

## Review

# The magnitude and spatial extent of influence of *Faidherbia albida* trees on soil properties and primary productivity in drylands

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## ABSTRACT

*Faidherbia* (*Faidherbia albida*) is being promoted widely in interventions for combating desertification, greening of the Sahel and agroforestry projects in dry lands. Some scientists have questioned the wisdom of its wider promotion without clear evidence of its impacts. This review provides novel analyses of the magnitude and spatial extent of its influence on soil properties and primary productivity. A meta-analysis provided evidence for significant increases in soil organic carbon (SOC) (by 46%), total nitrogen (50%), phosphorus (21%), potassium (32%), and yields of maize (150%) and sorghum (73%) under the tree canopy compared to the open area. However, larger increases in SOC and nutrients occurred on inherently nutrient-poor sites than on nutrient-rich sites. Similarly, large increases in crop yields occurred in suboptimal conditions for crop productivity than in optimal conditions. The tree created predictable patterns in soil nutrients and crop yields consistent with distance–decay models of spatial interaction. Its growth and canopy development appear to explain the size dependence of the spatial extent of its influence, with a marked influence observed under large trees than small trees. The review also identified enormous variability in study design and statistical rigor, which appear to mask the expected patterns. Study designs and inferential statistics in current use neither address the intrinsic causality of patterns nor do they offer a mechanistic insight into the observed patterns. The major concerns and their implications are discussed and improvements for future research on single-tree influences on ecosystem properties in dry lands are suggested.

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## 1. Introduction

Faidherbia (*Faidherbia albida*) is widely distributed throughout the dry zones of Africa and the Middle East including Israel, Lebanon, Oman, Palestine, Saudi Arabia, Syria and Yemen (Barnes and Fagg, 2003; Boffa, 1999). It is adapted to a wide range of soils and altitudes ranging from 270 m below sea level in Palestine to over 2000 m in the Sudan (Barnes and Fagg, 2003) and Ethiopia (Hadgu et al., 2009). Unlike other trees, it remains leafless during the wet season and in leaf during the dry season, a phenomenon termed 'reverse phenology'. Its presence in the crop fields has been widely reported to increase soil fertility and crop yields, termed the 'albida effect' (Barnes and Fagg, 2003; Boffa, 1999). This has been recognized in the Sahel and East and Southern Africa for several centuries, and Faidherbia has been effectively managed in agroforestry parklands (Boffa, 1999; Kho et al., 2001). Faidherbia is also being increasingly promoted in various development projects such as combating desertification (Kirmse and Norton, 1984) and greening of the Sahel (Reij et al., 2009). Some authors (Phombeya et al., 2005) have even proposed nationwide campaigns for planting Faidherbia in areas where this tree does not grow. With the advent of climate change, Faidherbia has also gained prominence in climate-smart agriculture. At the Durban Climate Change Convention in December 2011, the late Prime Minister of Ethiopia announced that a government initiative will establish 100 million Faidherbia trees on smallholder cereal croplands across the country. A large-scale effort in Eastern Zambia by a small landholder cooperative of 19,000 farmers is also promoting planting of the trees in conservation agriculture fields (Bosco, 2012).

Although over five decades of research has been conducted, there is no consensus on the distribution of yields in the canopy of Faidherbia (Boffa, 1999). Enormous variability also exists in study design, details of studies, and statistical rigor making it difficult to compare the results and draw widely applicable conclusions. Many of these studies do not evidently state about the status of the soil nutrients and yields beyond the influence of the tree canopy. The magnitude of the tree influence is variable and this appears to be determined by a complex interaction of factors including tree size, soil, water regimes and tree/crop management (Barnes and Fagg, 2003; Boffa, 1999). The relative contribution of each of these factors has not been quantified and the following questions still remain unanswered (Barnes and Fagg, 2003): (1) Does the tree's root system mine the soil beyond the reach of its crown? (2) Is Faidherbia any more effective in increasing soil fertility than other tree species in the ecosystem? (3) Is there any consistent increase in the soil nutrient pools and crop yields due to Faidherbia trees and how large is the effect size? (4) What is the spatial extent of the tree influence? Although there has been an increase in plot-level studies recently (Adamu, 2012; Bosco, 2012; Hadgu et al., 2009; Kho et al., 2001; Umar et al., 2013; Yengwe, 2011), we still lack a mechanistic understanding of the magnitude and extent of its influence on soils. In many studies, the differences between observations under the canopy and open area have been reported as nonsignificant (Table 1). Lack of statistical significance could be attributed to the high spatial variability, for example, in crop yields in dry lands (e.g. Buerkert et al., 1996). Lack of significance could also be an artefact resulting from inappropriate choice of sampling units, plot location

and low statistical power of tests. The frequency of non-significant results has led some scientists to question the wisdom of its promotion in development projects.

Development of evidence-based policies and practice for scaling up Faidherbia will require a mechanistic understanding of its impacts at the individual tree and plot levels so that such information could be quantitatively scaled up to whole farm and landscape levels. A key element in this endeavour is a good knowledge of the area that a single tree is able to influence and how this relates to tree size and structure. This is important because the structure of individual trees determines the properties at the level of populations and spatial organization of vegetation (Enquist et al., 2009; West et al., 2009). For example, the scaling relationships between tree crown and root play an essential part in ecosystems stability in desert conditions and soil resource limitation in dry lands (Lefever et al., 2009). Unlike most tree species, Faidherbia is characterized by high variability in growth, anomalous crown development and peculiar phenological rhythms (Ismail, 1986; Werger and Ellenbroek, 1982). Information is virtually lacking on how its growth and crown development affect its influence on soil and primary productivity. Therefore, the objective of this paper is to (1) establish the magnitude and spatial extent of Faidherbia influence; (2) provide mechanistic explanations for observed patterns through inferences from theory; and (3) point out areas of concern in research design and application of inferential statistics.

## 2. Methods

### 2.1. Data collection

Secondary data on soil nutrients, plant productivity and tree growth variables were assembled by searching the literature in both published and unpublished sources.

#### 2.1.1. Soil and plant data

Soil and plant data were assembled from several studies in order to estimate the magnitude of tree influence through meta-analysis. The selection and inclusion of studies were based on strict criteria to satisfy the requirements of meta-analysis. For a study to be included in the analysis, it must (1) have been published in a refereed journal, book chapter or peer-reviewed proceeding or any other report; (2) have soil or crop yield measurements 'under canopy' and a corresponding measurement 'outside canopy' to be treated as a well-defined control; (3) have reported the mean as numerical or graphical data; and (4) reported soil properties for each soil depth separately.

From the studies thus selected, pairs of observations (under canopy and corresponding values in the open area) on soil organic matter (SOM) and/or soil organic carbon (SOC), total nitrogen (N), extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and pH, and crop yields or plant dry matter were extracted. The number of studies that qualified for inclusion in the meta-analysis is summarized in Table 1. As SOM consists of C, H, O, N, P and S, it is difficult to actually measure. Therefore, most analytical methods determine the SOC, which can be readily measured, and estimate SOM through a conversion factor. Conventionally, the Bemmelen factor (1.724) has been widely used

**Table 1**

Studies included in the meta-analysis and the combined subject sizes (pairs of means) for organic carbon (OC), total nitrogen (N), phosphorus (P), potassium (K), pH and yields of maize, sorghum and groundnut. The number of statistically non-significant comparisons (numerator) and total number of comparisons (denominator) in those studies that conducted ANOVA are indicated at the bottom of the Table.

Author	SOC	N	P	K	Mg	Ca	pH	Maize	Sorghum	Groundnut
Bekele (1982)	1	1	–	–	–	–	1	–	–	–
Charreau and Vidal (1965) <sup>a</sup>	1	1	1	1	–	–	–	–	–	–
Dancette and Poulain (1969) <sup>a</sup>	1	1	1	1	1	1	–	–	2	2
Depommier et al. (1992) <sup>b</sup>	4	4	4	1	4	4	1	1	3	–
Dunham (1991)	1	1	1	1	1	1	–	–	–	–
Hadgu et al. (2009)	3	3	3	–	–	–	3	–	–	–
IRHO (1966) <sup>a</sup>	–	–	–	–	–	–	–	–	–	4
Jaiyeoba (1996)	1	1	–	3	1	1	3	–	–	–
Jung (1969) <sup>c</sup>	–	1	1	1	–	–	–	–	–	–
Kho et al. (2001)	1	1	1	1	1	1	1	–	–	–
Louppe et al. (1996)	–	–	–	–	–	–	–	–	–	2
Phombeya (1999)	2	2	2	2	1	2	–	–	–	–
Rhoades (1995)	2	–	2	2	3	3	2	–	–	–
Rhoades (1997)	1	1	–	–	–	–	–	–	–	–
Poschen (1986)	–	–	–	–	–	–	–	1	2	–
Saka et al. (1994)	6	2	3	3	3	3	3	–	–	–
Selenje et al. (1991)	21	24	24	24	–	–	–	53	–	–
Shitumbanuma (2012)	–	–	–	–	–	–	–	67	–	83
Umar et al. (2013)	4	4	4	4	–	–	4	–	–	–
Weil and Mughogo (1993)	–	9	8	–	–	–	–	–	–	–
Yengwe (2011)	2	2	2	2	–	–	–	–	–	–
<i>Number of studies included</i>	13	16	14	13	8	8	8	4	3	4
<i>Combined sample size</i>	50	58	57	48	15	16	20	119	8	91
<i>Non-significant results</i>	7/13	7/16	11/14	10/16	6/15	7/16	12/13	1/4	2/6	16/18
<i>% non-significant results</i>	53.8	43.8	78.5	62.5	40.0	43.8	92.3	7.1	33.3	88.9

<sup>a</sup> References in Boffa (1999) Table 3.2.

