffer from the drain and addition of the Morawa site allowed for a more comprehensive analysis of deep drainage effects.

Unlike traditional field-based assessment (sampling) such as the site-specific crop productivity trials reported by Bell et al. (2010), the remote sensing approach used in this study provided an overview (census) of the whole study region and at each site over time. Like aerial photography, satellite images can be interpreted visually (using expert-designed interpretation keys), however digital image processing yields much more objective and repetitive results which can be tested quantitatively.

As in many previous studies, this study used free satellite data archives. The vegetation greenness in the form of NDVI provided robust comparisons among the years. NDVI can be correlated to indicators of land productivity, such as leaf area index, crop biomass and crop yield (Hodgson et al., 2004; Smith et al., 1995). Changes in NDVI values with distance from the drain can be related to degradation or remediation.

Masking to remove areas without crops removed a major source of variation in NDVI. The average NDVI was much higher (0.39-0.44) where cropping only occurs, compared to around 0.24 for areas excluding native vegetation and roads.

4.2. Additional approaches to assessing the zone of benefit

While the bulk of the data extraction in this study was pixel by pixel so that the entire data set of NDVI values within the 500 m buffer was sampled, there are alternative approaches that could be employed that decrease the computing power required to analyse the large datasets, to minimize the effects of geomorphology and geology on the efficacy of the drain and to minimize the variability in NDVI due to uncertainty about crop type or land use. Sampling of NDVI using transects (perpendicular or parallel to the drain) may be a simpler and faster approach, especially if field reference sites were established. Previous study by van Dongen (2005) analysed the time series of NDVI using a single line (transect) across the drain at Narembeen, the line being the spatial unit to extract NDVI data from the time series. The NDVI plot after drainage (2004) was implemented showed marked increase on both sides of the drain compared to before the drain. This approach also allows for tracking conditions for individual paddocks, which has the advantage that information on land use changes is more readily available (e.g. shift from samphire communities to grazing plants or a change in crop type from year to year). With the large variation in the soil types and crops grown along and across the drain, it may at times be difficult to average out the results and comment on the overall value of the drain. By sampling transects, one could evaluate at the paddock scale changes in NDVI with greater confidence in known crop histories.

If data on productivity/yield for individual paddocks were available, these figures could be related to the NDVI data over time at that paddock scale. Such yield data or even information on types of crops was not available for the large areas sampled over many years in this study. With yield monitors on harvesters now comparatively common in south-west Australia, it should be feasible to record crop yields along transect lines and to examine temporal patterns in crop production in response to the deep drain. Additional information on geology would also provide useful context (Salama et al., 2007). The amount of rainfall and the temperature regime would vary from year to year, thereby affecting growth rates of plants. Soil and crop types will vary within sites, and at times it was not possible to determine if the area was fallow or cropped and, therefore, included or excluded in the data extraction. Other factors could be playing an important role, such as soil type and condition, degree of salinisation and waterlogging, terrain slope, type of crops and their growth stage at the time of satellite data acquisition. Extent of waterlogging was not known, but it is likely to play an important role in plant growth (McFarlane et al., 1992b) and NDVI values (Lenney et al., 1996; Dwivedi and Sreenivas, 2002). An advantage of restricting the analysis to specific transects is that the influence of these variables can be removed or accounted for more explicitly.

Another approach would be to plot and examine the NDVI data for an upstream to downstream section, the assumption being that certain regions along the drain may be improving faster after the drainage is implemented than others due to variations in morphology and geology of the surrounding landscape. The Beacon site was used as an example of such an approach. No masking was applied to the data set before extraction, and data were extracted 50 m west of the drain line. The lowest values corresponded to the 1987 data set, the year with very low rainfall (240 mm). The post drainage data (2004) showed higher NDVI values in the upper reaches from the drain compared to the downstream section (Figure 6). This plot illustrates the potential for an alternative spatial sampling to analyse either all data points within the buffer or a series of transects across the drain. Depending on the site characteristics, either of these approaches could be used as a monitoring tool. Both transect orientations (perpendicular and parallel to the drain) would be useful to determine the spatial extent of the zone of benefit, which was the aim of the present study, while decreasing the sampling and analysis costs of examining the whole data set.

