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Abstract

A number of studies have tested the effect of woody and herbaceous legumes on soil fertility and maize yields in sub-Saharan Africa. Results have been mixed, however, generating debate about their effects on maize productivity. A meta-analysis was conducted with the aim of evaluating the evidence of yield benefits, or otherwise, from woody legumes and herbaceous green manure legume (HGML) treatments (Ts). Ninety-four peer-reviewed publications from West, East and Southern Africa had data complete enough to qualify for inclusion in the analysis. With unfertilized maize as the control (C) in all studies, 54 publications compared maize yield using HGMLs, 28 using non-coppicing woody legumes, 10 using coppicing woody legumes, 29 using natural fallows and 52 using fully fertilized maize monoculture. Mixed linear modelling of yield difference (D = T-C) and response ratio (RR = T/C) indicated that the yield response to legumes is positive. The mean yield increase over unfertilized maize was highest at 2.3 tonnes per hectare (t ha^{-1}) for fully fertilized maize and lowest at 0.3 t ha^{-1} following natural fallows. The increase in yield over unfertilized maize was 1.6 t ha^{-1} using coppicing woody legumes, 1.3 t ha^{-1} using non-coppicing woody legumes and 0.8 t ha^{-1} using HGMLs. The coefficient of variation in D was highest using natural fallows at 229%, followed by HGMLs at 136%, non-coppicing legumes at 113% and coppicing legumes at 92%. Fertilized maize monoculture had the lowest variability at 70%. Doubling or better maize yields relative to the control (mean RR > 2) was recorded with coppicing woody species in 67% of the cases, non-coppicing woody legumes 45%, HGMLs 16% and natural fallows 19%. However, the doubling or better yields occurred only in sites with low-to-medium potential. Response was higher on Lixisols, which have few plant nutrients compared with Ferralsols and Nitisols. Amending postfallow plots with half of the recommended fertilizer dose further increased yields by over 25%. This suggests that organic inputs from legumes have synergetic effects with mineral fertilizer and that legume rotations can play an important role in reducing mineral fertilizer requirements. In all cases, the 95% confidence intervals did not include 0 for D or 1 for RR, indicating significant increase in yield response. It is therefore concluded that maize yield response to green manure legumes is significantly positive and yield is higher than in unfertilized maize and natural vegetation fallows.

Keywords

Cover crops, relay intercropping, green manure, improved fallow, response ratio, soil fertility

Acknowledgements

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Contents

List of Figures and Tables

1. Introduction

Maize (*Zea mays*) is one of the most widely adapted crops in the world, cultivated at latitudes ranging from 58° N to 42° S. Globally, maize is planted on 130 million hectares annually, accounting for 35% of the crop production. North America ranks first in the world in terms of area planted to maize, followed by Asia, Africa and Latin America. Maize rapidly gained popularity in Africa following its introduction to the continent. The past 25 years have seen farmers in many parts of Africa switch from traditional crops to improved maize varieties. It is now a staple crop (Byerlee et al. 1994, Smale 1995) supplying half of the calories consumed in some countries. Maize accounts for 60% or more of the cropped area in Malawi, Zimbabwe and Zambia, and is almost as dominant in Kenya and Tanzania (Smale and Jayne 2003). Production often does not keep pace with consumption, and African countries import up to 10 million tonnes of maize each year (Cassman 2007). According to statistics compiled by the Food and Agriculture Organization of the United Nations (FAO 2008), the price of maize rose by over 50% in 2001–2007 in most sub-Saharan African countries. This rise is being driven by a rapid rise in petroleum prices and, in response, a massive global expansion of biofuel production from maize (Cassman 2007).

African smallholders have readily adopted improved maize varieties in a number of locations and at various times (Byerlee and Eicher 1997, Smale and Jayne 2003). Since the late 1990s, improved varieties have accounted for an estimated 47% of the maize area in sub-Saharan Africa, and 58% in East and Southern Africa (Byerlee et al. 1994, Morris 2001). The average grain yield in sub-Saharan Africa has stagnated at around 1–2 t ha^{-1} (Figure 1) despite the crop's genetic potential to yield up to 10 t ha^{-1} and the availability of improved cultivars and such inputs as mineral fertilizer. Southern Africa has experienced by far the highest year-on-year variability in yield. The quantity produced and the area harvested has increased in the eastern and western parts of the continent. On the other hand, trends in total area harvested for 1961–2007 show decline in Southern Africa and stagnation in Central Africa (Figure 1). This indicates that little or no suitable farmland remains uncultivated in these regions and that production cannot be increased by area expansion but will require productivity gains.

