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Water table response to an experimental alley farming trial: dissecting the spatial and temporal structure of the data

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Abstract. Clearing vegetation for traditional agriculture diminishes native habitat and reduces plant transpiration, leading to increased groundwater recharge and onset of dryland salinization due to rising groundwater and mobilization of salt stores in the soil profile. This change in hydrology and salinity can also negatively affect biodiversity in many semiarid regions. Alternating native perennial tree belts with mono-species agriculture within the tree belt alleys is one possible system that can provide recharge control and recover some of the ecosystem services of degraded agricultural landscapes. To assess the effect of this agroforestry technique on groundwater levels, an alley farming trial was established in 1995, incorporating different combinations of belt width, alley width, and revegetation density. Transects of piezometers within each design have been monitored from October 1995 to January 2008.

The data set consisted of 70 piezometers monitored on 39 dates. Two trends were observed within the raw data: An increase in water table depth with time and an increase in the range of depths monitored at the site were clearly discernible. However, simple hydrograph analysis of the data has proved unsuccessful at distinguishing the effect of the tree belts on the water table morphology. The statistical techniques employed in this paper to show the effect of the experiment on the water table were variation partitioning, principal coordinates of neighbor matrices (PCNM), and canonical redundancy analysis (RDA). The environmental variables (alley farming design, distance of piezometer from the tree belt, and percentage vegetation cover including edge effect) explained 20–30% of the variation of the transformed and detrended data for the entire site. The spatial PCNM variables explained a further 20–30% of the variation. Partitioning of the site into a northern and southern block increased the proportion of explained variation for the plots in the northern block. The spatial PCNM variables and vegetation cover remained the most significant variables. The PCNM analysis revealed no spatial pattern that could be attributed to the trial. The high proportion of unexplained variation may be due to site variables that have not been considered in this study.

Key words: agroforestry; alley farming; principal coordinates of neighbor matrices; salinity; tree belt; variation partitioning; water logging; water table dynamics; Western Australia.

Introduction

Land use change is the principal cause of alteration to catchment water and nutrient balances (Ayyad 2003). A consequence of this change is deterioration of ecosystem health and biodiversity, leaving ecologically sensitive regions highly susceptible to extensive physical and biogeochemical land degradation (Cramer and Hobbs 2002, Ayyad 2003, Holmgren et al. 2006). Increasing demand on food production caused a rapid replacement of native vegetation by selected mono-species agriculture (Peck and Williamson 1987, Hatton et al. 2003). It was estimated that ~15% of the total land area of the world has undergone clearing of native vegetation due to demand for food production (Wild 2003). The extent and location of this clearing is highly variable; in the southwest of Western Australia, 87% of the agricultural lands are the result of clearing over the past 150 years (Froend et al. 1997). The replacement of native vegetation has been shown to cause extensive land degradation by prompting an increase in wind and water erosion (Pimentel and Kounang 1998), waterlogging (Hobbs 1993), and dryland salinity (Hatton 2001, Clarke et al. 2002).

The impacts of these processes is strongly linked to significantly different water use regimes and rooting depths between native vegetation and agricultural crop (Greenwood et al. 1985, Hatton et al. 2003). Both water logging and dryland salinity are a consequence of an

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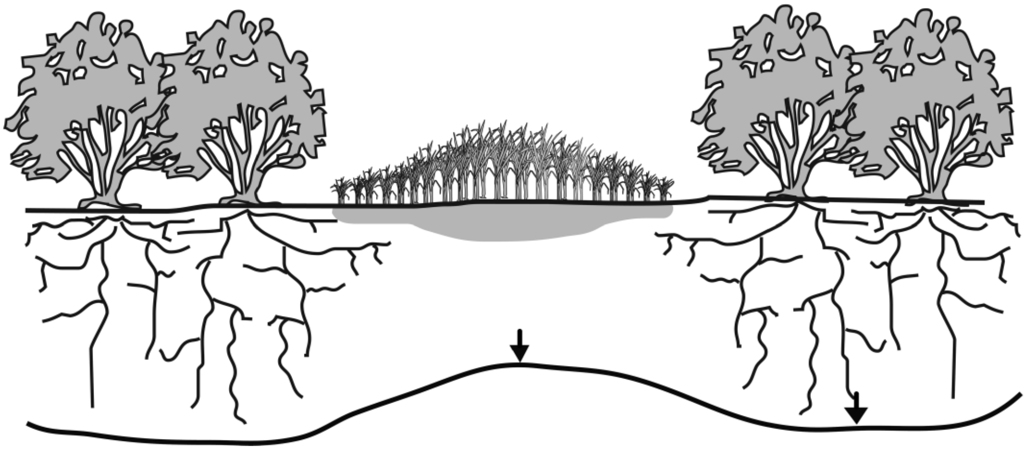

FIG. 1. One-dimensional conceptual diagram of water table response to tree belt. The line with arrows indicates the water table level.

increase in recharge due to a decrease in annual evapotranspiration by the agricultural crops (Hatton and Nulsen 1999, Hatton et al. 2003, Brown et al. 2005). The proliferation of dryland salinity in low-lying areas where the water table has risen and mobilized salt previously stored in the soil profile has a detrimental effect on agricultural crop yields, as well as on the health of native remnant vegetation; this has prompted the need for mitigation and remediation in affected areas (George et al. 1991, Salama et al. 1993).

Long-term control of a rising water table is achieved by increasing the interception of precipitation and use of groundwater. The most ecologically sensitive way to achieve this is by the introduction of vegetation species that have a capacity to intercept and use greater volumes of water, both from the water table and precipitation (Fig. 1). Native woody perennials have the capacity to achieve greater water use due to their ability to intercept large proportions of precipitation and their extensive root networks, which have access to groundwater on a perennial basis, thereby effectively engineering a return to the preclearing environmental conditions (Malajczuk et al. 1984, Hatton and Nulsen 1999, Cooper et al. 2005). However, the necessary proportion of land required to re-instigate hydrological equilibrium in the required manipulation of the water table is under some debate. Estimates of the proportion of revegetation required vary from 80% to 20% of the total catchment area depending on the author, which poses economic concerns for potential agricultural crop yields (George et al. 1997, Bartle 1999). As such, implementation of remediation strategies needs to be a compromise between the economics and logistics of the farming industry, environmental protection, and remediation. One approach to mitigation is to incorporate banded woody vegetation structures into traditional mono-species agriculture. The strategic placement of native perennial tree belts within the landscape (i.e., typically along topographic and groundwater contours) has the potential to provide both environmental and economic compensations. The capacity of alley farming or runoff agroforestry (alternate native perennial belts and cropped alleys) to maximize the use of rainfall by vegetation is best utilized in semiarid, rainfall-reliant agricultural areas (Kang et al. 1984, Lefroy and Stirzaker 1999, Droppelmann and Berliner 2003, Ogunlana et al. 2006).

Previous research on the use of deep-rooted native perennials has focused on (1) the relationship between water use and biomass output (Wildy et al. 2004, Cooper et al. 2005), (2) the interaction between trees and crops (Oliver et al. 2005, Ellis et al. 2006), and (3) the design and implementation of such systems (Lefroy and Stirzaker 1999, Connor 2004). The remedial effects of tree belts for water logging have already been established (Hodgson et al. 2002, Silberstein et al. 2002). Investigation of the positive environmental impacts suggests that banded vegetation structures (alleys) provide wind protection (Bird et al. 1994), increased pest and disease control, and food sources and habitat for native biota (Lefroy et al. 2005). They also control the depth of the water table (Morris and Thompson 1983, Eastham et al. 1993, Sudmeyer and Goodreid 2007) and produce timber, biofuels, carbon sequestration (Bartle et al. 2007), as well as other products (Eastham et al. 1993). Extensive research into various agroforestry techniques have been conducted within Australia (Hajkowicz and Young 2002, Hodgson et al. 2002). However, the limitations due to the financial constraints of large-scale experiments and the long-term monitoring required for adequate analysis have limited the establishment of such investigations.

This study aimed at investigating the effects of tree belts on the water table over a 12-year period. We hypothesized that the seasonal response in the water table beneath the belts would be dampened, while within the alleys (agricultural crops zones), a comparatively greater seasonal fluctuation would be observed. The