<sup>b</sup> Reference in Rhoades (1997) Table 3.

<sup>c</sup> Reference in Barnes and Fagg (2003).

based on the assumption that SOM contains 58% C. However, many studies have consistently shown that this factor is too low for most soils. After a review of empirical studies and theoretical considerations, Pribyl (2010) proposed 2 as a better correction factor. For the purposes of this analysis, all SOM data were converted to SOC as SOM/2 before meta-analysis. The analysis of soil data focused only on the 0–30-cm soil depth due to the widely varying depths used in the various studies. This was also considered satisfactory because over 75% of SOC and plant roots in drylands are known to be concentrated in this depth (Jobbagy and Jackson, 2000).

For the meta-analyses, the response ratio (RR) was chosen as the most appropriate effect size. RR was calculated as the ratio of measurements under the canopy (U) to the open area (or patches taken furthest from the tree trunk) considered as the control (C). Thus RR (= U/C) is a dimensionless and unit-less quantity. It has clear advantages over other metrics such as the relative net tree effect proposed by Kho et al. (2001). Firstly, it makes combining data collected through different analytical methods or at different times more straightforward than other metrics. For example, soil analyses (e.g. phosphorus) conducted using different methods (e.g. water, Olsen, Bray, Mehlich extraction) can be combined and analysed using RR. Another advantage of RR is that it is related to biological indices such as the relative competition intensity (=  $1 - RR$ ) and relative growth rate (=  $\ln(RR/t)$ ) used in plant ecology (Oksanen et al., 2006).

For assessing the spatial extent of tree influence, those studies that provide measurements at several (>4) distances from tree trunks were chosen. These included Kamara and Haque (1992), Saka et al. (1994), Payne et al. (1998) and Verinumbe (1993). Data from these were used for modelling variations in effect size (i.e. RR) with distance from the tree trunk.

### 2.1.2. Tree growth data

This review also aimed to make inferences about the spatial extent of tree influence from scaling relationships between growth and canopy structure. For that purpose, pairs of measurements of tree height (H), diameter at breast height (D) and crown radius (CR) of individual trees were extracted from a database compiled by Sileshi et al. (2014). Crown projection area (CPA) was then estimated from the CR as  $CPA = CR^2\pi$  following Pretzsch et al. (2015). In total, 204 pairs of H, D and CR data points were used for modelling growth and canopy development.

## 2.2. The analytical framework

### 2.2.1. Meta-analysis

The meta-analysis aimed to answer the question 'Is there any consistent increase in soil nutrient pools and crop yields due to Faidherbia trees and how large is the effect size?' It is difficult to answer such questions by individual studies because data are usually contaminated by random variability (noise) despite researchers' efforts to minimize extraneous influences. Meta-analysis integrates data from the studies that qualified for inclusion and estimates the expected value of the tree effect, that is, the response ratio (RR). The first step in this analysis involved estimating the expected value of RR of the individual response variables. Statistical inference was based on the robust (Winsorized) estimates of RRs and their 95% confidence intervals (95% CI). The 95%CI quantifies both the magnitude and direction of change under the canopy with respect to the open area. If there is no significant difference between the canopy and open area for a given variable, the 95%CI of RR will encompass 1. On the other hand, if the 95% CL of RR is greater than 1 it means significant increases under the canopy. The second step in this analysis involved estimating the probability of

overall increase in response ( $RR > 1$ ) and doubling ( $RR \geq 2$ ) under the canopy relative to the open area was estimated from the data.

The effects of the tree were also hypothesized to vary with inherent site productivity. In order to test this hypothesis, the RR data for each soil nutrient and crop yield were categorized into two groups: 'below-average' and 'above-average' representing proxy site conditions. When soil nutrient content or crop yield is below or above the average value for the open area (i.e. C), site conditions were labelled below-average or above-average, respectively. The RR data were transformed to  $\log(RR)$  and analysed using a linear mixed modelling framework that included site productivity as the fixed effect and study as the random effect. The model was fitted using the MIXED procedure of the statistical analysis system (SAS). The 95%CI and Tukey–Kramer-adjusted  $P$  values were used for comparison of the above-average with below-average site conditions. If *Faidherbia* does not influence a given variable, RR will be equal to 1 and the 95%CI of RR will include 1. In order to assess how the magnitude of change in soil nutrients and sub-canopy vegetation vary with the respective measurements in the open area (or the C) across studies, RR values were plotted against the respective values from C. As there was no prior information about the parametric form of the relationship between RR and C, a power function ( $RR = \alpha C^\beta$ ) was used to reveal the functional form of the variation. This function was chosen because its linear form  $\log(RR) = \log\alpha + \beta\log(C)$  gives a reasonable approximation of the observed patterns in the scatter plot. Inferences from this were used to answer the question 'Does the tree's root system mine a particular nutrient from the soil beyond the reach of its crown?' If RR remains the same across all C values, *Faidherbia* tree influence is neutral across the site conditions. If RR increases with an increase in C, it means *Faidherbia* acquires resources in direct proportion to the pre-existing conditions in the open area and concentrates them under its canopy. This scenario represents nutrient 'mining'. If RR decreases with an increase in C, it means the tree enriches inherently poor sites than rich sites. This scenario constitutes nutrient 'enrichment'.

### 2.2.2. Modelling spatial extent of tree influence

This analysis was motivated by the question 'Does the tree's root system mine the soil beyond the reach of its crown?' [Barnes and Fagg \(2003\)](#) argue that if the tree is mining nutrients from the surrounding area, a rise in yields should be seen beyond the influence of the trees roots. This implies that yield is a parabolic function of distance. However, a rise in yields (or other variables) beyond the influence of the trees roots may result from factors other than nutrient mining. Therefore, an alternative hypothesis stating that crop yields either decrease or increase monotonically with distance from the trunk was proposed. This was then compared with the implied model of [Barnes and Fagg \(2003\)](#). If *Faidherbia* has a positive influence on the yields (e.g. due to soil enrichment or improvement in microclimate), the highest yield is expected under its canopy and the lowest in the most distant patch outside the sphere of its influence. Conversely, if *Faidherbia* has a negative influence on the yield (e.g. due to shading or allelopathy), the lowest yield is expected in patches closest to the trunk and the highest in the open area. The tree influence and its spatial extent may be best indexed by an effect size metric such as RR that allows visualization of the magnitude and direction of tree influence. In this analysis, the RR was computed as  $U/C$  if the measured variables increase under the canopy (U) relative to the open area (C). Conversely, RR was calculated as  $C/U$ , where the measured variables decrease relative to the open area. The variations in RR could be modelled using a simple two-variable function as follows:

$$RR_z = f(D_z) \quad (1)$$

where  $RR_z$  is the effect size at distance  $z$  (RR values),  $D_z$  the distance and  $f(D_z)$  the monotonically decreasing function of distance (in  $m$  or as a proportion of the CR). This expectation is inherent in the distance–decay models of spatial interaction, the neutral theory of biogeography and biodiversity ([Nekola and McGill, 2014](#)) and ecological field theory ([Liu and Halvorsen, 2012](#)). Initially, the data from [Kamara and Haque \(1992\)](#), [Jiru \(1996\)](#), [Saka et al. \(1994\)](#), [Payne et al. \(1998\)](#) and [Verinumbe \(1993\)](#) were analysed by specifying Eq. (1) as a linear, quadratic, power or exponential functions. However, the exponential function seemed to fit the data better than the others. Therefore, an exponential distance–decay model (EDDM) was chosen as the appropriate analytical framework because it has been empirically demonstrated for single tree influence ([Liu and Halvorsen, 2012](#)), broadly accepted and widely used for modelling spatial behaviour ([Nekola and McGill, 2014](#)). In an unconstrained system, the EDDM is described as follows:

$$RR_z = \alpha e^{-\beta D_z} \quad (2)$$

where  $RR_z$  and  $D_z$  are defined as in Equation (1),  $e$  is the base of the natural logarithm,  $\alpha$  is the intercept and  $\beta$  is the slope. If the magnitude of *Faidherbia* influence is a decreasing function of distance,  $\beta$  will be  $<0$  (i.e. the 95%CI of  $\beta$  will not include 0 or positive values).  $\beta = 0$  represents neutral response. All patches with  $RR > 1.0$  (at distance  $D_z$ ) are interpreted to be within the influence zone of the tree.