As discussed above, crop productivity trials at Beacon and other sites suggest that it takes 3-5 years following the drainage before crop yields are restored to levels that area comparable to non-saline land (Bell et al., 2010; George and Steiner, 2009; McFarlane and George, 1992). Hence, there may be merit in splitting post-drain images into those covering the recovery period of 3-5 years after drainage from those taken more than 5 years after drainage.

Insert Fig 6

4.3. Factors affecting zone of benefit

Ground slope and elevation are potentially confounding the effects of the deep drain. This can be attributed to the fact that drains are placed in lower elevations, since this is where salinisation often occurs first (Cox and Tetlow 2008), and a low elevation position should maximise the discharge of groundwater into deep drains. Consequently, adjusting for slope and elevation in the linear mixed effects model is important, and we note that the effect of distance from the drain is still significant after adjusting for slope and elevation. However, it is suggested that the slope variable only roughly captures contour as it is averaging over the entire pixel. Hence, the distance variable could be in part capturing a slope effect not adequately reflected by the slope variable. For instance, Cox and Tetlow (2008) concluded that the deep drain at Dumbleyung was effective in decreasing groundwater levels because of the continuous upslope gradient which increased discharge from the regional aquifer into the drain.

Apart from ground slope and elevation effects on discharge into drains, underlying geology may also affect groundwater discharge (e.g. Clarke et al., 2000). This factor was not accounted for in the present study.

While no cost-benefit analysis was attempted to quantify the benefit of recovery after drainage for agricultural production, it should be possible to undertake a determination with the data assembled for this project. A relationship between change in NDVI and increase in crop yield will be needed to estimate the value of additional grain produced. Continuation of such monitoring programs is important especially as climate change predictions indicate decline in rainfall for the region.

5. Conclusions

Satellite-derived greenness index for the pre- and post-drain spring months appears to be a useful indicator of the effectiveness of the deep drains in increasing plant greenness cover on areas previously affected by waterlogging and dryland salinity.

While it was not the primary aim of this project to conclude on the efficacy of the deep drains, analysis indicated that all sites benefitted from the implementation of the drains (but not all to the same extent).

One NDVI image per spring season was not adequate to track the absolute health of crops as there are potentially too many variables affecting the NDVI values. Masking out non-annual crop zones improved the usefulness of data on relative gains/losses of NDVI with distance from the drain.

Acknowledgements

This project was financially supported by Murdoch University and the Department of Water (Western Australia). We are also very thankful to the Remote Sensing Services of the Landgate (Western Australia) for access to satellite data and to Dr Richard George from the Department of Agriculture and Food WA for encouragement and comments on an earlier draft of this paper.

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Table 1. Summary of areas within 500 m buffers, areas masked and within 700-1000 m buffers of the deep drains.

Site	Area (ha) within 500 m buffer	Proportion of the 500 m buffer masked (%)	Area (ha) of the control (700 – 1000 m buffer)	Length (km) of drain
Morawa	831	71	385	6.6
Pithara	2415	28	470	13.4
Beacon	2357	29	403	20.8
Narembeen	1014	21	148	8.7
Dumbleyung	327	28	168	1.9

Table 2. Parameter estimates, test statistics and *p*-values for the linear mixed effect model for the five study sites. The model includes ground elevation, ground slope, and distance from the drain, site, whether or not the drain had been installed, and all possible interactions among the distance from the drain, site and whether or not the drain had been installed. Random effects were included for individual pixels.