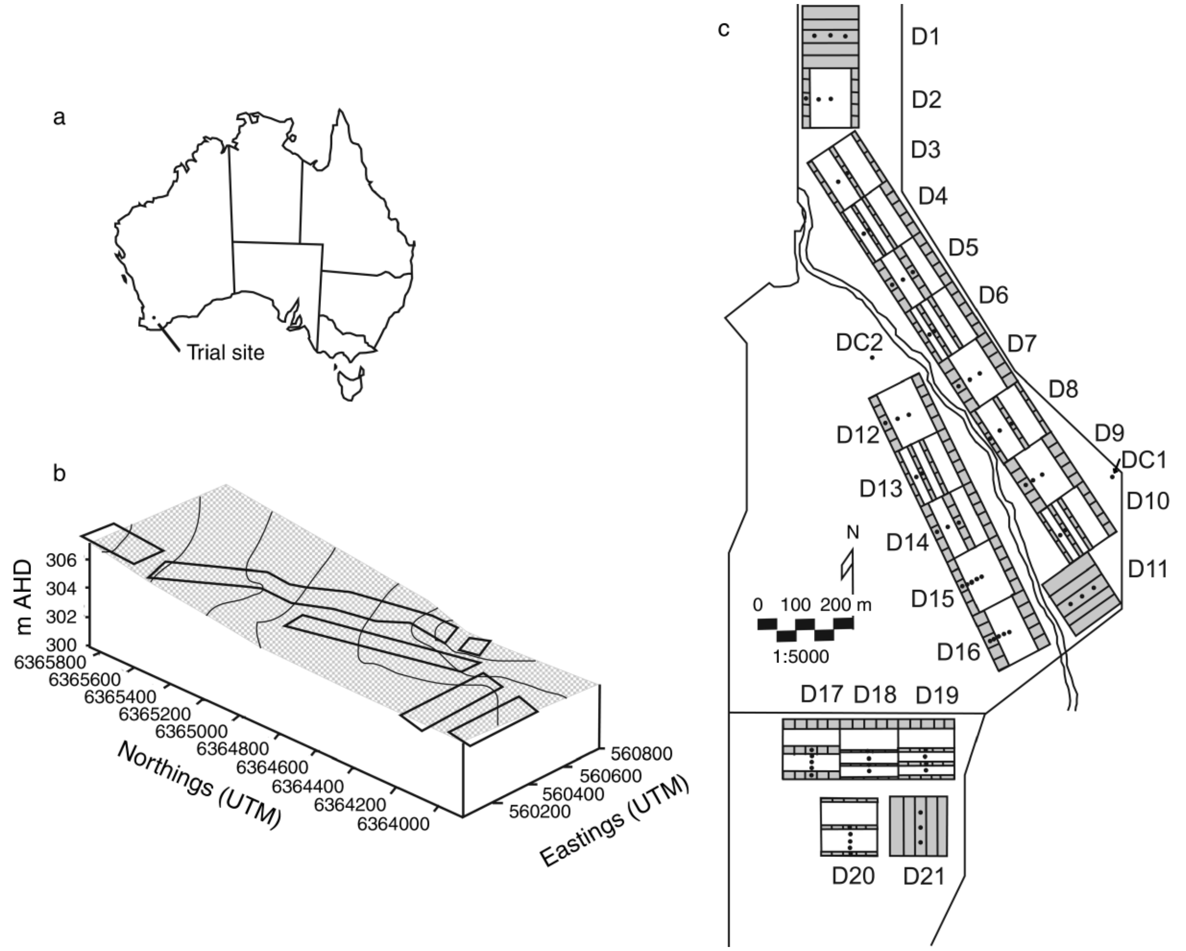

FIG. 2. Davenports trial site. (a) Location of the trial site in Western Australia. (b) Topography at the site (in meters above Australian height datum, AHD); black boxes outline the location of the trial plots, shown in Universal Transverse Mercator Northings and Eastings. (c) A plan of the trial site: the black boxes identify locations of the trial plots (D1–21) and control plots (DC1, DC2), and the small black dots show locations of the transects with piezometers (which measure changes in hydrostatic pressure).

additional complexity of tree root morphology would result in a dampening effect that would diminish as the distance from the tree belt increases. Therefore, to facilitate this investigation, an adequate monitoring network was required to fully assess the spatial impacts of the tree belts. A number of different combinations of belt widths and alley widths were created to further our knowledge of the effect of different alley farming designs. However, due to the spatial heterogeneity across the site, we did not anticipate an even response. So, to further gauge the spatial variability, plots containing all the different alley farming designs were distributed across the site. Determination of the optimal planting design for salinity mitigation would be defined by its impact on the water table. The best design would hopefully create a maximum draw-down >2 m BGL (below ground level; Nulsen 1981). Determination of this optimal design was necessary prior to widespread agroforestry application. Analysis of the simple hydrographic trend in the shallow piezometers throughout the site has proved unable to distinguish the effect of the different alley farming designs. We have therefore applied spatial statistical techniques in order to investigate design effects on the water table response.

METHODS

Site description

The trial site formed part of the Toolibin Alley Farming Trial and is located on privately owned farmland within the Toolibin Lake Natural Diversity Recovery Catchment, located 8 km north of Toolibin Lake in Western Australia (32°50′36″ S, 117°38′65″ E; Fig. 2). The site, which experiences a mediterranean climate (Table 1), consists of 21 plots, with three repetitions of seven different alley farming treatments designs (A to G in Table 2). The treatment designs (Table 2, Fig. 2) involved variations in alley width, belt width, and woody perennial species. Each belt contained

TABLE 1. Climate characteristics of the Davenports site, Toolibin Alley Farming Trial, Western Australia.

Period	Rainfall (mm)	Mean pan evaporation (mm/yr)	Temperature range (°C)	Rainfall (%)
Annual	370–420	1800		
Summer (Sep–Apr)			9–30	23–44
Winter (May–Aug)			5–20	60

three main woody perennial species: *Eucalyptus vegrandis*, *E. occidentalis*, and *Casuarina obesa*. Each plot contained a transect of shallow piezometers (instruments that measure changes in hydrostatic pressure), which extended from the center of the native tree belt to the center of the alley to assess the impact of the tree belt on the water table morphology through time. The number of piezometers per plot differed according to treatment designs; one of the replicate plots for each treatment design included intermediate bores. Control piezometers were also installed on the site to measure the open paddock water table responses. The piezometers were installed to a depth of 3.7 m. The lower 2 m of the piezometers were cased using slotted casing in order to focus water table monitoring on the superficial aquifer.

Data acquisition and calibration

Water table response in terms of static water level (SWL) depths, in meters below ground level (m BGL), was measured at various time intervals. Piezometers were monitored monthly for the first 1–2 years (to establish seasonal patterns); this was subsequently reduced (see Fig. 3). For the period October 1995 to January 2008, Davenports was sporadically monitored

TABLE 2. Detailed description of Toolibin Alley Farming Trial at the Davenports, Western Australia, organized by treatment design (A–G).

Treatment type and plot	Belt width (m)	Alley width (m)	Revegetation (%)	Cover plus edge (%)†	No. bores
A					
D7	32	74	30.2	33.02	3
D9	32	74	30.2	33.02	3
D16	32	74	30.2	33.02	5
B					
D2	18	102	15	17.50	3
D12	18	102	15	17.50	3
D15	18	102	15	17.50	5
C					
D5	18	42	30	40	3
D14	18	42	30	40	3
D17	18	42	30	40	5
D					
D3	11	56	16.4	25.37	3
D8	11	56	16.4	25.37	3
D20	11	56	16.4	25.37	5
E					
D6	11	22.5	32.8	41.79	2
D13	11	22.5	32.8	41.79	2
D19	11	22.5	32.8	41.79	4
F					
D4	4	27.5	12.7	22.22	2
D10	4	27.5	12.7	22.22	2
D18	4	27.5	12.7	22.22	4
G					
D1	138	0	100	100	3
D11	138	0	100	100	3
D21	138	0	100	100	3
Control					
DC1	···	···	0	···	1
DC2	···	···	0	···	1

Note: The two control plots, DC1 and DC2, represent 100% annual vegetation. They were not located within the influence of any of the tree belt treatments.

† Vegetation cover including edge effect (%).

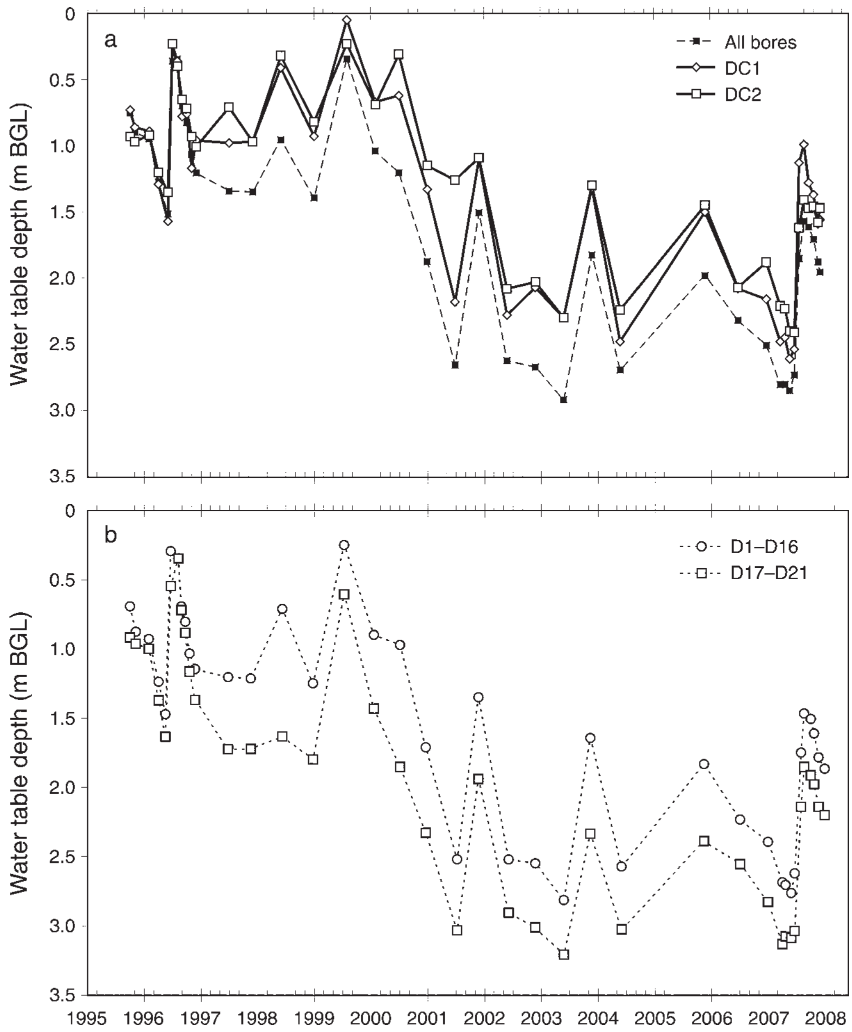

FIG. 3. (a) Hydrograph of the mean water table depth (meters below ground level, BGL) of all bores (solid squares) at the experiment site. Solid black lines and open symbols represent hydrographs of the two control piezometers (DC1 and DC2 in open paddock). (b) Hydrograph of the mean water table depth of those bores located in the northern block (D1–D16, circles) and southern block (D17–D21, squares) at the site. Data are for the years 1995–2008.

on 39 dates. A number of piezometers from each plot were selected for falling head slug test analysis to assess the hydraulic conductivity at the site (Hvorslev 1951, Bouwer and Rice 1976); a survey of the piezometers allowed meters above Australian height datum (m AHD) to be estimated using a local datum. The data set was rationalized, excluding piezometers where inconsistent monitoring, meaning insufficient data, was available for all dates. For piezometers where estimations were considered consistent and usable, the depth to the water table was approximated by assessing plot and treatment water table trends. The rationalized water table data set included 70 piezometers (rows) monitored on 39 dates (columns of the three data tables). Due to the relative nature of the water table, the condensed data set was transformed into three types: absolute, relative, and normalized. The absolute data set consisted of SWL data in m AHD (relative to height datum), which enabled analysis of the data while excluding any reference to the surface topography, i.e., relative to an underlying flat surface. The relative data set represented the SWL data in m BGL (relative to the ground surface), which is of greater use when accessing ecohydrological impacts of the water table; however, variations in surface topography were not considered. Therefore, the normalized data set was included, which removed any topographic variation in the ground level from the m BGL data set on a per plot basis using the survey data. This allowed the water table data to be expressed relative to a level ground surface. Data sets will be referred to as SWL_{abs}, SWL_{rel}, and SWL_{norm}, respectively.