### 2.2.3. Modelling growth and canopy development

In order to infer the magnitude and spatial extent of *Faidherbia* influence from tree growth and crown development, both empirical and theoretical scaling models were fitted to the growth and crown size data. This was based on the assumption that H, D and CR conform to the universal scaling rules and optimization theories of plant growth and biomass allocation ([Enquist et al., 2009](#); [West et al., 2009](#)). A number of models based on different theoretical arguments and assumptions predict that H, D and CR scale with each other ([Enquits et al., 2009](#); [Pretzsch and Dieler, 2012](#); [West et al., 2009](#)). Earlier analyses by [Sileshi et al. \(2014\)](#) have shown that the allometric relationship between CR, D and H in *Faidherbia* conforms to predictions of the metabolic scaling theory (MST) more than the other models. In order to estimate the spatial extent of the canopy influence, CPA was estimated from either H or D using allometric models of the following form:

$$CPA = \alpha X^\beta \quad (3)$$

where  $X$  is either H or D,  $\alpha$  is the normalization constant and  $\beta$  is the scaling exponent. For ease of parameter estimation, non-linear models such as Eq. (3) are expressed in linear form as  $\log(CPA) = \log(\alpha) + \beta\log(X)$ . In this expression,  $\beta$  can be perceived as a distribution coefficient for the growth resources between CPA and  $X$ ; when  $X$  increases by 1%, CPA increases by  $\beta\%$  ([Pretzsch and Dieler, 2012](#)). For the empirical model, estimates of  $\alpha$  and  $\beta$  were obtained using Bayesian analysis from the log–log transformed data. In the case of MST,  $\beta$  was set at its theoretical value of  $4/3$  and  $\alpha$  was estimated. In order to assess the model fit to the data, a linear regression analysis of the observed values against the fitted values was conducted. If the model under consideration predicts CPA from either H or D consistently, the resulting regression line will coincide with the 1:1 line (constant slope of 1 and zero intercept).

Based on the predictions of the CPA from the empirical model and MST, size-dependent scenarios were built for the spatial extent

**Table 2**

Robust estimates of the magnitude of *Faidherbia* effects (in RR) on soil properties and crop yields, and the probability (in %) of overall increase or doubling under the canopy relative to the open area.

Category	Variable	Effect size (RR)	Probability of	
		Mean (95% CL) <sup>a</sup>	Increase <sup>b</sup>	Doubling <sup>c</sup>
Soil variables	SOC	1.46 (1.32–1.60)*	96	12
	Total N	1.50 (1.34–1.67)*	86	20
	Extractable P	1.21 (1.03–1.38)*	58	12
	Extractable K	1.32 (1.19–1.45)*	79	8
	Extractable Mg	1.00 (0.91–1.10) <sup>NS</sup>	40	0
	Extractable Ca	1.14 (0.97–1.31) <sup>NS</sup>	31	6
	Soil pH	1.01 (1.00–1.02) <sup>NS</sup>	60	0
Crop yields	Maize	2.50 (2.25–2.76)*	100	49
	Sorghum	1.73 (1.22–2.29)*	NA	NA
	Groundnut	0.84 (0.75–0.94) <sup>NS</sup>	25	6

NA = Sample size not adequate. NS = non-significant.

\*\*Indicates significant increases under canopy compared to open area. Responses under canopy are not significantly different from the open area if the 95% CL of RR encompasses 1.

<sup>a</sup> Figures in parenthesis are 95% confidence limits.

<sup>b</sup> Increase representing overall increase (i.e. RR > 1) relative to the open area.

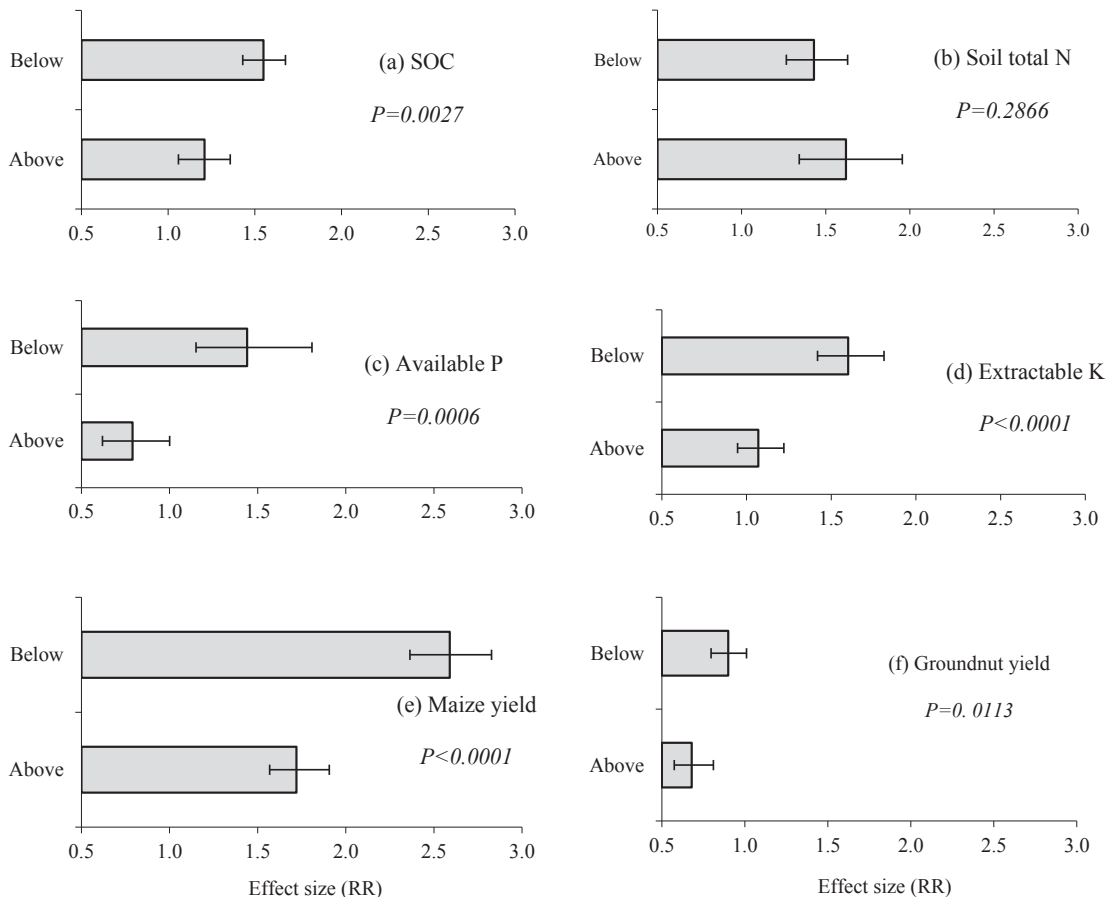
<sup>c</sup> Doubling means RR ≥ 2, i.e. the canopy is two or more times richer than the open area.

of the canopy influences. This was based on the fact that CPA can be used as a proxy for the spatial extent of tree influence because it is a measure of leaf area, leaf biomass (Pretzsch et al., 2015) and the ability of the tree to provide shade, ground cover and protect the soil against erosion. Scenarios of the spatial extent of roots were