		Coef.	Std. Err.	t	p-value
Intercept		-0.176	0.045	-3.905	<0.001
Distance		0.00005138	0.00000946	5.432	<0.001
Drain		0.12227008	0.00410468	29.788	<0.001
Site:					
	Dumbleyung	0.20291715	0.01366145	14.853	<0.001
	Morawa	0.31361891	0.01400558	22.392	<0.001
	Narembeen	0.24405407	0.00787588	30.988	<0.001
	Pithara	0.04203679	0.0090873	4.626	<0.001
Control		-0.03817778	0.00407938	-9.359	<0.001
Slope		0.01047326	0.00215573	4.858	<0.001
Elevation		0.00102222	0.00012283	8.322	<0.001
Interactions:					
Distance : Drain		0.00004514	0.0000089	5.071	<0.001
Distance : Site (Dumbleyung)		0.00002874	0.00001593	1.804	0.071
Distance : Site (Morawa)		-0.00012588	0.00001544	-8.154	<0.001

Distance : Site (Narembeen)	0.00004899	0.00001215	4.031	<0.001
Distance : Site (Pithara)	0.000047	0.00000953	4.931	<0.001
Drain : Site (Dumbleyung)	0.00470181	0.01102921	0.426	0.670
Drain : Site (Morawa)	-0.08473419	0.01299995	-6.518	<0.001
Drain : Site (Narembeen)	-0.08751658	0.00611621	-14.309	<0.001
Drain : Site (Pithara)	-0.03962975	0.00565686	-7.006	<0.001
Distance : Drain : Site (Dumbleyung)	-0.00006443	0.00001934	-3.332	<0.001
Distance : Drain : Site (Morawa)	-0.00003461	0.00001966	-1.761	0.078
Distance : Drain : Site (Narembeen)	-0.00008792	0.00001391	-6.318	<0.001
Distance : Drain : Site (Pithara)	-0.00012488	0.00001218	-10.255	<0.001