Data transformation and detrending

The declining trend observed in the response data with time (Fig. 3) is primarily driven by rainfall decline

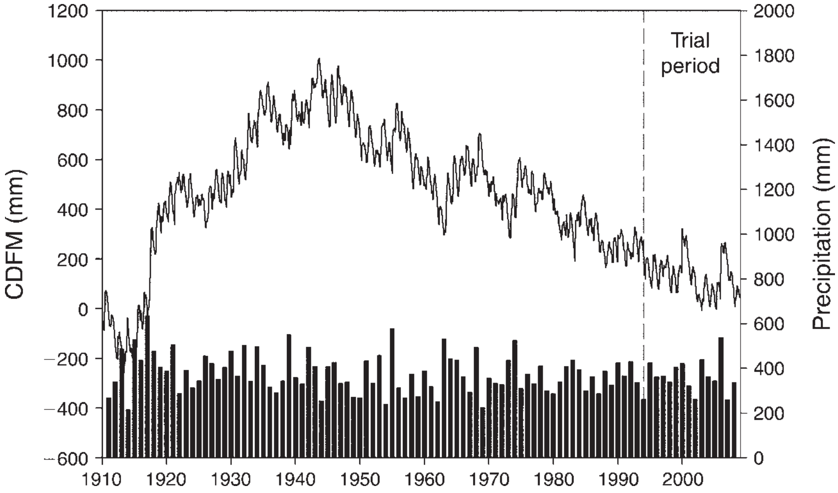

FIG. 4. Cumulative deviation from the mean (CDFM) monthly rainfall (line) and total annual rainfall (bars) recorded at Corrigin meteorological station, Western Australia, for the period from January 1911 to 2007. The dashed vertical line identifies the start of the experiment.

in the area (Smith et al. 2000, Indian Ocean Climate Initiative 2002, Hope et al. 2006). The Corrigin meteorological station (~50 km north of the study site) has the longest rainfall record near the study site; therefore, that station was used to illustrate the general trend in both monthly (CDFM) and annual rainfall depths from 1910 to 2008 (Fig. 4). An overall decline in winter rainfall (May–October) of 10–15% has been observed over the last 25–30 years compared to the preceding 50-year average (Indian Ocean Climate Initiative 2002). Trend analysis has been shown to have limited application for shallow-water table responses; the proximity of the land surface to the water table locally brings new water balance processes (evaporation and transpiration) into action (Ferdowsian et al. 2001). To overcome this added complexity, the data were Hellinger-transformed. The transformation consisted of expressing each datum as a proportion of the sum of all dates for each piezometer, which controls for any effect of the temporal rainfall trend, and taking the square root of the resulting value (Legendre and Gallagher 2001).

The Shapiro-Wilk test for normality was used to assess the distribution of the data for each of the data sets on each date (Shapiro and Wilk 1965). In most cases, the hypothesis of normality was rejected. The following statistical methods can be applied to both normal and non-normally distributed data.

Preliminary redundancy analyses (described in *Statistical analyses*) of the three Hellinger-transformed data sets on the x, y coordinates of the piezometers identified significant linear spatial trends across the trial site. The geographic coordinates significantly explained 14.6%, 17.2%, and 16.9% of the variation in the SWL_{abs}, SWL_{rel}, and SWL_{norm} data sets, respectively. This suggests the presence of a large-scale spatial structure, due, for example, to the distribution of rainfall and the basement structure, broader than the extent of the sampling area, and therefore impossible to analyze within the trial. In order to remove these influences, the data were spatially detrended by computing the residuals of a linear model of each column of the data tables on the site coordinates, prior to further analyses (Legendre and Legendre 1998).

Statistical analyses

The use of techniques commonly applied to studies in the field of community ecology has been shown to be effective for the assessment of spatial relationships within other fields (Bellier et al. 2007). The statistical techniques utilized in this study are described in the following sections.

Principal coordinates of neighbor matrices

We can safely hypothesize that the spatial structures found in the field data are multi-scale, resulting from a combination of induced spatial dependence (i.e., the response variables are spatially structured because of the spatial structure in influencing environmental variable) and spatial autocorrelation resulting from the spatial dynamics of the response variables themselves (Legendre and Legendre 1998). Multi-scale spatial modeling was carried out in two steps. The first step consisted of using the geographic coordinates of the 70 piezometers to create a set of variables that represent a spectral decomposition of the spatial relationships among the 70 points. These variables are called principal coordinates of neighbor matrices (PCNM) eigenfunctions. They basically model the spatial relationships among the points at all scales that can be perceived by the sampling design. Their construction has been described in recent papers (Borcard and Legendre 2002, Borcard et al.

TABLE 3. Variables included in the statistical analyses.

Variable or matrix	Code	Units	Explanation
Treatment design	TreatDes	letter	related to the belt and alley width (see Table 2), nominal variable (factor)
Distance of bore from belt	Dist	m	location of bore in relation to the edge of the tree belt
Vegetation cover including edge effect	VegCov	%	the percentage of revegetation including 3-m edge effect for each plot or subsection where TreatDes did not extend across the entire plot; see Fig. 2
Principal coordinates of neighbor matrices eigenfunctions	PCNM	number	variables used to model the spatial relationships among the bore locations across the site

2004). The second step consisted in using these eigenfunctions as explanatory variables of the piezometer water table data in a form of multivariate regression called canonical redundancy analysis. PCNM analysis carried out in that way has proven a highly efficient technique to describe the multi-scale spatial structures of multivariate response data (Dray et al. 2006).

The PCNM eigenfunctions modeling positive spatial autocorrelation (i.e., those that had Moran's I statistics larger than the expected value, $E(I)$) were identified; only those were kept for the next step since negative autocorrelation does not correspond to processes of interest in the present study, as described at the beginning of the previous paragraph. A forward selection procedure implementing a permutation test was applied to those PCNM variables to determine which ones had a significant relationship with the response data. The significant PCNMs were then incorporated as explanatory variables in canonical redundancy analysis and variation partitioning, described in the next section, to describe the spatial structures present in data observed at the trial site.

Variation partitioning

The technique of variation partitioning determines how much of the variation of a response data table is explained by linear models of two or more sets of explanatory variables (Legendre and Legendre 1998). We studied how much of the spatial variation in the SWL data can be explained by the treatments and other intervening variables. The explanatory data consist of four variables or tables: X_1, the treatment types; X_2, the distance of piezometer from tree belt; X_3, the percentage vegetation cover per plot (with the inclusion of a 3-m belt width extension due to interaction effect between tree belt and alley, as in edge effect, see Wildy et al. 2003); and X_4, the significant PCNMs (Table 3). The adjusted R^2 (R^2_a) statistic was used to assess the proportion of the response variation explained by each explanatory data set and their combinations. The R^2_a provides unbiased estimates of the explained variation (Peres-Neto et al. 2006). Variation partitioning was carried out using the "varpart" function of the "vegan" R-language library (Oksanen et al. 2008, R Development Core Team 2008); in that function, the variation explained by each explanatory data table and their combinations is assessed by RDA.

Canonical redundancy analysis (RDA)

Canonical redundancy analysis (RDA) was used to assess how much of the variation of a matrix of response variables, containing the values of a SWL variable from different bores (rows) and at different times (columns), was explained by a set of explanatory variables, and obtain a P value for the relationship. If the response data were univariate, RDA would simply be multiple regression. The influence and significance of the independent explanatory variables was measured by the canonical R^2 and tested by permutation; 10 000 permutation of residuals of the null model were performed in each test (Anderson and Legendre 1999). The P value of the test of significance is obtained by comparing the reference (unpermuted) value of the F statistic derived from the canonical R^2 to the sampling distribution of F obtained by permuting at random the rows of the response matrix. Permutation tests of significance have correct levels of Type I error (and are thus valid) for normal, as well as for extremely non-normal data (Legendre and Legendre 1998, Anderson and Legendre 1999). Partial canonical analysis allows one to determine the partial explanation and significance provided by each variable or group of variables in the presence of a matrix of covariables containing other explanatory variables. The spatial correlation pattern modeled by the PCNM variables is of importance and can be examined individually or for groups of PCNMs. A partial RDA and permutation test of all the selected PCNM variables, controlling for the effects of the environmental variables, assesses the exclusive influence of the PCNMs; it may display spatial patterns related to as yet unmeasured explanatory variables. The canonical axes resulting from that analysis can be plotted on maps. These axes are linear combinations of the spatial PCNM variables while controlling for the environmental variables used as covariables in the analysis. The eigenvalues measure the variance of the observations along the canonical axes (Legendre and Legendre 1998). The RDA and tests of significance were carried out using the "rda" and "anova.cca" functions of the "vegan" library (Oksanen et al. 2008).

RESULTS

Entire site

The PCNM analysis for the trial site produced 32 spatial autocorrelations for the truncation distance of

TABLE 4. Spatial PCNM variables retained by forward selection ($\alpha = 5\%$) for three data sets (absolute, relative, and normalized static water level response, SWL) and cumulative R_a^2 values for the entire site and the northern and southern blocks.