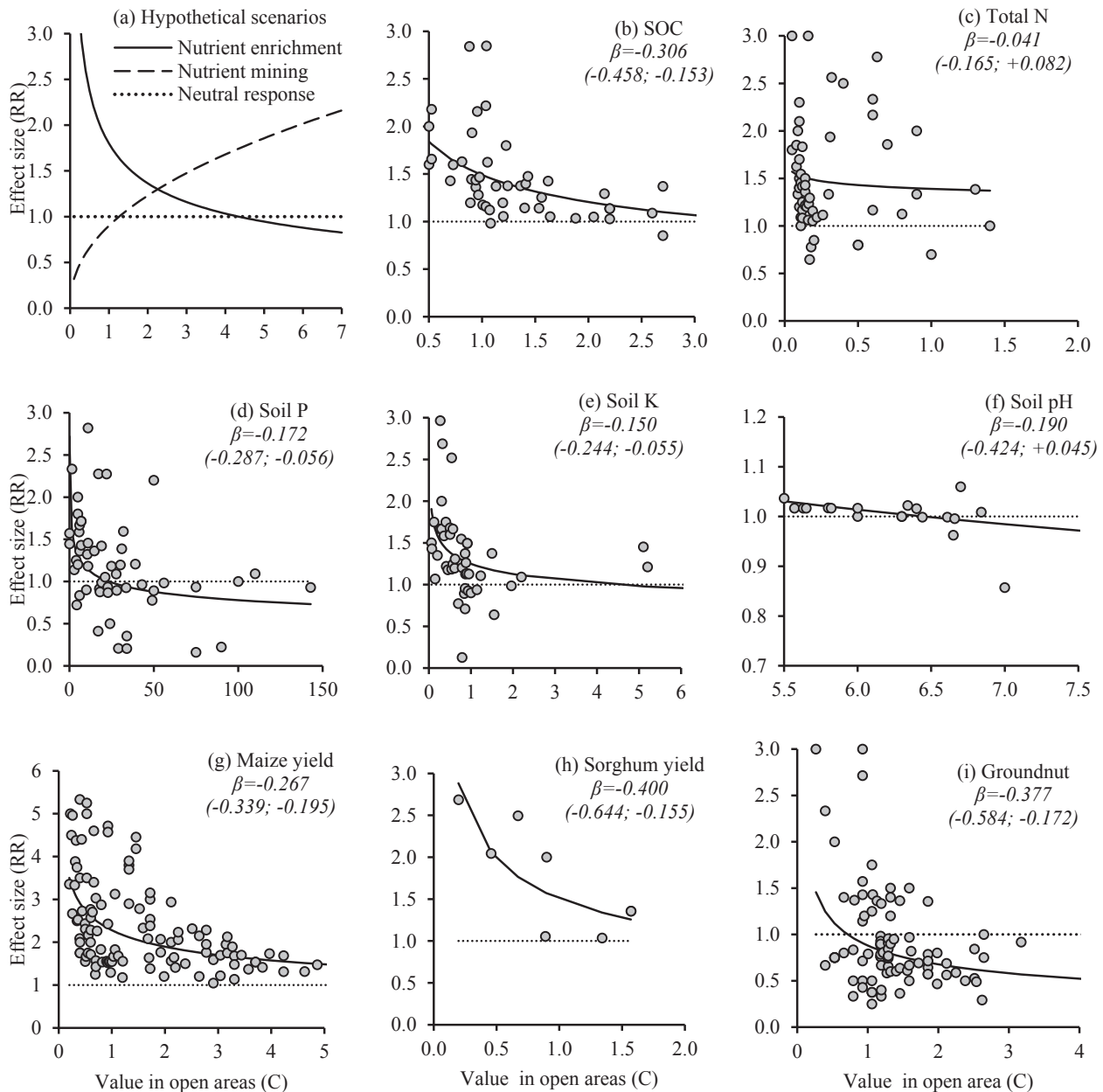
derived from CR based on models of lateral root extension (Gilman, 1989) and empirical observations on *Faidherbia* root growth (Barnes and Fagg, 2003; Dunham, 1991; Phombeya, 1999). According to Gilman (1989), columnar trees will have roots extending 3 times the CR away from the drip line, whereas trees with a broad spreading crown are likely to have roots extending to somewhat 1.5–3 times the CR. *Faidherbia* could assume a columnar crown in its early growth but broadly spreads in later growth. Therefore, three scenarios each based on the empirical model and MST were included: (1) roots remain within the drip line of columnar trees (100% of CR); (2) roots extend up to 2 times the CR (200%); and (3) roots extend up to three times the canopy radius as in broadly spreading trees (300%). These occur in each tree at different stages of stem growth in D. In all cases, the scenarios assume that the root system is symmetrical about the trunk.

2.2.4. Parameter estimation

Parameters of Eqs. (2) and (3) were estimated using a Bayesian approach through the GENMOD procedure in the SAS system. Bayesian analysis was chosen because it (1) is more intuitive than the traditional methods of null hypothesis testing (Kruschke, 2013); (2) provides exact inferences that are conditional on the data; (3) allows small sample inference in the same manner as a large sample; and (4) provides graphical and statistical diagnostics to protect the analyses against potential pitfalls. In this approach, the model parameters are treated as random variables and inferences about parameters are based on their posterior distributions, given the data. GENMOD uses a Markov Chain Monte Carlo (MCMC)



**Fig. 1.** The magnitude of influence of *Faidherbia* trees on soil nutrients and crop yields on below-average and above-average sites. Tukey–Kramer adjusted *P*-values and 95% confidence limits (95%CL) were used to judge the significance of differences between below- and above-average values of each variable.



**Fig. 2.** Comparison of hypothetical scenarios (a) with observed patterns in soil organic carbon (b), nitrogen (c), phosphorus (d), potassium (e), soil pH (f), maize yield (g), sorghum (h) and groundnut (i). Best-fit lines (—) represent Bayesian posterior predictions of  $RR = \alpha C^\beta$ . Dashed lines (.....) represent the 'neutral response' scenario, that is,  $RR = 1$  remains the same across all values in the open area (C) and  $\beta = 0$ . Figures in parenthesis are 95% credible intervals of  $\beta$  for each variable.

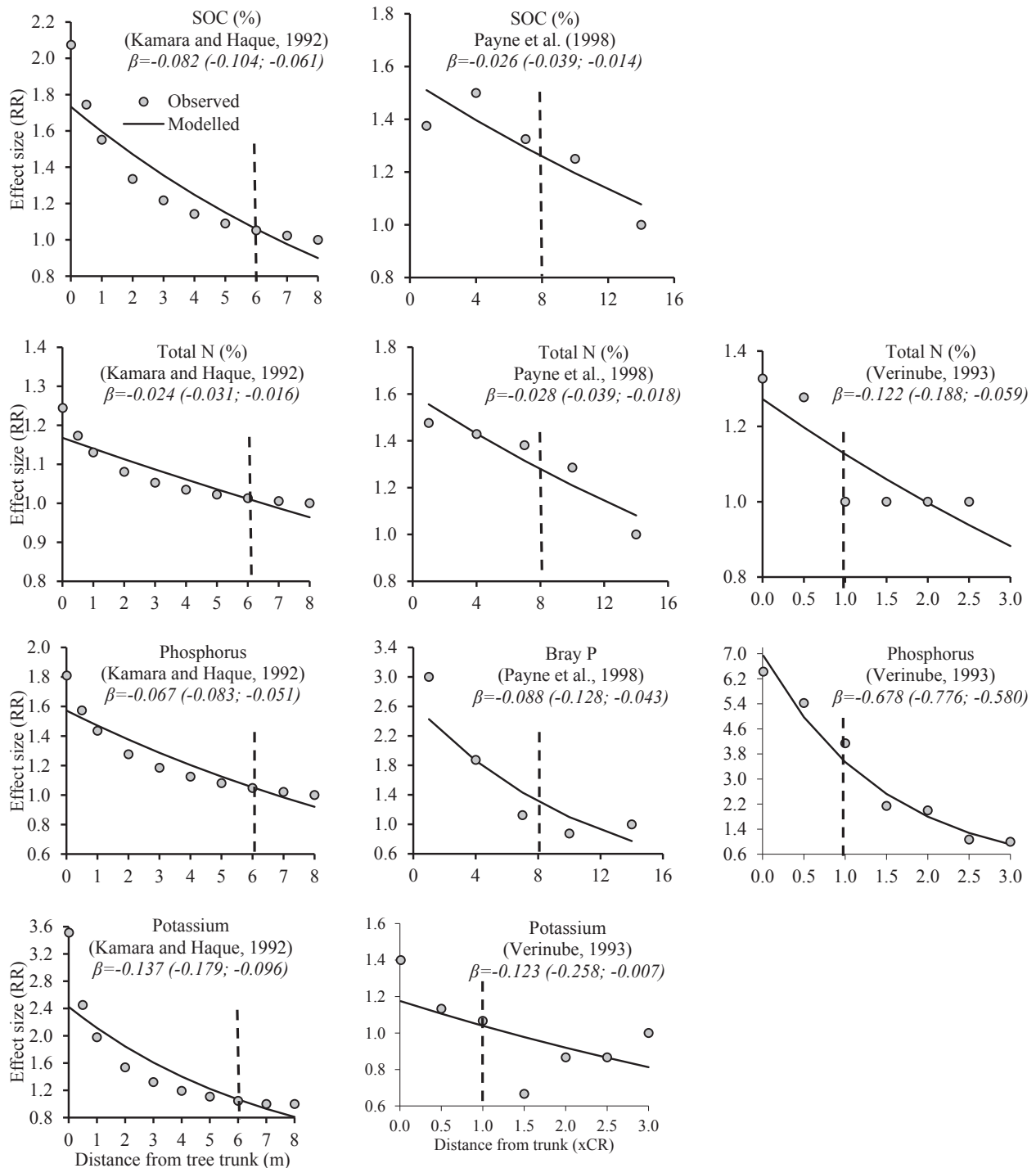
simulation by Gibbs sampling to simulate samples from posterior distributions. The parameters  $\alpha$  and  $\beta$  and their 95% credible interval were estimated through MCMC. These values were used to plot the predicted values in all graphical presentations.