In most African countries, maize production per capita has not kept pace with population growth over the past 40 years (Smale and Jayne 2003). Therefore, the prospects for meeting food demand in sub-Saharan Africa—which depends mainly on rainfed, smallholder agriculture (Conway and Toenniessen 2003)—will likely remain bleak without major efforts to reverse current unfavourable trends in productivity. Central to this equation is declining soil fertility. Although mineral fertilizer can contribute to overcoming the problem, most smallholder farmers use little or none (Mwangi 1999). This is partly because world fertilizer prices have increased over the years (Hargrove 2008), with the most dramatic increases taking place within the last 2 years. For example, the US

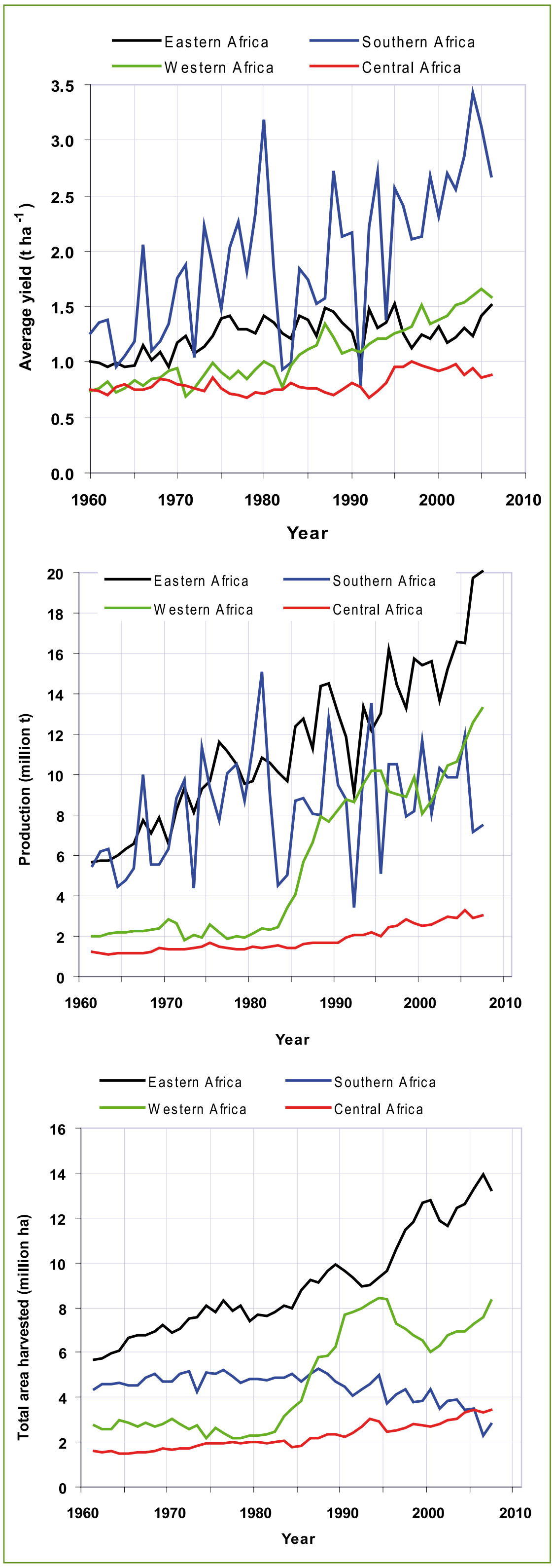

Figure 1. Trends in average maize yield, production quantity and total harvested area in the various regions of Africa. Average yields for 1961–2007 in each region were obtained from FAO (2008).

Gulf price of di-ammonium phosphate soared almost threefold from \$252 t^{-1} in January 2007 to \$752 t^{-1} in January 2008. The Arab Gulf price of prilled urea rose from \$272 to \$415 t^{-1} in the same period, and the Vancouver price of muriate of potash rose from \$172 to \$352 t^{-1}. The reasons for these increases include new demand for food crops including maize as they are diverted to produce biofuels, increased fuel and freight prices, and higher demand for grain-fed meat in such emerging economies as China, India and Brazil (Hargrove 2008). As prices rise, fertilizers become ever more out of reach for poor farmers in developing countries. Structural adjustment programmes and the removal of government subsidies have also made fertilizer less available (Gladwin 1991). Because imported fertilizer must travel long distances over often difficult roads, African farmers pay the highest fertilizer prices in the world (Mwangi 1999, Sanchez 2002). In any case, mineral fertilizers alone cannot sustain crop yields on acidic and poorly buffered Alfisols, as they accelerate the decline in soil pH and exchangeable cations (Juo et al. 1995, Kang and Balasubramanian 1990). Agricultural production needs to be intensified through the application of agro-ecological technologies that do not require a lot of capital or labour. Therefore, organic matter technologies have became important options for improving soil fertility and maize yields in sub-Saharan Africa (Juo et al. 1995, Sanchez 2002, Snapp et al. 1998). The development and extension of this type of agriculture has been called the Doubly Green Revolution (Conway and Toenniessen 2003).