	Entire site		Northern block D1–D16		Southern block D17–D21	
Data set	PCNM rank	Cumulative R_a^2	PCNM rank	Cumulative R_a^2	PCNM rank	Cumulative R_a^2
SWL_{abs}						
	8	0.072	3	0.122	1	0.133
	19	0.102	8	0.218	2	0.248
	9	0.128	21	0.282		
	5	0.153	6	0.332		
	6	0.178	7	0.381		
	4	0.203	4	0.421		
			9	0.453		
			1	0.474		
			17	0.497		
SWL_{rel}						
	6	0.044	3	0.117	1	0.148
	7	0.08	8	0.202	2	0.221
	8	0.114	6	0.283		
	4	0.142	17	0.323		
	5	0.168	9	0.364		
	2	0.188	7	0.405		
	9	0.208	4	0.443		
	19	0.227	21	0.469		
	10	0.244	10	0.486		
	3	0.26	1	0.503		
SWL_{norm}						
	2	0.104	3	0.093	1	0.19
	1	0.203	6	0.176		
	8	0.237	8	0.256		
	3	0.271	9	0.308		
	7	0.299	1	0.347		
	4	0.325	2	0.381		
	6	0.347	17	0.413		
	19	0.364	7	0.443		
	5	0.378	4	0.474		
			21	0.497		

Notes: The northern block includes control plots. The adjusted R^2 (R_a^2) provides unbiased estimates of the explained variation.

316.7 m (Table 4). The number, rank, and scale of the PCNM variables selected by forward selection varied among the three detrended data sets implying that, although the spatial and temporal trends within the data have been reduced, variability between the data sets still exists. The largest portion of variation explained by the PCNMs was found in the SWL_{norm} data. The ranking of the PCNM variables provides an insight into the scales of variability across the site since the first PCNM variables model broad-scaled patterns and the last, fine-scaled patterns. Most notable are the differences in the influences of broad and fine scales among the data sets.

The impact of the variables included in the variation partitioning can clearly be seen in Table 5. There remains a large portion of unexplained variation across all three data sets; the values range from 0.46 to 0.63 R_a^2. The largest fraction of explained variation is always modeled by the PCNMs (0.20 to 0.38 alone, 0.19 to 0.31 when considering covariables); it is statistically significant in all data sets. Among the environmental variables, vegetation cover has the highest R_a^2 (0.14 to 0.34 alone, 0.001 to 0.056 when considering covariables). Treatment design and distance from tree belt remain consistently low and are not statistically significant across all data sets. The impact attributed to the variable treatment design is related to the width of the tree belt and alley; intrinsic to this is the percentage of revegetation (belt width/(alley width + belt width)). The consistently low R_a^2 of the response data explained by this variable indicates that the overall impact of treatment design is not as important as vegetation cover. Similarly, distance from tree belt only has a small R_a^2; this suggests that the response expected from the conceptual model had not been achieved and that the area of influence by the trees is wider than expected, possibly due to the greater than anticipated lateral extent of tree roots. The influence of topography can be observed in the increase in explained variation when the SWL_{abs} and SWL_{rel} data sets are compared; the rise in R_a^2 is best observed for the vegetation cover (0.136 for SWL_{abs} to 0.205 for SWL_{rel}) and PCNM variables (0.303 for SWL_{abs} to 0.261 for SWL_{rel}) (Table 5). The variation in the results among the data sets indicates that, although the topography at the site is relatively flat, it accounts for 10% of the variation of the data. The SWL_{norm} data set has the lowest residual variation (0.465) of all three data sets (0.637 for SWL_{abs} and 0.539 for SWL_{rel}) reaffirming that site topography has an

TABLE 5. Results of variation partitioning (adjusted R^2, R_a^2) across the entire site and the northern and southern blocks for the three response data sets.

Variable	Entire site			Northern block D1–D16		
	SWL_{abs}	SWL_{rel}	SWL_{norm}	SWL_{abs}	SWL_{rel}	SWL_{norm}
TreatDes [aeghklno]	0.068	0.092	0.081	0.125	0.129	0.091
Dist [befiklmo]	0.051	0.073	0.093	0.067	0.08	0.083
VegCov [cfgjlmno]	0.136	0.205	0.166	0.264	0.344	0.287
PCNM [dhijkmno]	0.203	0.261	0.378	0.497	0.503	0.497
[a]	0.006**	0.020*	0.016*	0.019†	0.014	0.019*
[b]	0.020***	0.029**	0.032**	0.028†	0.015	0.026**
[c]	0.044***	0.038**	0.029**	0.056	0.049**	0.041***
[d]	0.191***	0.220***	0.311***	0.282†	0.203***	0.271***
[e]	−0.004	−0.005	−0.011	−0.003	−0.005	−0.009
[f]	0.048	0.042	0.048	0.01	0.016	0.026
[g]	0.029	0.045	0.032	−0.004	−0.002	−0.005
[h]	0.005	−0.004	0.007	0.009	0.008	0.001
[i]	0.01	−0.001	0.016	0.000	0.009	−0.008
[j]	0.01	0.039	0.022	0.05	0.106	0.086
[k]	−0.001	−0.001	−0.003	−0.003	−0.002	0.003
[l]	0.018	0.033	0.011	−0.006	−0.003	−0.005
[m]	−0.027	0.003	−0.004	0.045	0.06	0.055
[n]	0.028	0.031	0.024	0.118	0.128	0.093
[o]	−0.013	−0.026	0.004	−0.004	−0.01	−0.005
[p] = residual of the column	0.637	0.539	0.465	0.404	0.414	0.41

Notes: The explanatory variables included the treatment design (TreatDes), the distance of the bores from tree belt (Dist), the vegetation cover (VegCov), and the spatial PCNM variables. The main fractions [a] to [d] were tested for significance by partial canonical analysis. Fraction names correspond to Fig. 5. Negative R_a^2 values are interpreted as zeros since the corresponding effects are less than those of random numbers with normal distribution.

† Highly significant (***) when VegCov is excluded from RDA.

* $P < 0.5$, ** $P < 0.01$, *** $P < 0.001$.

influence, which along with hydraulic gradients, will control the depth of the water table.

Much of the variation is explained by the environmental variables. Treatment design, distance of piezometer from tree belt, and vegetation cover including edge effect are in intersection with each other; the fraction of explained variation attributed to each independently ([a], [b], [c]) is only minor (Table 5). These intersections display variation that are explained jointly, by two or more data sets, they do not equate to an interaction between the variables, it is necessary to identify causal links by testing specific hypotheses (Borcard et al. 2004). The fraction intersecting the two variables, treatment design and distance from tree belt (fraction [e + k + o + l] in Fig. 5), remain negative for all data sets. This response indicates that the two variables together explain the response data better than the sum of the individual effects of the variables (Legendre and Legendre 1998). When assessed in combination (as one grouped variable), their significance remains high for all data sets as opposed to a reduction in the levels of explained variation when separated. Though fraction of explained variation remained unaltered compared to individual assessment, this would suggest that these two variables may best be assessed in combination.

The response observed by mapping the first canonical axis of the PCNM variables across the three response data sets (Fig. 6a–c) varies considerably. The variation in the magnitude of the response is markedly different when comparing the data sets. Variability in the magnitude of the pattern across the site appears much more pronounced in the SWL_{abs} data, for both the first and second canonical axes (Fig. 6d–f). This implies a greater influence of fine-scale spatial structures, as opposed to SWL_{norm}, which appears to be dominated by a broader pattern. The portion of variation represented by Fig. 6 suggests that the southern plots respond in a significantly different way to those in the northern portion of the site. An RDA of the three response data sets by all environmental variables (treatment design, distance from tree belt, and vegetation cover) was conducted for the entire site to assess the impacts of those variables on the water table data. The

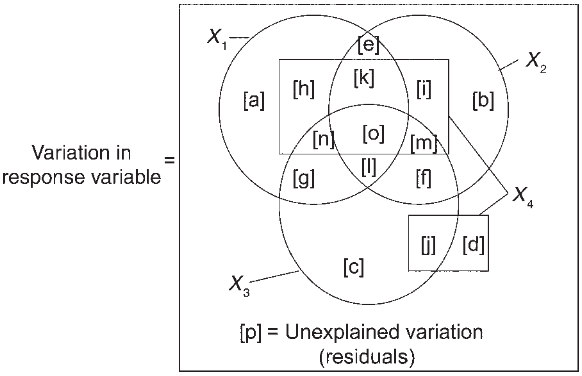

FIG. 5. Venn diagram representing partitioning the variation of a response variable or data table among four sets of explanatory (environmental and spatial) variables (X_1, X_2, X_3, X_4). The rectangles represent 100% of the variation in the response variable (Legendre 1993).

TABLE 5. Extended.

Southern block D17–D21		
SWL_{abs}	SWL_{rel}	SWL_{norm}
0.062	0.066	0.087
0.016	0.034	0.027
0.106	0.153	0.182
0.248	0.221	0.19
0.018	−0.001	0.001
0.052*	0.04	0.058
0.001	0.031	0.027
0.140**	0.100*	0.054
−0.011	−0.005	−0.01
−0.001	0.000	0.004
0.011	0.012	0.013
−0.003	−0.001	−0.001
0.016	0.018	−0.001
0.063	0.06	0.072
−0.003	−0.003	0.000
−0.003	0.004	0.001
−0.017	−0.013	−0.017
0.07	0.068	0.09
−0.018	−0.007	−0.007
0.685	0.699	0.717

response of a number of the plots appears to correspond well to the conceptual model (Fig. 1). Plots D3, D5, D14, D15, and D16 (Figs. 2 and 6) clearly and consistently identify the location of the tree belt as having a positive magnitude and those piezometers within the alley as negative. This clear delineation is also identified in the response of the 100% revegetation plots (D1 and D11) and the control piezometers. PCNM 19 (fine-scale) retained by all data sets (Table 4) clearly separates the trial site into two sections by the difference in magnitude across the site (Fig. 7). The greater magnitude exhibited by plots D17–D21 from the mean for PCNM 19 compared with the remaining plots prompted the subdivision of the site. This is corroborated by a Levene's test for homogeneity of variance of the normalized SWL_{rel} data (Fig. 8) organized by general soil types at the site: sandy soil (D5), clayey sand-dominated soil (D1 to D4 and D6 to D11), and clay rich soil (D17 to D21) ($F = 61.9$, $P < 0.001$).