AIC: -52593.74 BIC: -52368.27

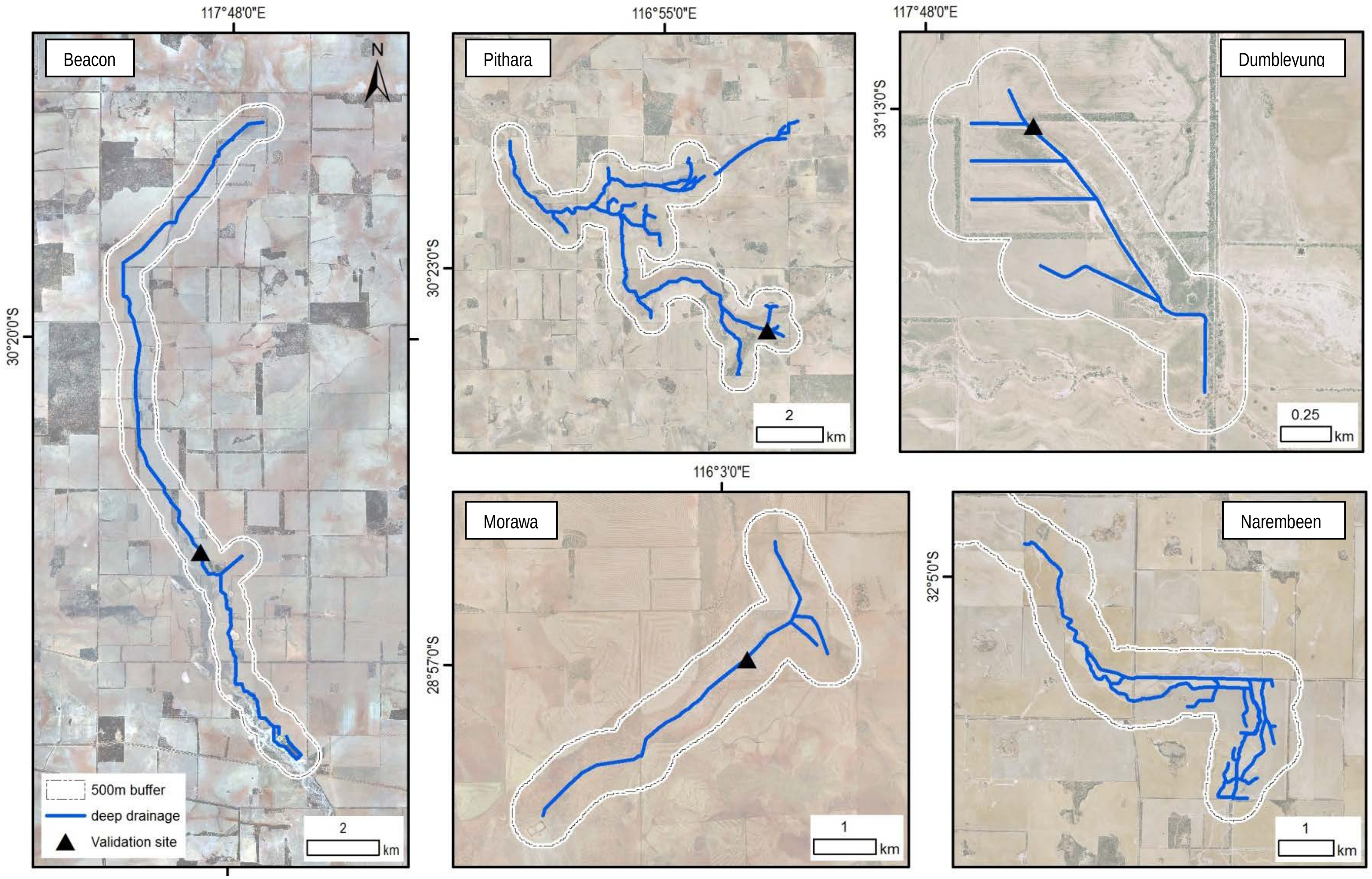

117°48'0"E
Beacon
N
30°20'0"S
500m buffer
deep drainage
Validation site
2
km
116°55'0"E
Pithara
30°23'0"S
2
km
117°48'0"E
Dumbleyung
33°13'0"S
0.25
km
116°3'0"E
Morawa
28°57'0"S
1
km
Narembeen
32°5'0"S
1
km

Figure 1.

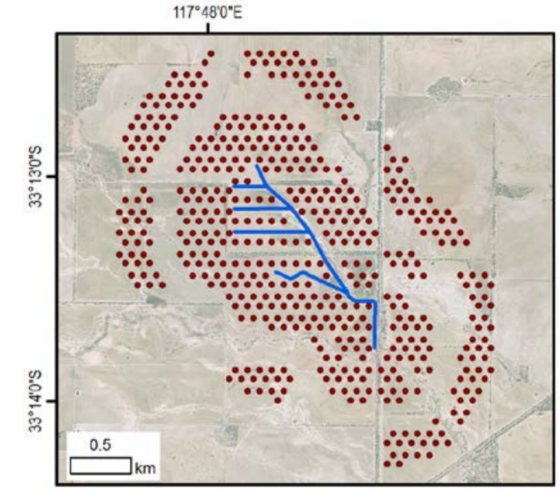


Figure 2.