Promising alternatives include the use of nitrogen-fixing and weed-suppressing tree or herbaceous legumes planted as improved fallows, cover crops or green manure (Cherr et al. 2006, Hauser et al. 2006, Mafongoya et al. 2006, Styger and Fernandes 2006). Since colonial times, green manure legumes have been widely tested in many parts of Africa. In the past 2 decades, research has focused on introducing fast-growing woody legumes into

farming systems. Both woody and herbaceous legume fallows harness biological nitrogen fixation, the process by which legumes draw nitrogen from the air and produce compounds that enrich the soil (Cherr et al. 2006, Giller et al. 1997, Sanchez 1999).

Several attempts have been made to review and synthesize knowledge of the functions, processes and capabilities of planted fallows and green manure legumes in Africa (Drechsel et al. 1996, Hauser et al. 2006, Rao et al. 1998, Sanchez 1999, Szott et al. 1999). Though enhanced soil fertility has been widely reported (Rao et al. 1998, Sanchez 1999, Styger and Fernandes 2006), the effects on crop productivity are much debated. The results of individual studies are highly varied, with legumes increasing crop yield in some cases but, in others, having no effect or depressing yields (Hauser et al. 2006, Rao et al. 1998). Attempts to integrate disparate study results through narrative reviews have generally failed to reveal any clear patterns. The limited syntheses that attempted to compare the options have been overly data hungry and often faulty in methodology. For example, Hauser et al. (2006) summarized data from published studies in West and Central Africa by classifying crop responses as 'significant increase', 'neutral' or 'significant decrease' and concluded that 60% of experiments with planted tree fallows had a neutral response.

Such analyses are problematic as they are built on researchers' preoccupation with tests, causing confusion between biological and statistical significance (Lortie and Dyer 1999, Osenberg et al. 1999). Some researchers erroneously equate a small probability (*P*-value) of <0.05 with a 'large effect' and large *P*-values with the 'absence of an effect' (Gurevich and Hedges 1999, Lortie and Dyer 1999, Osenberg et al. 1999). A single study often cannot detect or exclude with certainty a difference in the effects of two treatments that is modest but nevertheless biologically relevant. A trial may thus show no significant treatment effect when in reality such an effect exists—that is, it may produce a false negative result. Single studies often have few replications and generate experiments with low statistical power or false negatives (Arnqvist and Wooter 1995). Likewise, focusing on *P*-values does not reveal effects that are biologically positive but agronomically unimportant.

The diversity of results and lack of clarity regarding maize yield responses have fomented debate among researchers over the effect of legumes on maize yield, as well as confusion among extension and development workers. The lack of a quantitative synthesis of the nature and magnitude of response, and the contrasting reports regarding the potential utility of legume fallows and green manures, highlight the need for a comprehensive and quantitative analysis. The primary goal of this meta-analysis is to provide a more complete representation of maize yield response across different locations, types of soils and weather conditions. This will aid the formulation of evidence-based practical guidelines and policies on the role of organic methods of soil fertility management in sub-Saharan Africa. This paper is an extended version of an article by the authors published in *Plant and Soil* (Sileshi et al. 2008). It has been expanded and reformatted to make the information more relevant and accessible to a wider audience.

2. objectives of this analysis

The specific objectives of this study were to:

1. provide a comprehensive, quantitative synthesis of published reports on the effect of woody and herbaceous green manure legumes on maize yield,

2. conduct parametric estimation of the magnitude of yield response, and

3. determine the factors that moderate the response.

3. Method

We conducted a meta-analysis with the aim of assessing whether or not there is consistent evidence for yield benefits from herbaceous and woody green manure legumes in sub-Saharan Africa. A meta-analysis is a statistical analysis of a large collection of results from individual studies conducted to integrate the findings and address a common question or test a common hypothesis (Arnqvist and Wooster 1995). The basic assumption underlying a meta-analysis is that each study result is an observation that can be thought of as one data point in a larger dataset containing all available observations. If many trials in different geographic areas yield similar results in the various studies, it can be concluded that the effect of the intervention under study has some generality. A meta-analysis reveals what is general among studies and highlights variation among them. Compared with traditional narrative reviews, meta-analysis has the advantage of objectivity and better control of false negative results (Arnqvist and Wooster 1995) and thus the potential to resolve longstanding scientific debates (Gurevich and Hedges 1999).