Site separation

The partitioning of the site into plots D1–D16 (northern block) and D17–D21 (southern block) allowed us to reduce the truncation distances to 194.7 m and 156.1 m, respectively, thus allowing finer-scale spatial patterns to be detected. These separate analyses produced 29 and 11 PCNMs with positive eigenvalues, respectively. PCNMs with the same identification number are not the same in the three columns of Table 4. The proportion of variation explained by the PCNM variables increases for the northern block (0.497 to 0.503 alone, 0.203 to 0.271 when considering covariables) for all data sets compared to results for the entire site; whereas, this is not the case for the southern block (Tables 4 and 5).

The distribution of the significant PCNM variables for the northern block indicates the dominance of broad-scale patterns across the site, similar to the response for the entire site. This is corroborated by the results of the separate variation partitionings of the northern and southern blocks (Table 4). PCNM 3 is selected first in all three data sets because it has the highest R_a^2 (Table 4 and Fig. 9) and clearly displays a sine-shaped pattern within the paddock, describing the relationship of those plots in the north and south of the site, in plots D1 and D11 (100% revegetation). Equivalent fine-scale patterns are manifest in the selection of PCNM 21, which coincides with a narrow layer of coarse sand, ~1 m deep, associated with an old fence line in the paddock (W. O'Sullivan, *personal communication*). Variation partitioning of the northern block indicates that the influence of the PCNMs remains consistently high when compared to the other explanatory variables (Table 5). However, only for the SWL_{norm} data set for the northern block do all explanatory variables remain significant. In Table 5, fractions [h] and [i] are very close to 0 for the northern block. Fraction [j] is a bit larger (intersection of vegetation cover [VegCov] with PCNM, with R_a^2 ranging from 0.050 to 0.106); this reflects the presence of correlations between the spatial structure and vegetation cover. For the northern block, a greater amount of the variation in the data is explained (residual R_a^2 ranges between 0.404 and 0.414 in Table 5), though for the southern block the residual is higher than for the whole site (residual R_a^2 ranges from 0.685 to 0.717).

The first canonical axes of the PCNMs for the SWL_{rel} and SWL_{norm} data sets of the northern block, controlling for the environmental variables, are positively correlated (R^2 of 0.69). A similar correlation is also calculated for the first canonical axes of the PCNMs for SWL_{abs} and SWL_{norm} (R^2 of 0.65). No correlation is present between SWL_{abs} and SWL_{norm} for either the first or second canonical axis. An inverse correlation is observed between the second canonical axes for SWL_{rel} and SWL_{norm} (R^2 of 0.51). Within-block variability in spatial pattern and magnitude is displayed by plots D5, D7, D12, and D16 (Fig. 10a–c). The response within the remaining plots is fairly uniform in magnitude and value. This suggests that those plots displaying differences may reflect elements of the trial not assessed in this study, or as yet unrecorded environmental characteristics. The difference in the response in the control piezometers for the northern block, in the SWL_{abs} and SWL_{rel} data sets, can also be observed in Fig. 10d–f. Within-treatment spatial patterns are present for the second canonical axis specifically for SWL_{abs} and SWL_{rel} (Fig. 10a, b). However, no consistent response can be identified with regard to location of the piezometers (belt or alley) within and between the three data sets. No significant relationships were observed between the environmental variables and the response

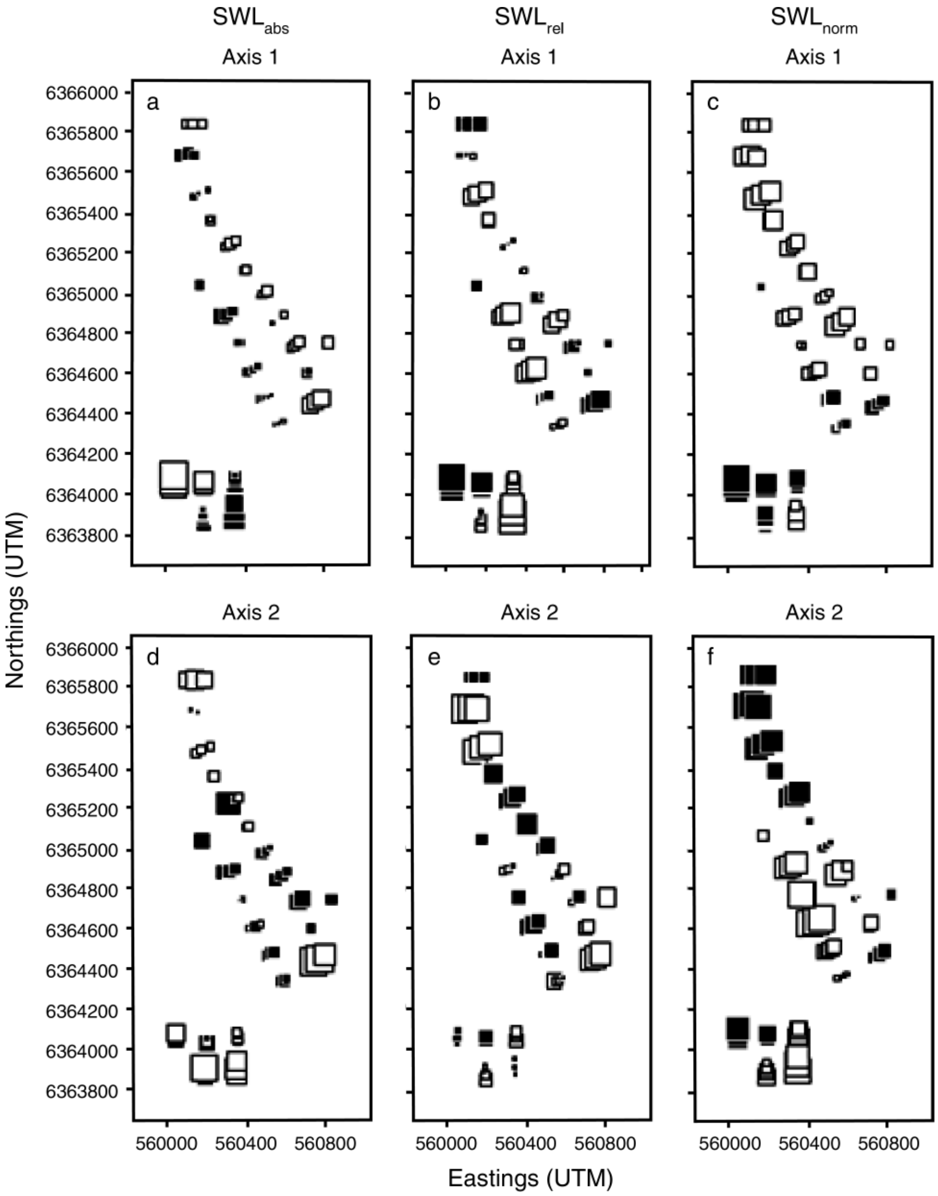

FIG. 6. Bubble maps of the (a–c) first and (d–f) second canonical axes of the partial canonical redundancy analysis (RDA) values of the Hellinger-transformed detrended static water level (SWL) data, where panels (a) and (d) are SWL_{abs} (absolute data set), panels (b) and (e) are SWL_{rel}, and panels (c) and (f) are SWL_{norm}, explained by the significant principal coordinates of neighbor matrices (PCNM) variables, with the three environmental variables (treatment, distance from tree belt, and vegetation cover [VegCov]) as covariables. Each pattern represents a portion of the variation explained by the PCNM variables; adjusted R_a^2 is (a) 12.7%, (b) 11.5%, and (c) 20.9%; R^2 is (d) 28.6%, (e) 8.7%, and (f) 6.0%. Solid squares represent positive values, and open squares represent negative values. The sizes of the squares are proportional to the mapped values.

data for the southern block; only the PCNM variables were significantly related to the response data (Table 4).

DISCUSSION

The statistical approach chosen to analyze the long-term data set is widely applied in the field of community ecology (Legendre and Gallagher 2001, Borcard et al. 2004). It has not been applied to a similar study in the field of hydrology and agroforestry. A comparative study of geostatistics and principal coordinates of neighbor matrices has shown that similar spatial patterns can be obtained by both methods (Bellier et al. 2007).

Implications of environmental trial variables

The current study indicates that, though treatment and distance from tree belt significantly explain a small proportion of the variation in the observed water table

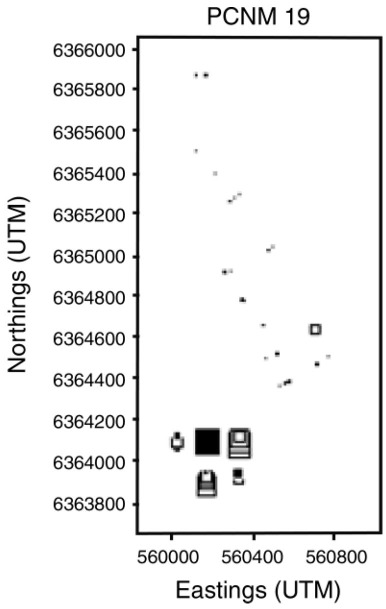

FIG. 7. Bubble maps of PCNM 19 obtained from the regular design of piezometers at the trial site. See Fig. 6 legend for explanation of symbols.

response, they do not display the causal impact identified in previous studies (Nulsen et al. 1986, Robinson et al. 2006) and expected. When fractions [a], [b], and [c] are compared, the greater proportion of variation is explained by vegetation cover. The influence of vegetation cover indicates the importance of the percentage of revegetation considered and the associated edge effect in the design of an alley farming system. The most effective form of revegetation for the control of water table depth would therefore be those with multiple narrow belts (single trees), which will increase the effective percentage of vegetation cover due to the edge effect. The intersection of vegetation cover with treatment and distance from tree belt (fractions [g], [f], and [l]; see Fig. 5) may not directly relate to an interaction; however, this can be implied. Extensive experimentation has been undertaken in the Western Australian agricultural zone of the impacts of tree belts and implications for controlling recharge, corroborating the conceptual model for revegetation with perennial woody belts (Ellis et al. 2005).