### 3. Results

#### 3.1. The magnitude of tree influence

The SOC contents under the canopy ranged from 0.8 to 5.3% while the values in the open ranged from 0.5 to 3.3%. Results of the meta-analysis indicated that SOC is significantly higher ( $RR > 1$ ) under *Faidherbia* canopy than in the open area (Table 2; Fig. 1). On average, SOC was 1.46 times (46%) higher under canopy than in the

open area. However, the magnitude of increase was significantly higher on sites with below-average SOC content compared to those with above-average SOC values in the open area (Figs. 1 and 2). Similarly, N, P and K were significantly increased ( $RR > 1$ ;  $P < 0.0001$ ) under the canopy than in the open area (Table 2; Fig. 1). Although soil N contents were increased significantly (by 50%) under the canopy (Table 2), the increases on above- and below-average sites did not differ statistically (Fig. 1b). P and K were significantly higher ( $P < 0.0001$ ) under the canopy on soils with below-average than above-average P and K contents in the open area (Fig. 1c and d). Maize yields were 1.5–3 times higher under the canopy compared to the open area. However, the increase is higher under suboptimal conditions, that is, where the yields in the open area are below-average (Figs. 1e and 2g–i). Groundnut yields under

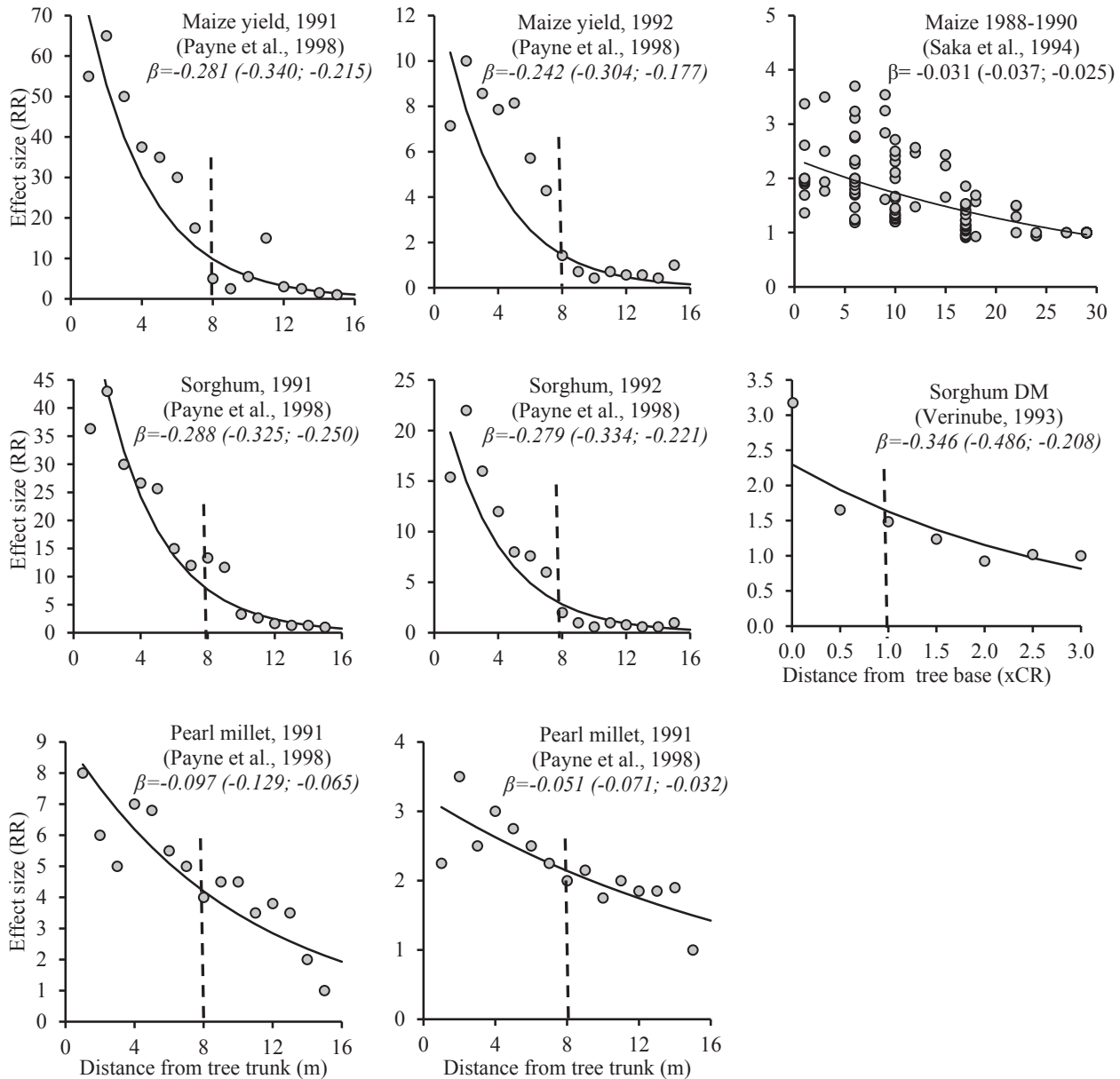


**Fig. 3.** Variation in Faidherbia influence on soil SOC, N, P and K with distance from the trunk. Predicted lines represent  $ES_z = \alpha e^{-\beta D_z}$  generated using the Bayesian posterior parameter values of  $\alpha$  and  $\beta$ . Figures in parenthesis are 95% credible intervals of  $\beta$  for each variable. The dashed vertical line represents the drip line.

the canopy were lower than the open area, except under conditions where the open area yields are  $<1 \text{ t ha}^{-1}$ . The decrease in RR with an increase in C (Fig. 2a–e) supports the nutrient enrichment scenario ( $\beta < 0$ ) rather than nutrient mining ( $\beta > 0$ ). Neutral response was observed only in the case of soil N and pH, where the 95% credible intervals of  $\beta$  included zero (Table 2; Fig. 2c and f).

### 3.2. The spatial extent of tree influence

Figs. 3–7 show that Faidherbia influences on soil properties and crops are greatest ( $R \gg 1$ ) near the tree trunk and gradually decrease towards patches outside the influence zone of the tree approaching  $RR = 1$ . The magnitude of tree influence on SOC, N, P, K (Fig. 3) and crop yields (Figs. 5–6) followed a common pattern of distance–decay. None of the datasets (Figs. 4–6) fitted the parabolic function implied by Barnes and Fagg (2003). Therefore, the



**Fig. 4.** Variation in Faidherbia influence on crop yields with distance from the trunk. Predicted lines represent  $ES_z = \alpha e^{-\beta D_z}$  generated using the Bayesian posterior parameter values of  $\alpha$  and  $\beta$ . Figures in parenthesis are 95% credible intervals of  $\beta$  for each variable. The dashed vertical line represents the drip line.

hypothesis that the tree mines nutrients from the surrounding area is rejected. Fig. 6 presents variation in crop yields with cardinal directions depending on the site. In all cases, the distance–decay pattern of tree influence was clearly demonstrated by the significantly negative values of  $\beta$  and its 95% credible intervals (Figs. 3–5).

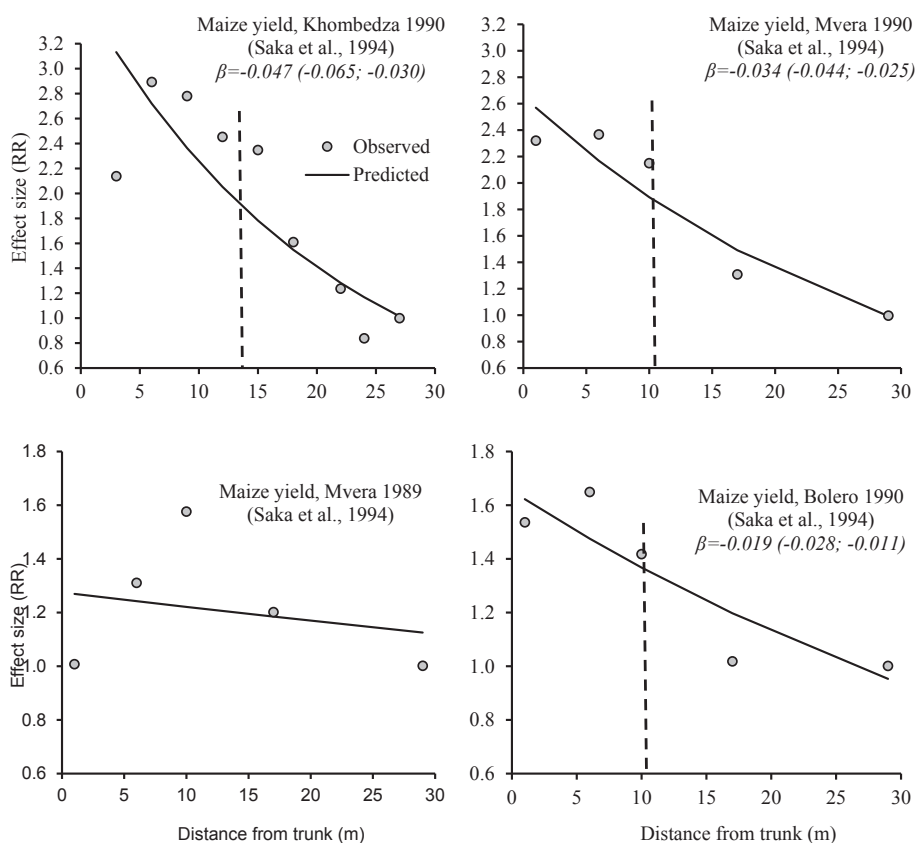
The information given in Figs. 3–5 and inferences from Fig. 7 also indicate that the influence of the tree extends beyond the drip line. It also suggests that the area influenced by single trees is related to the D–CPA relationship. D explained a larger proportion of the variation in CPA ( $R^2 = 0.892$ ;  $P < 0.0001$ ) compared to H, which explained a relatively smaller proportion of variation in CR ( $R^2 = 0.648$ ). The agreement between the observed and predicted CPA values was better with D (Fig. 7b and d) compared to H (Fig. 7a & c). Note that the 95% confidence interval of  $\beta$  was much closer to 1 when D was used to predict CPA (Fig. 7d) than H (Fig. 7c). Thus, tree height was deemed to be a poorer predictor of CPA and all inferences about the spatial extent of canopy influence were based on

predictions of CPA from D (Fig. 7b).