3.1. Treatments and management practices

Table 1 gives the treatments included in this analysis and the number of peer-reviewed publications for each treatment. The treatments were maize grown after (1) herbaceous green manure legumes (HGMLs), (2) non-coppicing woody legumes, (3) coppicing woody legumes, and (4) natural fallows, as well as (5) continuously cropped, fully fertilized maize monoculture and (6) continuously cropped, unfertilized maize monoculture. Maize rotation with food legumes was not considered in this study.

Green manure legumes are those that are grown to be incorporated as soil amendment and nutrient sources for subsequent crops (Cherr et al. 2006). Data for green manure legumes were obtained from 54 publications. The legume genera reported in the studies reviewed included *Aeschynomene*, *Canavalia*, *Calopogonium*, *Centrosema*, *Chamaecrista*, *Clitoria*, *Crotalaria, Desmodium*, *Glycine*, *Lablab*, *Macroptilium*, *Mucuna, Psophocarpus, Pseudovigna, Pueraria* and *Stylosanthes*. As some genera had many species, and some species were tested on only one site, species-based analyses were avoided. In this analysis, herbaceous green manure legumes managed as rotational fallows were distinguished from relay intercrops. In rotational fallows, legumes are left to grow for 1 year before their biomass is incorporated during land preparation in the following season. Then a maize monoculture crop is planted. In relay intercropping, the legumes are planted within a week to a month after planting maize. After the maize harvest, the legumes are left to grow as short fallows until land preparation for the following maize crop.

Non-coppicing species are woody shrubs or trees that do not regrow when cut at the end of a 2–3 year fallow (Sileshi et al. 2005). They have been widely used in improved rotational

fallows (Kwesiga et al. 1999). Data for this came from 48 publications. Non-coppicing species belonged to the genera *Cajanus*, *Sesbania* and *Tephrosia*. As with herbaceous green manure legumes, rotational fallows using non-coppicing species were distinguished from relay intercrops. In the literature, fallows of non-coppicing species have been variously referred to as 'improved fallows', 'sequential fallows' or 'rotational fallows'. The trees may be left to grow as 1-, 2- or 3-year fallows. In the analysis, this was defined as 'fallow length'. After clearing non-coppicing fallows, maize is cropped for 1, 2 or 3 consecutive seasons. This was defined as 'length of postfallow cropping' in the analysis. In some studies, 25%, 50% or 100% of the recommended dose of fertilizer was applied to the maize cropped after the fallow or in relay intercrops. This variable was defined as 'fertilizer amendment' in the analysis.

Coppicing species are leguminous woody trees that are able to resprout when cut back. Data on these species came from 10 peer-reviewed publications. Coppicing legumes are left to grow for 2 years as fallows. Then they are cut back and maize is planted every year between the stumps. In the long run, this essentially becomes an intercropping system (Akinnifesi et al. 2007). As the stumps resprout, the biomass is cut back 2–3 times during the maize cropping season and incorporated into the soil. Members of the genera *Acacia*, *Caliandra*, *Flemingia*, *Gliricidia* and *Leucaena* were the commonly used coppicing legumes (Sileshi et al. 2005).

Natural fallow develops when plots are left to vegetate naturally, usually with mixtures of native legume and grass species for one to several years (Hauser et al. 2006). At the end of the fallow period, the biomass is incorporated into the soil. Maize is cropped for one to several seasons before the land is left fallow again. Data on maize grown after natural fallows came from 29 publications.

Data on continuously cropped, fully fertilized maize monoculture came from 52 publications. In all cases maize received the fertilizer recommended for the specific site. All 94 publications had continuously cropped, unfertilized maize monoculture as the control. In this analysis, grain yield was used as the response variate because it is often the only true measure of productivity.

3.2. Data retrieval criteria

Meta-analysis requires that the population of studies of interest be explicitly defined. It also requires an explicit definition of criteria determining the eligibility of studies for inclusion, how their quality will be assessed, and what data will be extracted and comparisons made (Gates 2002). This is because, if not carefully considered, the selection criteria can exclude compelling studies or, alternatively, include studies that only tangentially address a hypothesis (Lortie and Callaway 2006). For data to be included in this analysis, the study must

1. have been published in a refereed journal, a peer-reviewed proceedings or as a book chapter;
2. originate in sub-Saharan Africa;
3. report maize yield from at least one legume species used for green manure or improved fallow (treatment) and a corresponding maize yield from an unfertilized plot (control);
4. be a well-designed, randomized and replicated experiment on either a research station or farmers' fields; and
5. report (or make available by personal communication) the mean (and if possible the standard deviation or variance) as numerical or graphical data.