The lateral spread of the belt root zone results in competition between the perennial tree belts and the vegetation in the neighboring alley, a competition generally won by the tree belt (White et al. 2002, Oliver et al. 2005). It is this impact that may account for the low value of explained variation for distance from tree belt. This spread of roots has been known to occur to distances of 20 m from the trunk (Zohar 1985, Ellis et al. 2005), and would result in an general increase in water table depth across the plot, not just beneath the belt. This spread of roots could be >20 m for many of these species (Canadell et al. 1996), and root infiltration of the piezometers was observed during sampling for this study at up to 15 m from belts. Those treatments with the greatest alley width (A and B) would, however, be expected to display a response in the water table similar to that shown in Fig. 1. The lack of such a response may be due to the design of the trial. Of the six plots of treatments A and B, only two (D12 and D16) are placed to have minimal interference (greatest

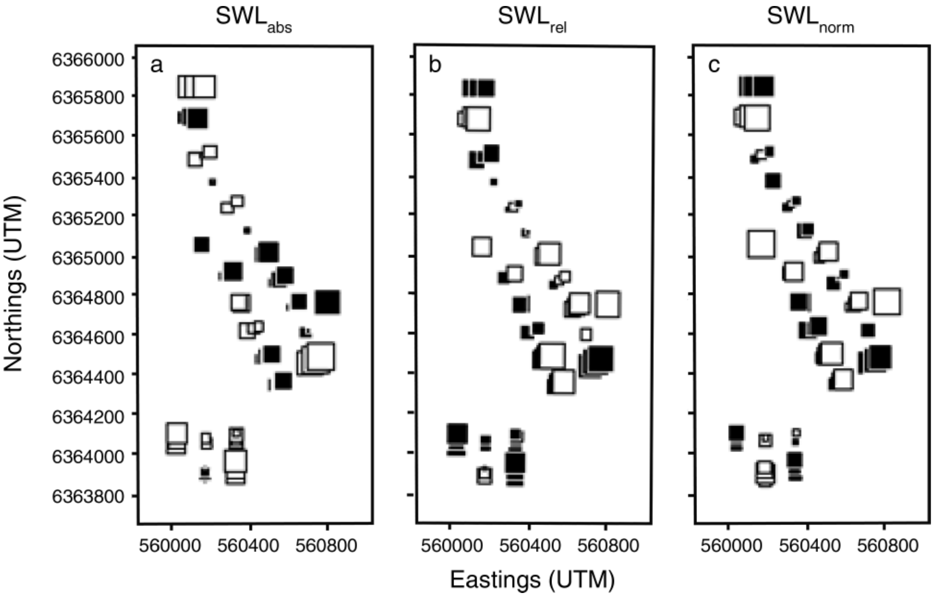

FIG. 8. Bubble maps of the first canonical axes of partial RDAs of the Hellinger-transformed detrended SWL data explained by the environmental variables (treatment, distance from tree belt, and VegCov) with the spatial PCNMs as covariables: (a) SWL_{abs}, (b) SWL_{rel}, and (c) SWL_{norm}. See Fig. 6 legend for explanation of symbols.

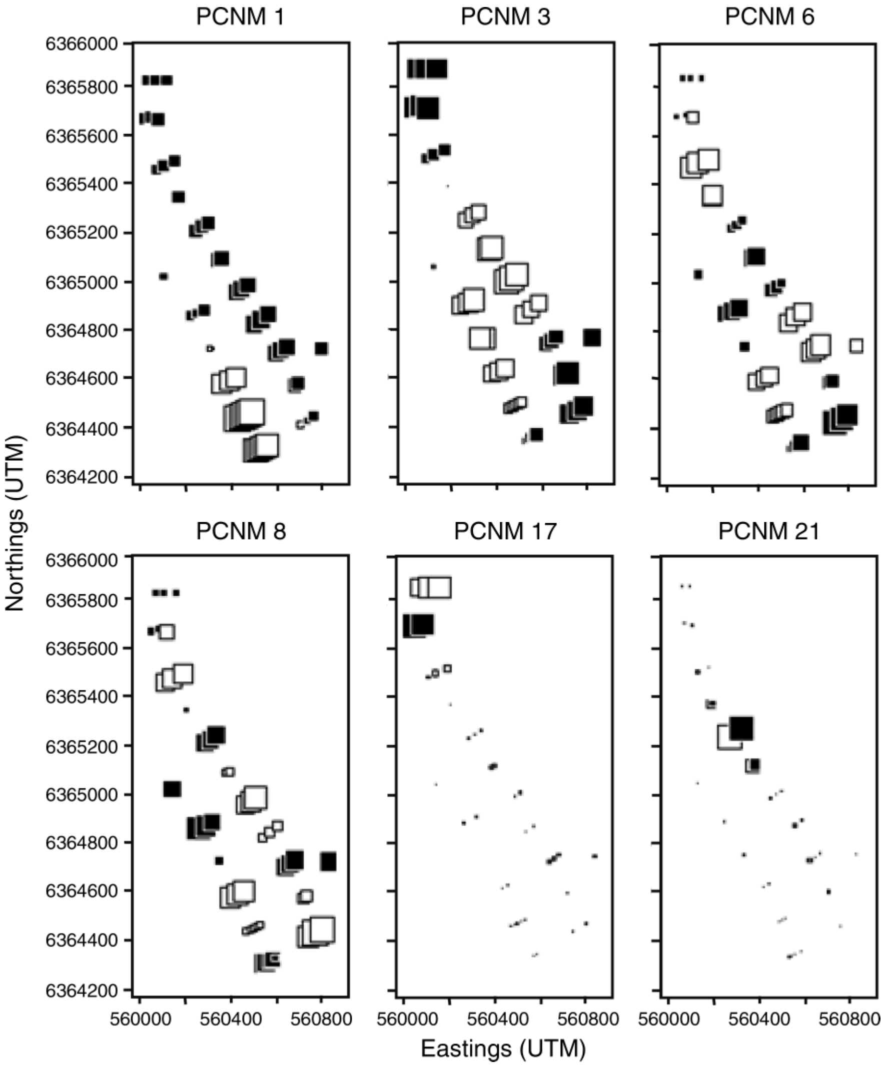

FIG. 9. Bubble maps of PCNM 1, 3, 6, 8, 17, and 21 obtained from the regular design of piezometers for plots D1–D16 (northern block) at the trial site. See Fig. 6 legend for explanation of symbols.

distance from) by adjacent plots (Fig. 2). Also, the proximity of trees to each other in wider belts may have limited their effectiveness due to competition for resources (i.e., water and nutrients). This suggests that, when designing similar trials, it is important to be aware of the scale over which to expect root extent and measure the response variable with this in mind. Separation of plots by untreated areas may have proven a better experimental design. Each enlarged plot would contain multiple transects of piezometers (both parallel and perpendicular to belts) to observe the spatial variability and extent of impact on the water table of the same treatment design. Although the design of the trial stipulates that sufficient distance between plots is allocated, proximity to plots with a higher revegetation percentage and/or multiple belts may influence the water table response of nearby plots, not necessarily only due to the lateral extent of the roots, but also by the creation of potential storage zone in the unsaturated zone beneath the belt(s). The majority of previous research has focused on single belts or one specific design with one transect of piezometers; therefore, the assumption regarding the design of the experiment may have been incorrect.

The use of soil water as a resource by vegetation will influence changes in the hydrological balance of a system. Research has shown that woody perennials will hydraulically redistribute soil water from the surface soils to those deeper in the profile via tap roots (Burgess et al. 1998, 2001) and preferential flow paths (Nulsen and Baxter 1986). White et al. (2002) found that trees can capture and redistribute up to 31 mm of water during the winter season; this presents an issue for the associated crop growth during this period. It is this movement of water within the soil profile that may impact the morphology of the water table. The capture