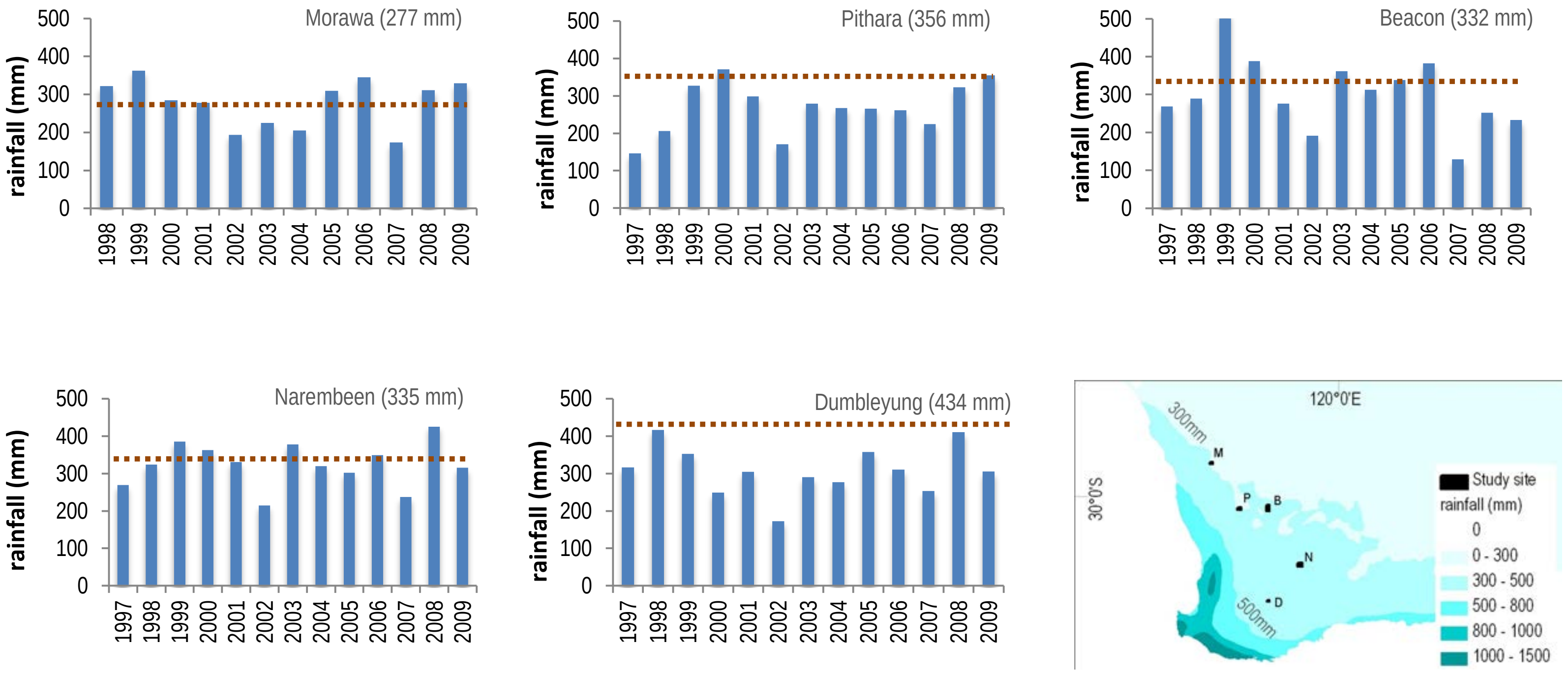

Morawa (277 mm)
Pithara (356 mm)
Beacon (332 mm)
Narembeen (335 mm)
Dumbleyung (434 mm)
rainfall (mm)
0
100
200
300
400
500
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
120°0'E
30°0'S
300mm
500mm
M
P
B
N
D
Study site
rainfall (mm)
0
0 - 300
300 - 500
500 - 800
800 - 1000
1000 - 1500

Figure 3.