Significant development in CPA appears to start when  $D > 40$  cm (Fig. 7b). The potential area of crown influence is about  $100 \text{ m}^2 \text{ tree}^{-1}$  when D is 40 cm and exceeds  $400 \text{ m}^2 \text{ tree}^{-1}$  when  $D > 120$  cm (Fig. 7b). Assuming densities of 20–30 trees  $\text{ha}^{-1}$  with small trees ( $D < 120$  cm), the potential area of canopy influence was estimated at  $2000\text{--}3000 \text{ m}^2 \text{ ha}^{-1}$ . The equivalent area of influence was estimated at  $4000\text{--}8000 \text{ m}^2 \text{ ha}^{-1}$  for mature trees ( $D > 120$  cm) that usually occur at about 10–20 trees  $\text{ha}^{-1}$ .

Fig. 8 presents size-dependent scenarios of the spatial extent of canopy and lateral root influence inferred from CR. The empirical model (Fig. 8a) predicts that canopy and root influence could extend up to 10 m away from the trunk for trees with D of 20–100 cm in conditions that restrict root spread within the drip line. In conditions that allow lateral root spread of 2–3 times the CR (200–300%), the root influence could extend up to 30 m away from the trunk with the same D range. For larger trees ( $D > 140$  cm), the





**Fig. 5.** Variation in Faiderberbia influence on crop yields with distance from the trunk. Predicted lines represent  $ES_z = \alpha e^{-\beta D_z}$  generated using the Bayesian posterior parameter values of  $\alpha$  and  $\beta$ . Figures in parenthesis are 95% credible intervals of  $\beta$  for each variable. The dashed vertical line represents the drip line.

root influence could extend up to 40 m away from the tree trunk. Predictions based on MST were more conservative; only trees with  $D > 160$  could influence up to 40 m (Fig. 8b).

## 4. Discussion

### 4.1. The magnitude, spatial extent and mechanisms of tree influence

The magnitude of tree influence on SOC, nutrients and crop yields from the meta-analysis provides evidence supporting previous studies. SOC, N, P and K generally fit the pattern of higher concentrations under the canopy of many other trees in semi-arid areas (see Table 4.10 in Breman and Kessler, 1995). Productivity of crops was also reported to be higher under Faiderberbia canopy than in the open area (Bekele, 1982; Dunham, 1989). However, the novel finding from the present analyses is that increases in SOC, N, P, K and cereal productivity under Faiderberbia canopy are generally more pronounced in below-average than above-average conditions. This supports earlier observations (e.g. Boffa, 1999; Libert and Matig, 1996) that Faiderberbia effects may be particularly remarkable in conditions of low soil fertility and below-average rainfall years. For example, cotton yield was higher beneath the trees on less fertile soils (Libert and Matig, 1996). The lower yield response in above-average conditions may be attributed to the 'saturated fertility' effect, that is, the soil by itself does exactly satisfy the nutrient demand of a crop (Janssen and de Willigen, 2006).

The second novel finding is the distance–decay of Faiderberbia influence on soil nutrients and sub-canopy vegetation. Close examination of data from other studies (e.g. Table 3 of Hadgu et al., 2009; Fig. 1 of Jaiyeoba, 1996; Table 2 of Umar et al., 2013; Figs. 3–6, Table 4.10 of Breman and Kessler, 1995) also supports this

trend even with just three distance classes. In addition, Jaiyeoba (1996) demonstrated decreasing trends in cation-exchange capacity paralleling those of SOM and clay with distance from the trunk. This is consistent with the concept of 'single-tree influence circles' proposed by Zinke (1962). A distance–decay pattern of spatial interaction is also implicit in the neutral theory of biogeography and biodiversity (Nekola and McGill, 2014) and ecological field theory (Liu and Halvorsen, 2012). Apparently many other tree species lead to the same pattern of distance–decay in SOC and nutrients. For example, Fig. 12 of Akpo (1998), Fig. 1 of Jaiyeoba (1996), Fig. 3a–c of Ludwig et al. (2004), Fig. 8a–d of Belsky et al. (1989), Table 2 of Weltzin and Coughenour (1990) and Table 3 in Verinumbe (1993) reveal similar patterns of N, P and K. However, unlike other tree species, the main advantage of Faiderberbia is its reverse phenology which allows crops to be grown under its canopy during the rainy season. In addition, the reverse phenology probably maintains favourable micro-scale hydrological processes around the tree. With reduced biomass of the tree crown during the rainy season, it could increase throughfall, decrease stem flow and consequently lower levels of soil erosion and nutrient loss (Libert and Matig, 1996). The spatial variability induced by the tree may also play a critical role in maintaining ecosystem functioning by concentrating limiting resources especially in arid and semi-arid ecosystems. Hence, the promotion of Faiderberbia (or any other tree species adapted to such environments) should be viewed as an important intervention towards increasing resource use efficiency and maintaining ecosystem stability and productivity.

The mechanisms for the improvement in soil nutrients have been widely debated (Barnes and Fagg, 2003; Boffa, 1999; Rhoades, 1997). Some authors have argued that the increase under the canopy is a reflection of nutrient mining by the root system from