Table 1. Treatments and their legume species, number of peer-reviewed publications and report country

Treatment	Legume species	Publications	Country
Herbaceous green manure	*Aeschynomene* spp.[a]	3	Nigeria, Kenya
	Calopogonium muconoides	3	Ghana, Kenya, Tanzania
	Canavalia ensiformis	5	Ethiopia, Ghana, Tanzania, Uganda
	Centrosema spp.[b]	4	Kenya, Nigeria, Zambia
	Chamaecrista rotundifolia	2	Nigeria
	Clitoria terenata	2	Kenya, Tanzania
	Crotalaria spp.[c]	37	Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Nigeria, Rwanda, Uganda, Zambia, Zimbabwe
	Desmodium spp.[d]	3	Cameroon, Kenya, Malawi
	Dolichos lablab[e]	7	Ethiopia, Kenya, Tanzania, Zimbabwe
	Glycine wigheti	1	Kenya
	Lablab purpureus[e]	19	Ghana, Kenya, Malawi, Nigeria, Tanzania, Uganda, Zambia, Zimbabwe
	Macroptilium atropurpurium	2	Kenya, Tanzania, Zambia
	Mucuna spp. [f]	33	Ghana, Ethiopia, Kenya, Malawi, Nigeria, Rwanda, Togo, Tanzania, Uganda, Zambia, Zimbabwe
	Pseudovigna argenta	1	Nigeria
	Psophocarpus palustris	1	Nigeria
	Pueraria phaseoloides	4	Ghana, Nigeria
	Stylosanthes spp.[g]	5	Ghana, Malawi, Nigeria, Zambia
Non-coppicing trees/shrubs	*Cajanus cajan*	21	Benin, Ghana, Kenya, Malawi, Nigeria, Tanzania, Togo, Zambia, Zimbabwe
	Sesbania spp.[h]	39	Ethiopia, Ghana, Kenya, Malawi, Zambia, Zimbabwe
	Tephrosia spp.[i]	20	Kenya, Malawi, Nigeria, Tanzania, Zambia, Zimbabwe
Coppicing trees	*Acacia* spp.[j]	5	Tanzania, Zambia, Zimbabwe
	Calliandra calothyrsus	2	Zambia
	Flemingia congesta	1	Zambia
	Gliricidia sepium	8	Malawi, Tanzania, Zambia
	Leucaena spp.[k]	5	Tanzania, Zambia
	Senna spp.[l]	4	Tanzania, Zambia
Fertilized maize		52	Burkina Faso, Ethiopia, Kenya, Malawi, Nigeria, Tanzania, Togo, Uganda, Zambia, Zimbabwe
Natural fallow		29	Kenya, Malawi, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe
Control		94	All countries listed above

[a]*Aschynomene* spp. (*A. afraspera, A. histrix*). [b]*Centrosema* spp. (*C. brasilianum, C. pascuorum, C. pubescens*).[c]*Crotalaria* spp. (*C. agatifolia, C. grahamiana, C. juncea, C. ochroleuca, C. paulonia, C. verrucosa, C. zanzibarica*). [d]*Desmodium* spp. (*D. discolor; D. distortum, D. uncinatum, D. viscosa*). [e]*Dolichos lablab* and *Lablab purpureus* refer to the same species, *Lablab purpureus*, but they are presented here separately according to authors' usage. [f]*Mucuna* spp. (*M. cochinchinensis, M. deergiana, M. pruriens, M. veracruz*). [g]*Stylosanthes* spp. (*S. capitata, S. hamata*). [h]*Sesbania* spp. (*S. aculeata, S. bispinosa, S. macrantha, S. speciosa, S. sesban*). [i]*Tephrosia* spp. (*T. vogelii, T. candida*). [j]*Acacia* spp. (*A. anguistifolia, A. crassicarapa, A. julifera, A. leptocarpa, A. nilotica, A. polycantha*). [k]*Leucaena* spp. (*L. diversifolia, L. leucocephala, L.*). [l]*Senna* spp. (*S. siamea* and *S. spectabilis*)

Studies were located by searching through library and computer databases. As this alone does not provide a comprehensive search (Gates 2002), it was supplemented with checking the references of published studies and manual searching through conference abstracts, published proceedings, books, monographs and direct contacts based on our extensive knowledge of studies conducted in sub-Saharan Africa. The study information was then coded, and a database was created in ®Excel. The search turned up160 publications that reported maize yield using improved fallow and green manure legumes, of which 94 fulfilled all the criteria listed above. These 94 were included for analysis (Table A in the appendix).

The publications covered a wide variety of agro-ecological conditions in humid tropical, savanna, semi-humid and semi-arid zones in West, Central, East and Southern Africa (Table 2). Study sites ranged in altitude from low-lying coastal areas of West and East Africa (Benin, Togo and Kenya) at 15 metres above sea level (masl) to as high as 2100 masl in Eastern Africa (Ethiopia). Average annual rainfall at the study sites ranged from 642 millimetres (mm) to 2400 mm. Over 60% of the study sites were in areas that receive unimodal rainfall, while the remaining sites received bimodal rainfall. HGMLs and non-coppicing species were recorded in almost all the countries, while data on coppicing legumes were available from only Malawi, Tanzania, Zambia and Zimbabwe.