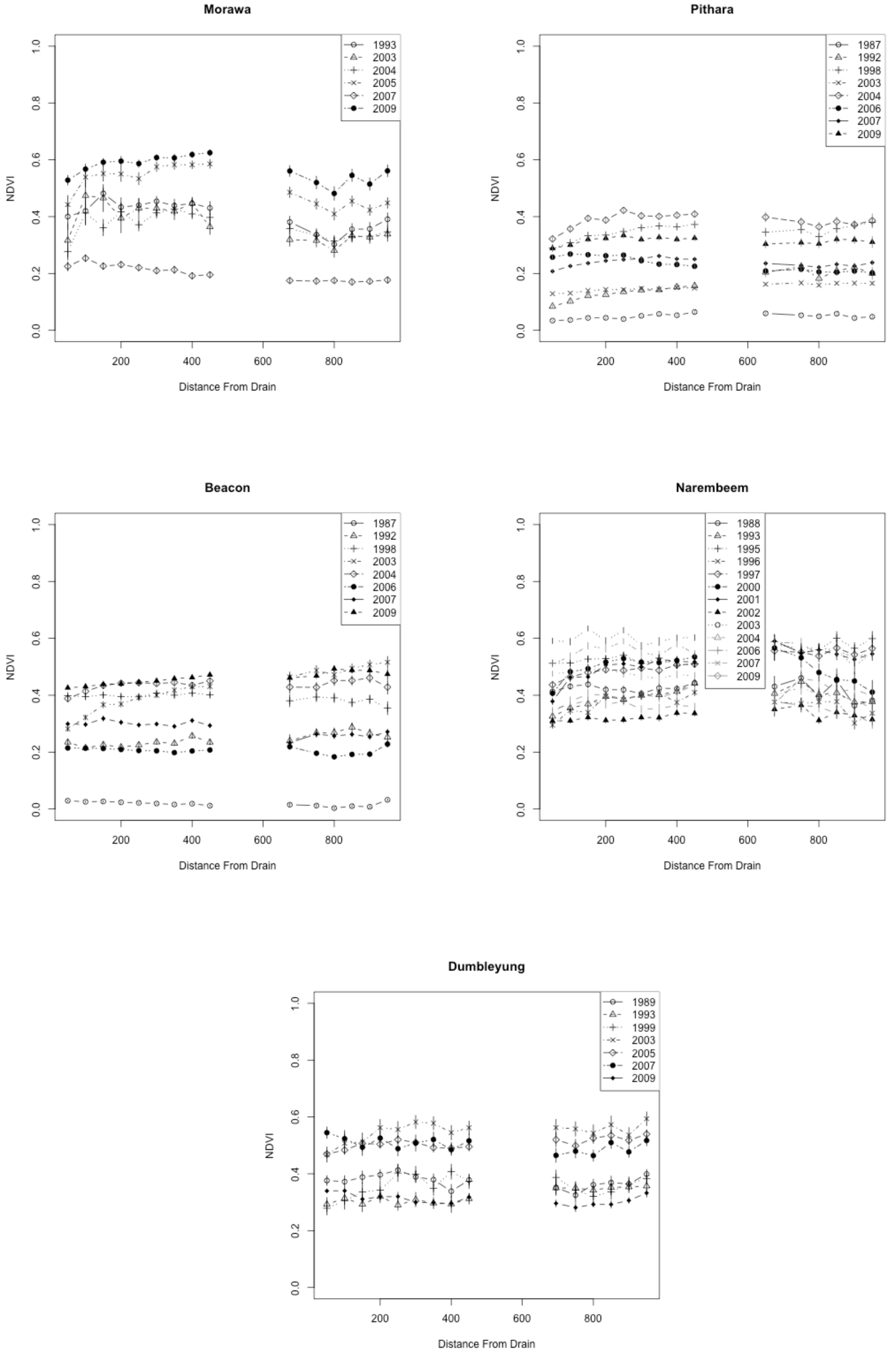
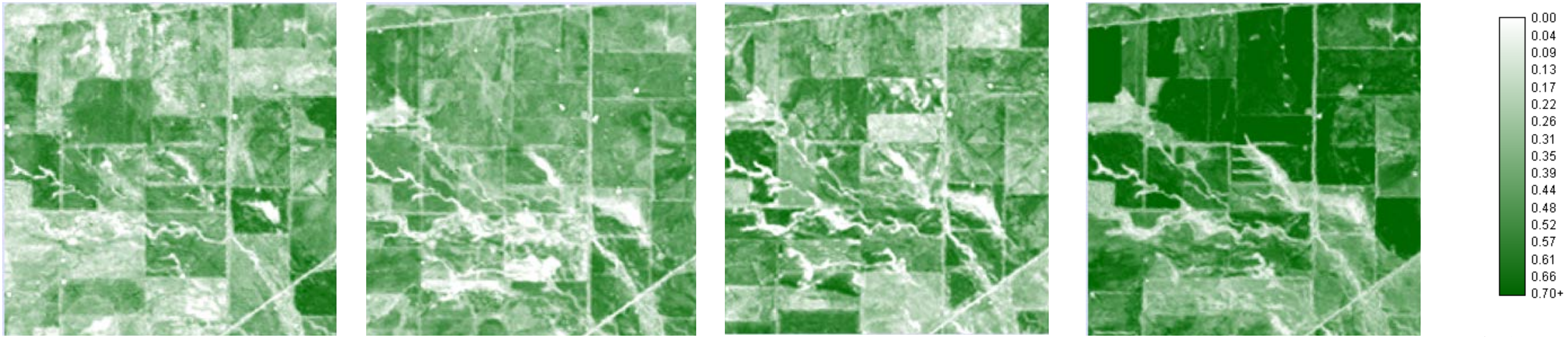