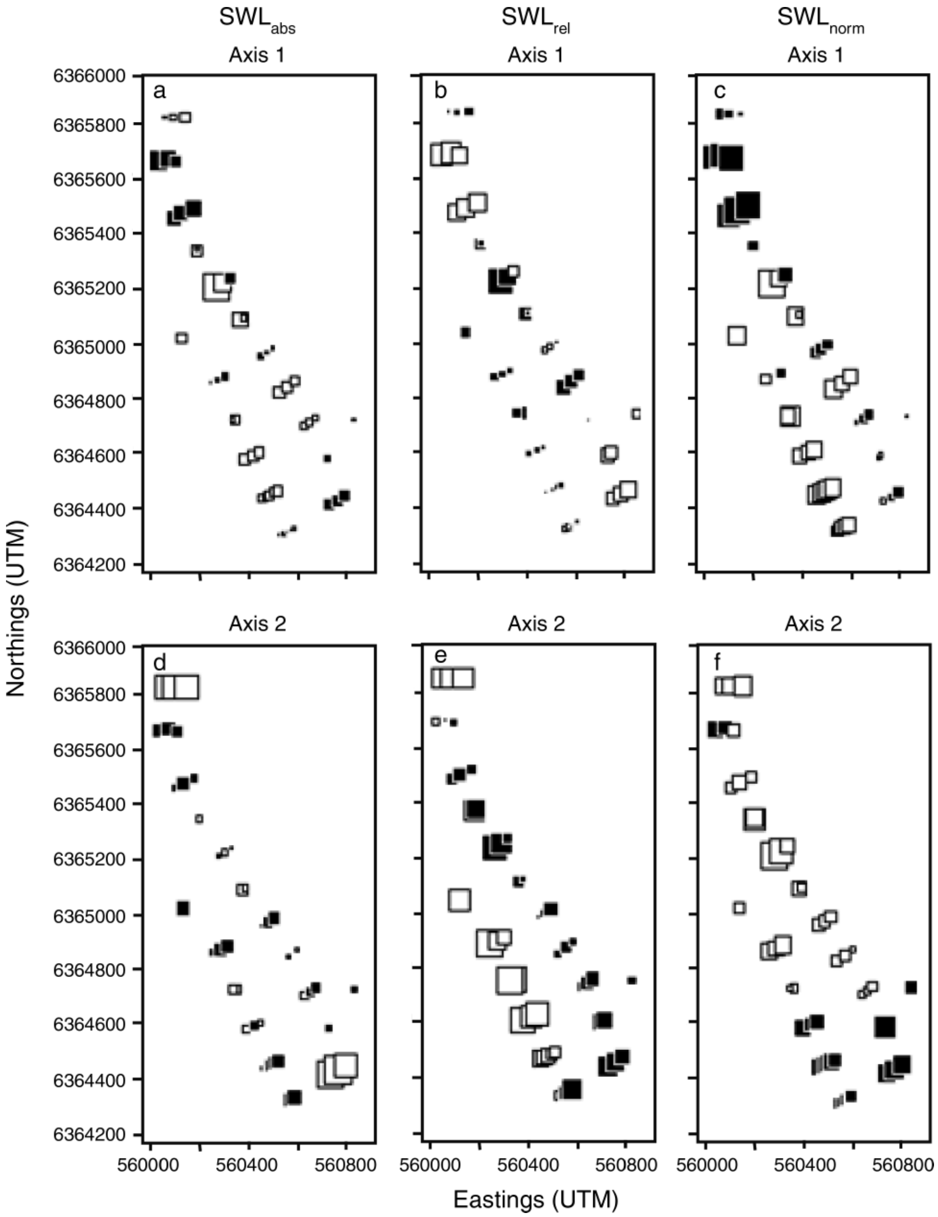

FIG. 10. Bubble maps of the first (a–c) and second (d–f) canonical axes of partial RDAs of the Hellinger-transformed detrended SWL data explained by significant PCNM variables, with the three environmental variables (treatment, distance of piezometers from tree belt, and VegCov) as covariables: analysis of (a, d) SWL_{abs}, (b, e) SWL_{rel}, and (c, f) SWL_{norm}. Each pattern represents a portion of the variation explained by the PCNM variables; R^2_a is (a) 19.1%, (b) 10.1%, (c) 11.1%, and R^2 is (d) 26.8%, (e) 8.7%, and (f) 12.5%. See Fig. 6 legend for explanation of symbols.

and subsequent redistribution of winter rainfall from the alley could result in a higher water table beneath the belt; the increased water store beneath the belt during the hot summer months would help maintain the water table to an accessible depth. This is obviously a distinctly complicating factor and suggests that the conceptual model may be somewhat flawed, i.e., that water table drawdown will be greatest under the belt. Further assessment of this impact, by undertaking a water balance analysis on a plot by plot basis, may prove informative.

Consideration of the water quality is also necessary to assess whether tree belts utilize groundwater for transpiration as a resource or simply rely on precipitation (Archibald et al. 2006). If the trees rely solely on precipitation, then any drop of groundwater level only result from recharge reduction. Prior to establishment, the water table was <2 m BGL and often at the surface, soil salinity within 2 m of the surface ranged between 2–

149 mS/m, groundwater pH ranged between 3 to 5, and electrical conductivity between 22.1–45.9 mS/cm. Research has confirmed that growth rates for trees established over shallow, saline water tables in low rainfall zones are low (Greenwood et al. 1985). The relatively good quality of the groundwater accessible by the tree belts at this site suggests that this resource could be used when required, but fresher rainfall derived recharge would be a preferential water source.

The effect of surface topography can also impact water table response. Although within-treatment topography is minimal (typically ±10–50 mm), designs of such systems need to take surface elevation into account. Utilization of microtopographic variation in agriculture and agroforestry site design is used to aid the management and application of resources to enable maximum output to be achieved (Cramer et al. 2004). The high proportion of variation explained by the environmental variables for the SWL_{norm} data sets highlights the importance of minor topographic variations on a small scale (between piezometers). The trend in water table response observed in the raw SWL_{rel} data set (Fig. 3) demonstrates an increase in the range of the data one year post-trial establishment. Although the water table surface roughly mirrors the topography at this site, this increase in range is not observed in the raw SWL_{abs}, indicating the spatial variability in the water table response. The general design of an alley farming system would involve placement of tree belts along topographic and groundwater contours (White et al. 2002) much the same as naturally forming banded structure (d'Herbès et al. 2001). The design of this trial has placed the belts for plots D1–D16 almost perpendicular to the topographic contours (see Fig. 1), and plots D17–D21 are orientated to a greater advantage for the capture of overland flow. This distinction in the design may have attributed to the selection of PCNM 19 for all data sets, which identifies a difference in the magnitude of the pattern for plots D1–D16 and D17–D21.

The placement of tree belts, as a means to control recharge and reduce the negative impacts of surface water, has been shown to impact on the water table. Therefore, observation of the water table should help to delineate the impact of such belts as opposed to unplanted areas; however, as discussed above, trial design needs to better reflect the site morphology and physiology of the belt vegetation type. Research of the impacts of the alley farming has identified its potential to aid in the re-establishing the water balance (Lefroy and Stirzaker 1999, Knight et al. 2002, Ellis et al. 2005, Lefroy et al. 2005). Ellis et al. (2005) finds that tree belts of 4–8 m in width can reduce recharge by 60% of that which occurs under conventional crops in South Australia, and White et al. (2002) observed that 8-m tree belts will reduce recharge to 5 mm/yr in Ucarro, Western Australia. However, financial restrictions will limit the amount of land available for revegetation; in a modeling study by Cooper et al. (2005), only 0.4–1.2% was applied as woody perennial cover due to this constraint. This needs to be refined and the potential implementation across all regions optimized. With the increased importance of the biofuels, optimizing agroforestry becomes even more important as belts of trees may become a source of biofuel in their own right (Bartle et al. 2007). Rather than the conversion of 100% of food-producing areas to biofuel production, a smaller percentage may still yield valuable energy resources, while allowing food production to continue.

Implications of spatial variables

The spatial PCNM variables contribute a large proportion to the explained variation for all explanatory variables at the site. The high value of the residual variation (fraction [p]) suggests that the overall importance of the spatial PCNM variables is to some degree limited. The indiscriminate pattern displayed by the combined PCNM variables may display the influence of an explanatory variable not yet identified. The selection of PCNM 21 for northern block would suggest that physical parameters such as soil type may be important and similarly with the selection of PCNM 19 for the entire site. This suggests that further detail of more variables is required to increase the proportion of explained variation within the water table response data.

Conclusions

The application of statistical techniques predominantly applied within the field of community ecology has been shown to be effective at identifying the impacts of this alley farming trial on the water table depth. Variation partitioning, principal coordinates of neighbor matrices (PCNM), and canonical redundancy analysis (RDA) have been successful at distinguishing between trial effects and site spatial autocorrelation. The amount of explained variation in the water table response attributed to the effects of the trial, i.e., treatment design, distance from tree belt, and vegetation cover (including 3 m edge effect) are significant for the absolute, relative, and normalized data sets. However, the proportion of variation explained by these variables is small. The spatial PCNM variables explain the largest portion of variation within the data, but no coherent pattern emerges that can be related to any physical parameter currently known at the site.

The fine-scale PCNM for the entire site identified a disparity between the southern and northern plots; accordingly, the site was divided and statistical analyses re-applied to each section. The proportion of explained variation attributed to the environmental variables increased for the northern sub division (plots D1–D16), but not for the southern subdivision (D17–D21). This suggests that the southern plots are, to a greater extent, under the influence of variables not considered in this study. The environmental variables display high degree of intersection, i.e., they share a large proportion of their variation, but this need not imply an interaction between the variables. However, previous research has shown how tree belts effect the water table (Ellis et al. 2005, Oliver et al. 2005, Robinson et al. 2006).

The low value of the explained variation could possibly arise from a number of factors including trial design, redistribution of soil water, and lateral root development from the tree belts interfering with neighboring plots. Site heterogeneity and associated variables not included in this study may link to the high value of unexplained variation across all data sets.

The overall results of the analysis of the long-term data set has identified that the placement of tree belts within the landscape will have an impact on the water table, but that the current study can only attribute a small amount of the variation to this impact.

Acknowledgments

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Literature Cited

Anderson, M., and P. Legendre. 1999. An empirical comparison of permutation methods for tests of partitional regression coefficients in a linear model. Journal of Statistical Computation and Simulation 62:271–303.

Archibald, R. D., R. J. Harper, J. E. D. Fox, and R. P. Silberstein. 2006. Tree performance and root-zone salt accumulation in three dryland Australian plantations. Agroforestry Systems 66:191–204.

Ayyad, M. A. 2003. Case studies in the conservation of biodiversity: degradation and threats. Journal of Arid Environments 54:165–182.

Bartle, J. B. 1999. The new hydrology: new challenges for landcare and tree crops. Washington State Landcare Conference, Esperance, Washington, USA.

Bartle, J., G. Olsen, D. Cooper, and T. Hobbs. 2007. Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia. International Journal of Global Energy Issues 27:115–137.

Bellier, E., P. Monestiez, J.-P. Durbec, and J.-N. Candau. 2007. Identifying spatial relationships at multiple scales: principal coordinates of neighbour matrices (PCNM) and geostatistical approaches. Ecography 30:385–399.

Bird, P. R., J. J. Lynch, and J. M. Obst. 1994. Effect of shelter on plant and animal production. Animal Production in Australia 15:270–273.

Borcard, D., and P. Legendre. 2002. All-scale spatial analysis of ecological data by means of principal coordinates of neighbour matrices. Ecological Modelling 153:51–68.

Borcard, D., P. Legendre, C. Avois-Jacquet, and H. Tuomisto. 2004. Dissecting the spatial structure of ecological data at multiple scales. Ecology 85:1826–1832.

Bouwer, H., and R. C. Rice. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research 12:423–428.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310:28–61.

Burgess, S. S. O., M. A. Adams, N. C. Turner, and C. K. Ong. 1998. The redistribution of soil water by tree root systems. Oecologia 115:306–311.

Burgess, S. S. O., M. A. Adams, N. C. Turner, D. A. White, and C. K. Ong. 2001. Tree roots: conduits for deep recharge of soil water. Oecologia 126:158–165.

Canadell, J., R. B. Jackson, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E.-D. Schulze. 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108:582–595.

Clarke, C. J., R. J. George, R. W. Bell, and T. J. Hatton. 2002. Dryland salinity in south-western Australia: its origins, remedies, and future research directions. Australian Journal of Soil Research 40:93–113.

Connor, D. J. 2004. Designing cropping systems for efficient use of limited water in southern Australia. European Journal of Agronomy 21:419–431.

Cooper, D., G. Olsen, and J. Bartle. 2005. Capture of agricultural surplus water determines the productivity and scale of new low-rainfall woody crop industries. Australian Journal of Experimental Agriculture 45:1369–1388.