Further screening was done on the data in the publications selected for analysis. In cases where the same data were presented by the same author in two or more publications, that result was included only once in this analysis. Meta-analysis assumes the independence of data being analyzed. Including multiple results from a single study may alter the structure of the data, inflate sample size and increase the probability of a false positive result. However, the loss of information caused by omitting multiple results in each study may become a more serious problem than that caused by violating the assumption of independence (Gurevich and Hedges 1999). In this analysis, when more than one treatment was available in the same publication, or when data from different seasons and sites were reported, all were included. This yielded 1681 separate pairs of means (k = treatment and control).

A large proportion of the studies, 63%, were trials located on research stations, and the remaining 37% were on-farm trials. More than 90% of the on-station trials were laid out as randomized complete blocks, and a few had split-plot and other designs with 3–6 replications. On-farm experiments mainly used farms as replicates. As the management of maize was assumed to be similar in the treatment and control plots, the control plots were subject to the same level of variation as the rest of the experiment. It is further assumed that maize variety and treatment effects were not confounded—that is, each study used the same variety in the treatment and control groups. It is assumed that the designs and methods were homogenous across studies and that they produced similar sampling errors (Gurevitch and Hedges 1999).

Table 2. The study sites in each country, altitude, annual rainfall and treatments

Country	Location	Elevation (masl)	Rainfall (mm)	Treatments
Benin	Houeton & Attotinga	80	1156	1, 2, 6
Burkina Faso	Farako Ba	405	1100	1, 5, 6
Cameroon	Minkoameyos	700	1600	1, 6
	Ntui	560	1400	1, 6
Ethiopia	Bako	1650	1210	1, 5, 6
	Jimma	1753	1554	1, 2, 5, 6
	Soboka	1800	1240	1, 5, 6
	Walda	1800	1240	1, 5, 6
Ghana	Kumayili	183	1043	2, 6
	Nyankpala	183	1100	2, 6
	Tingoli	183	1043	2, 6
	Wenchi	50	1150	1, 2, 6
Kenya	Bitange	2100	1800	1, 5, 6
	Bunyore	1420	1800	1, 2, 4, 6
	Ebukanga	1430	1800	1, 2, 4, 5, 6
	Embu	1480	1400	1, 5, 6
	Emwabi	1420	1800	1, 4, 6
	Gatanga	1500	1100	1, 5, 6
	Kabete	1940	1000	1, 5, 6
	Kakamega	1560	1900	1, 6
	Kamingusa	1100	750	1, 5, 6
	Kisi	1600	1700	1, 5, 6
	Kitale	1890	1100	1, 5, 6
	Machakos	1600	750	1, 5, 6
	Maseno	1600	1700	2, 4, 6
	Matoke	2100	1800	1, 5, 6
	Mongina	2100	1800	1, 6
	Mosomi	2100	1800	1, 5, 6
	Mtwapa	15	1209	1, 5, 6
	Muange	1920	900	2, 4, 6
	Nyambane	2100	1800	1, 5, 6
	Nyamweso	2100	1800	1, 5, 6
	Ochinga	1420	1800	2, 4, 6
	Omanga	2100	1800	1, 5, 6
	Ondieki	2100	1800	1, 5, 6
	Pala	1500	1200	1, 6
	Trans Nzoia	1800	1000	1, 5, 6
	Vhiga	1420	1800	2, 5, 6
	Wachara	1500	1000	1, 6
Malawi	Bembeke	1300	1000	1, 2, 6
	Bunda	1100	1100	1, 5, 6
	Champhira	1000	1100	1, 2, 6
	Chisepo	1100	700	2, 6
	Chitedze	1100	1000	1, 6
	Kamwendo	1100	1000	1, 6
	Kasungu	1100	700	2, 5, 6
	Lisasadzi	1100	700	1, 4, 5, 6