Morawa
1993
2003
2004
2005
2007
2009
Pithara
1987
1992
1998
2003
2004
2006
2007
2009
Beacon
1987
1992
1998
2003
2004
2006
2007
2009
Narembeem
1988
1993
1995
1996
1997
2000
2001
2002
2003
2004
2006
2007
2009
Dumbleyung
1989
1993
1999
2003
2005
2007
2009
NDVI
0.0
0.2
0.4
0.6
0.8
1.0
Distance From Drain
200
400
600
800

Figure 4.



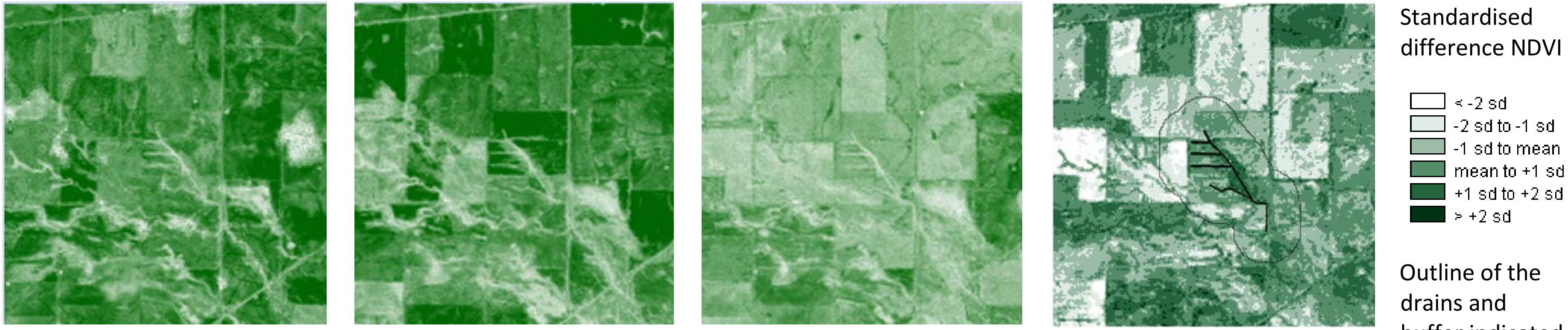
NDVI 1989 Aug

NDVI 1993 Sep

NDVI 1999 Aug

NDVI 2003 Sep

Scaled NDVI



Standardised difference NDVI

Outline of the drains and buffer indicated in dark grey

NDVI 2005 Jul

NDVI 2007 Aug

NDVI 2009 Aug

Standardised difference NDVI 2003-2007

Figure 5.