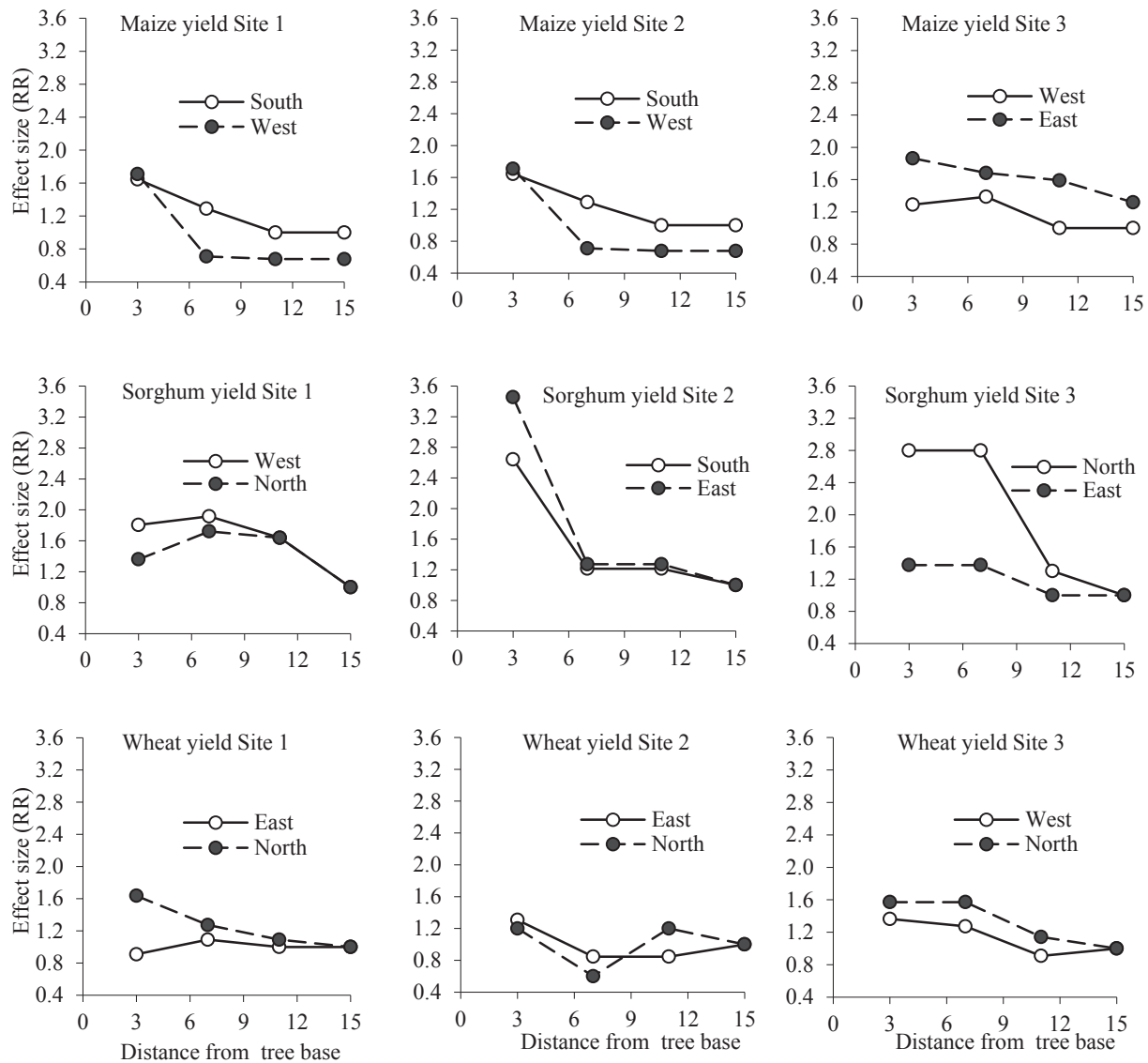


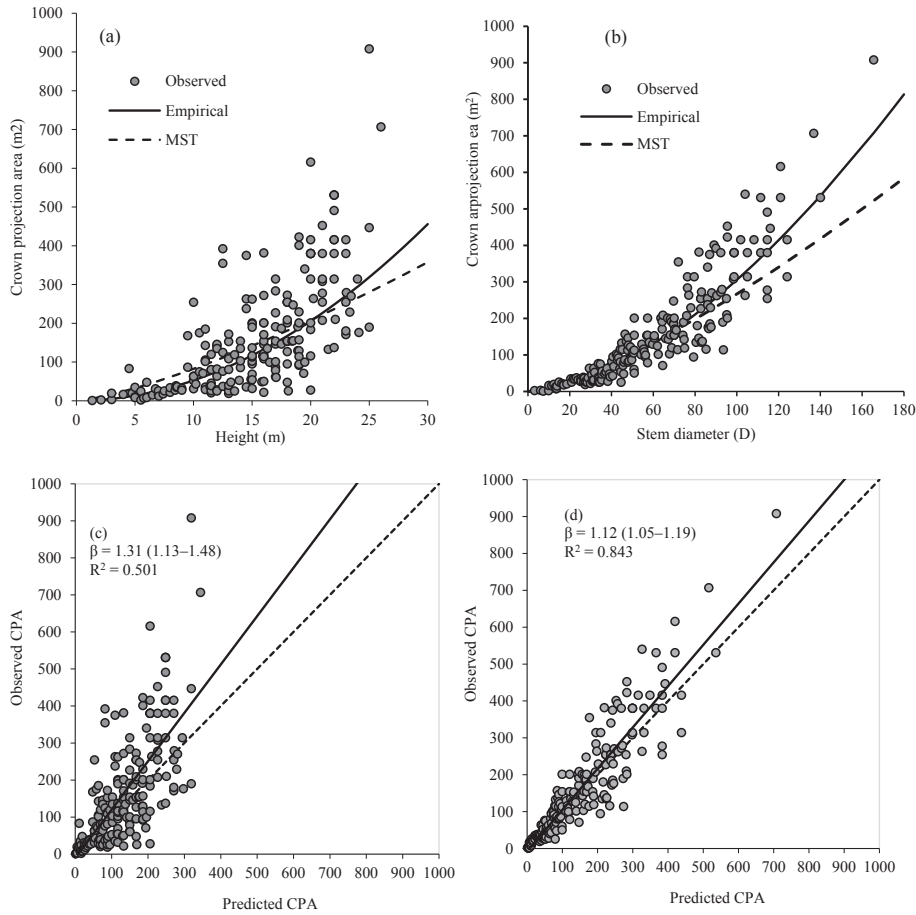
Fig. 6. Variation in maize, sorghum and wheat yield under *Faideherbia* with distance and cardinal directions (redrawn from Tables 1–3 of Jiru, 1998).

the soil beyond the reach of its crown. For example, Barnes and Fagg (2003) cited yield patterns reported by Saka et al. (1994) to support their argument. A closer look at the specific trees where this pattern was observed (Tree 4 in Fig. 1 of Saka et al., 1994) in fact provides evidence contrary to that argument. This specific tree had two neighbouring trees (one of which was only 16 m away), which clearly is responsible for the increase in yield away from Tree 4 (see footnote by Saka). In the nutrient mining scenario, values of RR will increase proportionally with an increase in soil nutrients and crop yields in areas furthest from the tree. However, Figs. 3–5 illustrate the opposite situation. If the tree roots extracted nutrients from outside canopies, this would result in an impoverished area around trees. The finding from this study is in agreement with the studies on other trees in savannas (e.g. Ludwig et al., 2004). These observations and results of the present analyses cast serious doubts about the validity of the nutrient mining hypothesis. More plausible and compelling mechanisms for soil enrichment include (1) deep capture and recycling of nutrients; (2) biological N fixation (BNF) and mycorrhizal association; (3) improvement in soil biological activity; and (4) faecal inputs and (5) atmospheric

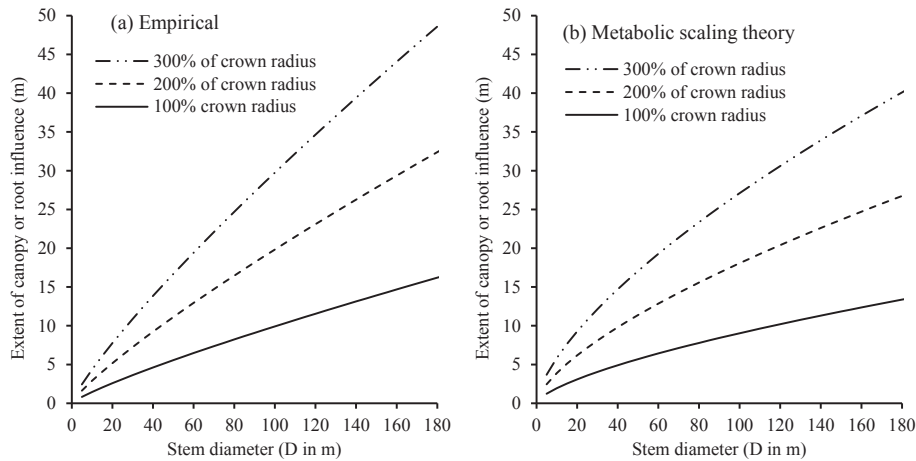
deposition (Rhoades, 1997).

Deep capture involves exploration of the deep soil horizons by the roots that bring nutrients up from depths not accessible to herbaceous plants. These nutrients become an input on being transferred to the soil via litter decomposition. The better growth of vegetation under the canopy could also contribute to the soil in the form of residues and litter. Over the decades of *Faideherbia* growth, organic matter will build up thus enriching the soil in nutrients and improving soil physical properties such as bulk density, porosity and infiltration. Deep capture and recycling through litter fall have been widely documented under *Faideherbia* (Dunham, 1989; Kamara and Haque, 1992; Phombeya, 1999; Umar et al., 2013).

The review of the literature also suggests substantial inputs from N through BNF. However, the role of this has usually been discounted because very few nodules had previously been recovered from *Faideherbia* roots in surface soils. The rhizobial symbionts of *Faideherbia* are slow growing (*Bradyrhizobium* species) occurring in high densities near the water table (Dupuy and Dreyfus, 1992). Other N-fixing bacteria (e.g. *Bacillus circulans*) sometimes found in higher densities (up to 20-fold) under



**Fig. 7.** Empirical and theoretical scaling relationships between crown projection area (CPA) and height (H) or stem diameter (D) per *Faidherbia* tree (a and b) and comparison of the CPA predicted from H (c) and D (d). The solid lines in c and d represent the actual relationship between the observed CPA and values predicted by the empirical model. The dashed lines represent the 1:1 line, that is, the perfect fit between the observed and predicted CPA.



**Fig. 8.** Scenarios of the spatial extent of *Faidherbia* crown and root influence developed based on empirical and theoretical predictions.

*Faidherbia* canopy (Jung, 1966 cited in Barnes and Fagg, 2003) could also contribute to N inputs.

The positive influence of *Faidherbia* on soils could also be attributed to improvement in soil biological properties. More active population of soil fauna and flora have been reported to build up under the canopy than in the open area (see references cited in Barnes and Fagg, 2003; Yengwe, 2011). However, there are serious

gaps in our understanding of how the tree influences changes in soil biological properties. Future research should focus on understanding the variation in soil biota around *Faidherbia* trees and how this influences the soil physical and chemical properties and ultimately primary productivity.

Enrichment through bird droppings, animal dung and urine may also contribute to improvements in soil nutrients. However, some

authors (e.g. Umar et al., 2013) argue that higher nutrient levels under the trees' canopies are not due to dung deposition because some trees in their study area have been fenced up. It must be noted that the residual effect of dung under the trees from distant past may persist even though livestock were excluded for a number of years. Reduced wind velocity below tree crowns may allow airborne particles to settle in soil at the base of trees (Rhoades, 1997).

The present analyses and earlier reports suggest decreases in herbage dry matter (Akpo, 1998) and yields of cereal crops such as barley, wheat, maize, sorghum and millet with distance away from the tree trunk (Boffa, 1999; Hadgu et al., 2009; Jiru, 1996; Louppe et al., 1996). Other crops may show neutral response or may not fit the distance–decay pattern. For example, Payne et al. (1998) recorded maximum yields of cotton within 6–9 m (closer to the drip line) than either outside the canopy or closer to the trunk. The increase in the productivity of cereals under the canopy may be attributed to increases in SOC, soil nutrients, and improvements in soil physical properties and/or microclimate under the tree canopy. The increase in SOC is expected to improve aggregate stability, reduce bulk density, increase infiltration rates and water availability under the canopy. Therefore, it is not surprising that various workers (cited in Barnes and Fagg, 2003) have reported reduction in bulk density and increases in water holding capacity (up to 50%), soil moisture (up to 68%) and available water (up to 100%) under *Faidherbia* canopy relative to the open area. As there is a linear relationship between rooting and grain yields, even small reductions in bulk density can result in substantial improvement in root growth and grain yield. Moderation of the soil temperature at the time of seedling establishment is also an important component of the tree effect. According to Vandenbeldt and Williams (1992) the canopy of the tree considerably reduces soil temperatures closer to the optimum for pearl millet. Similarly, Payne et al. (1998) found soil temperature reduction by as much as 6 °C inside than outside the tree canopy during the day. *Faidherbia* trees may thus play a key role towards increasing crop productivity in drylands. In addition, the spatial variability created by the tree may play a critical role in maintaining ecosystem functioning by concentrating limiting resources. Hence, the promotion of *Faidherbia* should be viewed as an important intervention towards increasing diversity and productivity especially in the nutrient-poor arid and semi-arid ecosystems.