Table 2. Continued

Country	Location	Elevation (masl)	Rainfall (mm)	Treatments
	Makoka	1030	1024	1, 2, 3, 5, 6
	Malosa	850	1100	2, 6
	Mathambi	1500	2200	1, 6
	Mbawa	1220	900	1, 6
	Nchenachena	1000	1100	1, 2, 6
	Ntcheu	1300	1000	1, 2, 4, 5, 6
	Vibangalala	1200	1000	1, 4, 5, 6
Rwanda	Karama	1400	1000	1, 4, 6
Tanzania	Hai	1300	1200	1, 6
	Mlingano	1070	1150	1, 5, 6
	Muheza	150	900	1, 6
	Ngomeni	120	1000	1, 6
	Tabora	1190	663	2, 3, 4, 6
	Tanga	60	1206	1, 5, 6
	Tumbi	1200	900	1, 2, 4, 5, 6
Togo	Djaka	79	968	1, 5, 6
	Lome	50	1000	1, 5, 6
Uganda	Bulegeni	1430	1850	1, 5, 6
	Buyemba	1100	1340	1, 5, 6
	Iganga	1160	1350	1, 4, 6
	Kawanda	1200	1400	1, 6
	Kibale	1132	1370	1, 5, 6
	Magada	1100	1340	1, 5, 6
	Mugaye	1100	1340	1, 5, 6
	Namulonge	1150	1250	1, 5, 6
Zambia	Chadiza	1177	1500	2, 3, 4, 5, 6
	Chalimbana	1280	900	2, 3, 4, 5, 6
	Chibombo	1300	1000	1, 6
	Chipata	1025	1000	1, 2, 3, 4, 5, 6
	Kagoro	1003	850	1, 2, 3, 4, 5, 6
	Kalichero	1025	1000	2, 3, 4, 5, 6
	Katete FTC	1003	1000	2, 3, 4, 5, 6
	Mangwe	1025	1000	2, 3, 4, 5, 6
	Mansa	1181	1100	1, 6
	Masumba	490	960	1, 2, 3, 6
Zimbabwe	Chihota	1200	1000	1, 2, 6
	Chiwundura	1200	800	1, 6
	Domboshawa	1475	750	3, 5, 6
	Hwedza	1400	900	1, 4, 5, 6
	Makoholi	1200	650	1, 5, 6
	Mangwende	1500	1100	2, 6
	Mlezu	1200	800	1, 5, 6
	Mugadza	1393	1100	2, 4, 6
	Zvimba	1200	800	1, 5, 6

1= herbaceous green manure, 2 = non-coppicing legume, 3 = coppicing legume, 4 = natural fallow, 5 = fertilized maize, 6 = unfertilized maize monoculture (control), masl = metre above sea level, mm = millimetre.

3.3. Choice of the effect size

In meta-analysis, choosing an effect size involves conceptual issues that link the metric to the hypothesis, as well as statistical ones that require some knowledge of the properties of possible estimators of the desired quantity (Gates 2002, Gurevitch and Hedges 1999, Hedges et al. 1999). Meta-analysis can provide meaningful summaries only if the effect size index is a meaningful summary of any one experiment (Gurevitch and Hedges 1999, Hedges et al. 1999). In this analysis we used the mean difference in yield between the treatment and control (D = *T*-*C*) because of its ease of interpretation in terms of absolute yield increase in t ha^{-1}. In addition to D, we used the response ratio (RR) in consideration of its application in ecology (Gurevitch and Hedges 1999, Hedges et al. 1999, Osenberg et al. 1999) and agriculture where yields from treatment and control were compared (Miguez and Bollero 2005, Tonitto et al. 2006). The RR is the ratio of the mean of some measured quantity in experimental (*T*) and control (*C*) groups that quantifies the proportionate change that results from experimental manipulation (Hedges et al. 1999). As the yield difference determines potential gains, to be weighed against the required investment and input costs, the bulk of the discussion addresses yield differences. RR was log-transformed to ensure normality (Hedges et al. 1999).

3.4. Assessing publication bias

Publication bias and normality in the data were assessed using descriptive statistics and normal quantile-quantile (Q-Q) plots. The normal Q-Q plot is an effective diagnostic tool for checking normality in the data and publication bias (Wang and Bushman 1998). It was constructed by plotting the empirical quantiles of the data against corresponding quantiles of the normal distribution of the log-transformed RR and D. If the empirical distribution of the data is approximately normal, the points on the plot will fall on a straight line defined by Y = X with the slope equal to unity, where Y is the ordinate and X is the abscissa. The natural variation of effect size can be expected to be approximately normally distributed, so skewing may be an indication of publication bias. The extent of bias can be estimated by the difference between mean and mode of the distribution (Wang and Bushman 1998).

3.5. The statistical model

Special analytic methods are needed because the log response ratios (L_i = log [RR_i]) and yield differences (D_i) are not expected to be identically distributed, as the variances of the observations (v_i) are assumed to be unequal (Hedges et al. 1999). There are two components of variation in the L_i and D_i , within studies (v_i) and between studies ($\bar{\sigma}^2_\lambda$). The variance within studies is due to sampling variation in the estimates for each experiment, i.e., variation of L_i and D_i about the parameter value. The variance (v_i) for each i^{th} study was computed following Miguez and Bollero (2005). Variance between studies represents the variation between experimental results that would remain even if the estimates from all of the experiments had negligible internal standard errors. This variance is often of scientific interest because it quantifies the degree of true, non-sampling variation in results across experiments (Hedges et al. 1999). In summarizing results from *k* independent studies (pairs of means), effect sizes were weighted by the reciprocal of their variances, as this gives greater weight to experiments whose estimates have greater precision and hence increases the precision of the combined estimate (Miguez and Bollero 2005).