Cramer, V. A., and R. J. Hobbs. 2002. Ecological consequences of altered hydrological regimes in fragmented ecosystems in southern Australia: impacts and possible management responses. Austral Ecology 27:546–564.

Cramer, V. A., R. J. Hobbs, L. Atkins, and G. Hodgson. 2004. The influence of local elevation on soil properties and tree health in remnant eucalypt woodlands affected by secondary salinity. Plant and Soil 265:175–188.

d'Herbès, J.-M., C. Valentin, D. J. Tongway, and J.-C. Leprun. 2001. 1. Banded vegetation patterns and related structures. Pages 1–19 *in* D. J. Tongway, C. Valentin, and J. Seghiere, editors. Banded vegetation patterns in arid and semiarid environments: ecological processes and consequences for management. Springer-Verlag, New York, New York, USA.

Dray, S., P. Legendre, and P. R. Peres-Neto. 2006. Spatial modelling: a comprehensive framework for principal coordinate analysis of neighbour matrices (PCNM). Ecological Modelling 196:483–493.

Droppelmann, K., and P. Berliner. 2003. Runoff agroforestry: a technique to secure the livelihood of pastoralists in the Middle East. Journal of Arid Environments 54:571–577.

Eastham, J., P. R. Scott, R. A. Steckis, A. F. M. Barton, L. J. Hunter, and R. J. Sudmeyer. 1993. Survival, growth and productivity of tree species under evaluation for agroforestry to control salinity in the Western Australian wheatbelt. Agroforestry Systems 21:223–237.

Ellis, T., T. Hatton, and I. Nuberg. 2005. An ecological optimality approach for predicting deep drainage from tree belts of alley farms in water-limited environments. Agricultural Water Management 75:92–116.

Ellis, T. W., S. Leguedois, P. B. Hairsine, and D. J. Tongway. 2006. Capture of overland flow by a tree belt on a pastured hillslope in south-eastern Australia. Australian Journal of Soil Research 44:117–125.

Ferdowsian, R., D. J. Pannell, C. Mccaron, A. Ryder, and L. Crossing. 2001. Explaining groundwater hydrographs: Separating atypical rainfall events from time trends. Australian Journal of Soil Research 39:861–875.

Froend, R. H., S. A. Halse, and A. W. Storey. 1997. Planning for the recovery of Lake Toolibin, Western Australia. Wetlands Ecology and Management 5:73–85.

George, R. J., D. J. Mcfarlane, and M. F. Lewis. 1991. A review of recharge and implications for management in saline agricultural catchments, Western Australia. Proceedings of the International Hydrology and Water Resource Symposium, Perth, Australia.

George, R. J., D. J. Mcfarlane, and R. A. Nulsen. 1997. Salinity threatens the viability of agriculture and ecosystems in Western Australia. Hydrogeology Journal 5:6–21.

Greenwood, E. A. N., L. Klein, J. D. Beresford, and G. D. Watson. 1985. Difference in Annual evaporation between grazed pasture and *Eucalyptus* species in plantations on a saline farm catchment. Journal of Hydrology 78:261–278.

Hajkowicz, S., and M. D. Young. 2002. An economic analysis of revegetation for dryland salinity control on the Lower Eyre Peninsula in South Australia. Land Degradation and Development 13:417–428.

Hatton, T. 2001. Land use and catchment water balance. Technical Report 18/01. CSIRO Land and Water, Canberra, Australia.

Hatton, T. J., and R. A. Nulsen. 1999. Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian Agriculture. Agroforestry Systems 45: 203–214.

Hatton, T. J., J. Ruprecht, and R. J. George. 2003. Preclearing hydrology of the Western Australia wheatbelt: Target for the future? Plant and Soil 257:341–356.

Hobbs, R. J. 1993. Effects of landscape fragmentation on ecosystem processes in the Western Australian wheatbelt. Biological Conservation 64:193–201.

Hodgson, G. A., G. A. Bartle, R. P. Silberstein, T. J. Hatton, and B. H. Ward. 2002. Measuring and monitoring the effects of agroforestry and drainage in the 'Ucarro' sub-catchment. Agricultural Water Management 53:39–56.

Holmgren, M., et al. 2006. Extreme climatic events shape arid and semiarid ecosystems. Frontiers in Ecology and the Environment 4:87–95.

Hope, P., W. Drosdowsky, and N. Nicholls. 2006. Shifts in the synoptic systems influencing southwest Western Australia. Climate Dynamics 26:751–764.

Hvorslev, M. J. 1951. Time lag and soil permeability in ground water observation. U.S. Army Corps of Engineers Waterways Experimental Station, Bulletin 36. U.S. Army Corps of Engineers, Vicksburg, Mississippi, USA.

Indian Ocean Climate Initiative. 2002. Climate variability and change in south west Western Australia. Indian Ocean Climate Initiative Panel, Perth, Australia.

Kang, B. T., G. F. Wilson, and T. L. Lawson. 1984. Alley farming: a stable alternative to shifting cultivation. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Knight, A., K. Blott, M. Portelli, and C. Hignett. 2002. Use of tree and shrub belts to control leakage in three dryland cropping environments. Australian Journal of Agricultural Research 53:571–586.

Lefroy, E. C., F. Flugge, A. Avery, and I. Hume. 2005. Potential of current perennial plant-based farming systems to deliver salinity management outcomes and improve prospects for native biodiversity: a review. Australian Journal of Experimental Agriculture 45:1357–1367.

Lefroy, E. C., and R. J. Stirzaker. 1999. Agroforestry for water management in the cropping zone of southern Australia. Agroforestry Systems 45:277–302.

Legendre, P. 1993. Spatial autocorrelation: trouble or new paradigm? Ecology 74:1659–1673.

Legendre, P., and E. Gallagher. 2001. Ecologically meaningful transformations for ordination of species data. Oecologia 129:271–280.

Legendre, P., and L. Legendre. 1998. Numerical ecology. Second edition. Elsevier Science, Amsterdam, The Netherlands.

Malajczuk, G., D. Morrison, J. Havel, G. Anderson, and R. Moore. 1984. An economic study of agroforestry in the Manjimup Region, Western Australia. Technical Paper Number 10. Forests Department of Western Australia, Perth, Australia.

Morris, J. D., and L. A. J. Thompson. 1983. Role of trees in dryland salinity control. Proceedings of the Royal Society Victoria 95:123–131.

Nulsen, R. A. 1981. Critical depth to saline groundwater in non-irrigated situations. Australian Journal of Soil Research 19:83–86.

Nulsen, R. A., and I. N. Baxter. 1986. Water use by some crops and pastures in the southern agricultural areas of Western Australia. Resource Management Technical Report Number 32. Department of Agriculture, Perth, Australia.

Nulsen, R. A., K. J. Bligh, I. N. Baxter, E. J. Solin, and D. H. Imrie. 1986. The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. Australian Journal of Ecology 11:361–371.

Ogunlana, E. A., V. Salokhe, and L. Ranghild. 2006. Alley farming: a sustainable technology for crops and livestock production. Journal of Sustainable Agriculture 29:131–144.

Oksanen, J., R. Kindt, P. Legendre, B. O'hara, G. L. Simpson, and M. H. H. Stevens. 2008. Vegan: community ecology package. R package version 1.11-4. ⟨http://cran.r-project.org/⟩

Oliver, Y. M., E. C. Lefroy, R. J. Stirzaker, and C. L. Davies. 2005. Deep-drainage control and yield: the trade-off between trees and crops in agroforestry systems in the medium to low rainfall area of Australia. Australian Journal of Agricultural Research 56:1011–1026.

Peck, A. J., and D. R. Williamson. 1987. Effects of forest clearing on groundwater. Journal of Hydrology 94:47–65.

Peres-Neto, P. R., L. Legendre, S. Dray, and D. Borcard. 2006. Variation partitioning of species data matrices: estimation and comparison of fractions. Ecology 87:2614–2625.

Pimentel, D., and N. Kounang. 1998. Ecology of soil erosion in ecosystems. Ecosystems 1:416–426.

R Development Core Team. 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. ⟨http://www.r-project.org⟩

Robinson, N., R. J. Harper, and K. R. J. Smettem. 2006. Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. Plant and Soil 286:141–151.

Salama, R. B., P. Farrington, G. A. Bartle, and G. D. Watson. 1993. Salinity trends in the wheatbelt of Western Australia: results of water and salt balance studies from Cuballing catchment. Journal of Hydrology 145:41–63.

Shapiro, S. S., and M. B. Wilk. 1965. An analysis of variance test for normality (complete samples). Biometrika 52:591–611.

Silberstein, R. P., G. A. Bartle, R. B. Salama, T. J. Hatton, P. Reggiani, G. Hodgson, D. R. Williamson, and P. Lambert. 2002. Mechanisms and control of water logging and groundwater flow in the 'Ucarro' sub-catchment. Agricultural Water Management 53:227–257.

Smith, I. N., P. McIntosh, T. J. Ansell, and K. McInnes. 2000. Southwest western Australian winter rainfall and its association with Indian Ocean climate variability. International Journal of Climatology 20:1913–1930.

Sudmeyer, R. A., and A. Goodreid. 2007. Short rotation woody crops: A prospective method for phytoremediation of agricultural land at risk of salinisation in southern Australia? Ecological Engineering 29:350–361.

White, D. A., F. X. Dunin, N. C. Turner, B. H. Ward, and J. H. Galbraith. 2002. Water use by contour-planted belts of trees comprised of four *Eucalyptus* species. Agricultural Water Management 53:133–152.

Wild, A. 2003. Soils, land and food: managing the land during the twenty-first century. Cambridge University Press, Cambridge, UK.

Wildy, D. T., J. Pate, and J. Bartle. 2003. Silviculture and water use of short-rotation mallee eucalypts. RIRDC/Land and Water Australia/FWPRDC/MDBC Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra, Australia.

Wildy, D. T., J. S. Pate, and L. T. Sefcik. 2004. Water-use efficiency of a mallee eucalypt growing naturally and in short-rotation coppice cultivation. Plant and Soil 262:111–128.

Zohar, Y. 1985. Root distribution of a eucalypt shelterbelt. Forest Ecology and Management 12:305–307.