The magnitude of tree influence (RR) does not abruptly approach 1 outside the drip line in all cases (Figs. 3–6). This indicates that the tree influence extends way beyond the canopy projection area. The zone of influence also appears to vary with tree size (height and diameter), crown development and management (e.g. pruning or lopping). Generally, large and mature trees have larger zones of influence than smaller trees (Fig. 7). *Faidherbia* crown develops asymmetrically; greater crown radii on one side of the tree than the other side depending on its location relative to the equator (Ismail, 1986; Werger and Ellenbroek, 1982). The crown of *Faidherbia* trees found south of the Equator show a North/North-west orientation (Werger and Ellenbroek, 1982), whereas crowns of those found north of the Equator show a South/South-west orientation (Ismail (1986). If the trees were to be divided by a plane through the trunk in an East–West direction, the crown biomass estimates of the southern and northern half would have a ratio of 3:1 or 5:2 (Werger and Ellenbroek, 1982). This can lead to the asymmetrical accumulation of SOM, nutrients and soil water.

According to the scenarios presented in Fig. 7b, significant development in CPA starts when plants attain  $D > 40$  cm. At the mean annual  $D$  increment rates of  $1.8 \text{ cm year}^{-1}$  (Gebrekirstos et al., 2014; Sileshi et al., 2014), this is estimated to take about 22 years. Once trees attain that age the potential area of crown influence is

expected to exceed  $100 \text{ m}^2 \text{ tree}^{-1}$  (Fig. 7b). This prediction is in agreement with the crown architecture analysis made in Mali (Barnes and Fagg, 2003). With average densities of 10–20 mature tree  $\text{ha}^{-1}$  commonly reported in the literature (Boffa, 1999), the potential area of canopy influence could exceed was estimated to exceed  $2000 \text{ m}^2 \text{ ha}^{-1}$  depending on the tree size. This is not surprising given the ranges reported in the literature: 200–4000  $\text{m}^2 \text{ ha}^{-1}$  in the Sahel and 500–3000  $\text{m}^2 \text{ ha}^{-1}$  in Western Sudan (Kamara and Haque, 1992). The literature reviewed (Barnes and Fagg, 2003; Dunham, 1991; Phombeya, 1999; Verinumbe, 1993) and the existing models (Gilman, 1989) suggest that extent of lateral root influence could be larger than canopy influence. For example, *Faidherbia* roots extend 2.5 times the CR in the Zambezi riverine woodlands (Dunham, 1991). Other tree species have even larger lateral root spread in dry lands. For example, the roots of *Vachelia* (formerly *Acacia*) *seyal* extended 5.6 times the CR, while *Sclerocarya birrea* roots extend 7.4 times the CR in the top 60 cm of soil (Boffa, 1999). Absorbing roots, which are essential for water and mineral element uptake, are predominantly found beyond the drip line. This is especially the case in water-limited areas and shallow soils (Barbier et al., 2008). As a response to increased aridity, trees generally grow large, lateral root systems with respect to canopy size to extract enough water from the topsoil (Barbier et al., 2008). This may lead to spreading out of the fertility influence, which probably explains the patterns observed in Figs. 3–6.

With expansion in crown and lateral roots, the area of influence may expand as litter and root inputs to the soil accumulate and nutrients are redistributed by lateral roots. Thus, large trees will have larger areas of influence than small ones. In Malawi, larger canopies (mean CR = 12 m or  $D > 120$  cm) resulted in 170% more N mineralization than in the open field during the same growing season, while small trees (mean CR = 3 m or  $D < 25$  cm) did not increase net N mineralization rates. Concentrations of exchangeable cations were also considerably higher under large trees than under small trees (Rhoades, 1995). Soil moisture was 4–53% higher under canopies of large trees than under small trees, while such changes were not apparent under small trees (Rhoades, 1995). Similarly, Bosco (2012) found significantly higher SOC and N content at 10 m beyond the edge of the canopies of large trees ( $D > 100$  cm) compared with smaller trees ( $D < 100$  cm) in the same area in Zambia.

#### 4.2. Areas of concern and recommendation for future research

The review and analysis revealed several areas of concern in research design and application of inferential statistics. Some of these problems are likely to blur patterns and mask tree effects. These are described briefly below and improvements for future research are suggested.

The most common designs involved comparison of measurements under the canopy with those in the open area (e.g. Bosco, 2012; Poschen, 1986; most studies cited in Boffa, 1999). An extension of this design involves further subdivision of the canopy into inner, middle and outer zone of influence based on crown measurements. In either case, researchers treated what is called 'under canopy' as discrete from what is called 'outside canopy' and applied conventional design-based sampling (i.e. random sampling). In most cases, statistical inference was based on analysis of variance (ANOVA) where distance classes were entered as fixed effects. This approach assumes that observations are identically and independently distributed in each distance class. In reality, the measurements are not independent as observations that are closer together show spatial autocorrelation due to their neighbouring physical locations. The problem with the use of ANOVA is further aggravated by the fact that the number of observations in the open area were

fewer (or just one) than under the canopy. It must be noted that the standard *F*-test was originally designed for balanced designs (samples of equal size) and assumes equality of variance. Results from *F*-test could be highly unreliable when samples of unequal size are combined with unequal variance and spatial dependence. These problems are probably the likely causes of the large number of non-significant tests often reported in many studies. Therefore, the usual binary comparison of plots 'randomly' placed under the tree canopy with those in the open area is uninformative. Future studies are encouraged to apply model-based geospatial sampling approaches.

Another key concern in most studies is the failure to include tree size as a variable in the study design and analyses. The majority of the studies focused on large trees of uniform sizes. This bias could distort conclusions about the population effect. As *D* is a good predictor of crown and root spread (Figs. 7 and 8), the study design should include grouping trees according to the *D* class to facilitate effective analysis.

A third concern revealed by the review is the use of the tree canopy vertical projection as the limiting zone in defining the control plots. The majority of studies used open fields or plots located farthest from the tree trunk as controls. Only a few researchers (e.g. Bosco, 2012; Saka et al., 1994) have either checked to make sure the control is truly outside the tree influence zone or acknowledge the problem. Bosco (2012) acknowledged that his assumption that 10 m beyond the canopy of trees ( $D > 40$  cm) could serve as a control was not adequate. The influence of the tree through canopy light interception may greatly exceed the drip line. Woody plants cast long shadows in the morning and late afternoon sunlight thus influencing areas far beyond the canopy. Light transmission approaches 100% only at a distance of about twice the canopy radius (Bremner and Kessler, 1995). From Fig. 8, it can be inferred that even plots located up to 3 times the CR away from the trunk may not be true controls unless trenching is used. Therefore, lack of significant difference between the canopy and what is called the control is probably that the latter is within the influence zone of the tree.

The fourth problem is the failure to account for directional variations and the anomalous crown development in *Faidherbia* (Ismail, 1986; Werger and Ellenbroek, 1982). Fig. 6 and reports by Kamara and Haque (1992) and Rhoades (1995) highlight the need for considering cardinal directions in study design and analyses. In future, researchers need to subdivide the area around each tree into distance classes and take replicate samples along the four cardinal directions. As measured variables change most rapidly close to the trees (Figs. 3–5), it is also advisable to take samples at smaller distance intervals near the bole, but increase the interval with the increasing distance from the tree. Precision for comparing distance will be maximized if sample locations fall in the four cardinal directions.

## 5. Conclusions and recommendations for future research

The main conclusion from the review and analyses is that *Faidherbia* induces significant changes in soil properties under its canopy. The second major conclusion is that *Faidherbia* probably does not mine nutrients from the surrounding open area. A third conclusion is that its influence on soil properties creates spatial patterns that vary with distance from the trunk in a predictable manner. The patterns revealed are consistent with ecological theory and probably many other tree species lead to similar patterns.

A key issue that emerged from the review is the inappropriate use of study design and inferential statistics that mask expected patterns. In the presence of spatial structure and autocorrelation, conventional sampling and statistical methods are inappropriate as

they ignore the effect of distance, direction and the correlation between neighbouring samples. The binary comparison of mean values under and outside tree canopies without taking into account spatial structure and size dependence of tree influence neither addresses the intrinsic causality of patterns nor does it offer a mechanistic insight. Therefore, the usual binary comparison of samples randomly taken under canopy with those outside the canopy should be discouraged. It is recommended that future studies be driven by theory to provide structure and gain mechanistic insights into spatial patterns of influence of the tree in dry lands. Without theoretical considerations, research will be the mere accumulation of situation-bound statements of statistical tests that are of limited predictive ability.

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