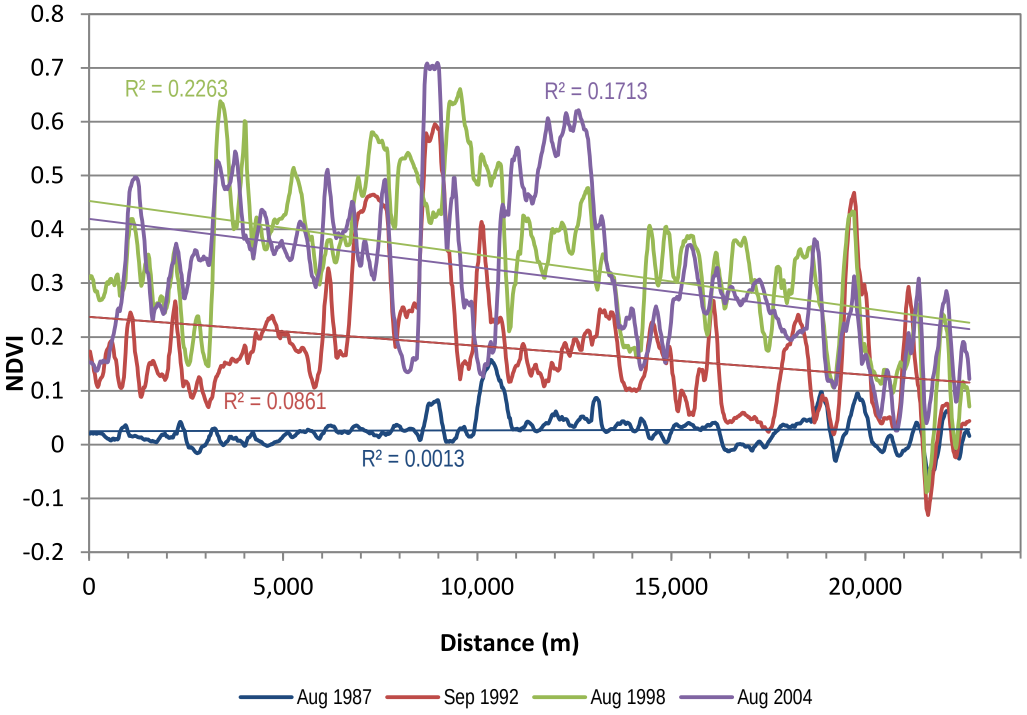

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
NDVI
0
5,000
10,000
15,000
20,000
Distance (m)
R² = 0.2263
R² = 0.1713
R² = 0.0861
R² = 0.0013
Aug 1987
Sep 1992
Aug 1998
Aug 2004

Figure 6.

Figure 1. Overview of location of the deep drainage (dark blue line) and the 500 m buffers (black line with white outline) at all sites. Field validation sites are marked with ▲. Note different scales of the individual maps. For simplicity, image masks are not show here. (Aerial photography sourced from the Department of Water).

Figure 2. Systematic subsampling routine based on a distance of 100 m between pixels, as illustrated for Dumbleyung. Drain location is shown in dark blue.

Figure 3. Annual rainfall (mm) at all deep drainage sites 1998-2009, with long-term average indicated by the dotted line (BoM 2012). Bottom right insert illustrates the long-term average rainfall with the key isohyets of 300 mm and 500 mm labeled and the five field sites depicted as black polygons, M- Morawa, P- Pithara, B- Beacon, N- Narembeen and D- Dumbleyung.

Figure 4. Plots of mean NDVI by distance from the drain for 50m blocks and by year for each of the five sites. Vertical bars are used to denote corresponding standard errors, and mean NDVI values corresponding to years following the installation of drains are denoted by solids symbols.

Figure 5. NDVI spring images for Dumbleyung. Values have been stretched to the range 0.0-0.7 and displayed using the NDVI colour palette, where the greener (darker) the image the higher the NDVI values. Deep drain was installed in December 2002, so the top four images represent data before the drain and the bottom three images (from the left) show vegetation response after the drain was installed. The bottom right image is a standardised difference image between NDVI for 2003-2007, with darker tone indicating areas of improvement. Average NDVI for 2003 (pre-drain) was 0.495 compared to an average of 0.502 in2007.

Figure 6. Illustration of spring NDVI values plotted as a function of distance from the start of the drain to its discharge, from pixels located in a transect 50m west of the drain, at Beacon site using spring data with no masking applied.