A mixed modelling approach was adopted in this analysis because it enables inferences about treatments that apply to a population of studies (Miguez and Bollero 2005). Also making the mixed modelling procedure appropriate was that the data gathered across studies were unbalanced with respect to predictor variables. The general form of mixed-effects linear models is as follows:

$$L_i = X\beta + Zb + \varepsilon$$

where L_i is the (n×1) vector of summary statistics (log RR or D) from a number of k-related but independent studies, X(n×p) is the design matrix describing study characteristics that influence fixed effects, β(p×1) is the vector of fixed-effects parameters, Z(n×q) is another design matrix describing the covariates for the random effects, b(q×1) is the vector of random effects or the residuals between studies, and ε(n×n) is the matrix of residuals within a study.

To make the model more realistic the following assumptions were made:

1. Observations from the same study will be correlated, which was allowed for by including a random term (s_j) with variance σ_s^2.
2. Many of the studies in the database contained observations from different seasons and/or locations, which imposes further structure on correlation within a study that can be represented by further nested or crossed random effects.
3. The treatment effect is assumed to vary among studies not just from sampling errors but because the environment of the study modifies the true effect in that study. This can be modelled with a random study × treatment interaction term with variance σ_t^2.
4. The variation in treatment effects across studies may not be the same for each treatment, so the random effect in assumption 3 should be heterogeneous among treatments.
5. The residual within a study could also be heterogeneous among studies, which is allowed for by letting the residual variance be σ_j^2 for study *j*.
6. The treatment effects may be modified by measured environmental covariates, and most of these modifications were needed to estimate the 95% confidence interval correctly. The Akaike information criterion (Akaike 1973) was used as a measure of parsimony in deciding on the linear mixed model that gives the correct estimate of the 95% confidence interval.

As a meta-analysis must be based on studies that specifically and correctly investigated a research question, comparison of treatments was restricted to those studies that satisfied specific criteria, and parameter estimation proceeded in two steps. In the first step, RR and D were estimated after excluding data where legume fallows were amended with mineral fertilizer to allow a reasonable comparison of legume fallows, natural fallows and fully fertilized maize. In the second step, analysis of coppicing and non-coppicing legume data was conducted separately to allow a comparison between legume fallows amended with fertilizer and those not amended.

We were specifically interested in how covariates describing biological characteristics of the study species or aspects of the experimental design and management influenced the magnitude of yield response. The covariates were soil type, altitude, rainfall, legume management (fallow or relay), length of fallow and length of postfallow cropping. Since individual studies reported soil types differently, soils grouped under the United States Department of Agriculture and other systems were assigned the equivalent FAO soil group (Figure 2) name through *pro parte* matching. About 13% of the data points were excluded from the analysis because the soil type was either not reported or generalized to cover a large area such as several farms. Some soil types, notably Andosols, were excluded as the data points for some treatments were very few. Altitudes were classified as high (>1400 masl), mid (700–1400 masl) and low (<700 masl). Long-term average annual rainfall was also classified as low (<700 mm), medium (700–1400 mm) and high (>1400 mm). A site productivity index was derived from the control maize yield as 1 = <0.50 t ha^{-1}, 2 = 0.51–1.00 t ha^{-1}, 3 = 1.01–1.50 t ha^{-1}, 4 = 1.51–2.00 t ha^{-1}, 5 = 2.01–3.00 t ha^{-1}, 6 = >3.00 t ha^{-1}. This is

based on the logic that the control maize yield can serve as a proxy for site productivity, as it represents the potential yield at a particular site under particular management conditions, integrating the effects of soil, climate, pests, etc. For convenience, scores 1 and 2 defined sites with low potential, scores 3 and 4 medium potential, and scores 5 and 6 high potential.

In all cases, means values and 95% confidence intervals of the yield differences and response ratios are presented. Since the response ratios were log transformed before analysis, the means were transformed back to the original scale in all presentations. Statistical inference was based on the means and their confidence intervals, rather than on the results of significance tests, to focus on the size and uncertainty of results. The 95% confidence interval functions as a very conservative test of hypothesis that attaches a measure of accuracy to a sample statistic (Sim and Reid 1999). It therefore allowed us to estimate the degree to which the observed value is likely to be the 'true' (or population) value. Means were considered to be significantly different from one another if their 95% confidence intervals did not overlap. Mean yield differences and response ratios were considered significantly different from 0 and 1, respectively, if their 95% confidence interval did not overlap those values.

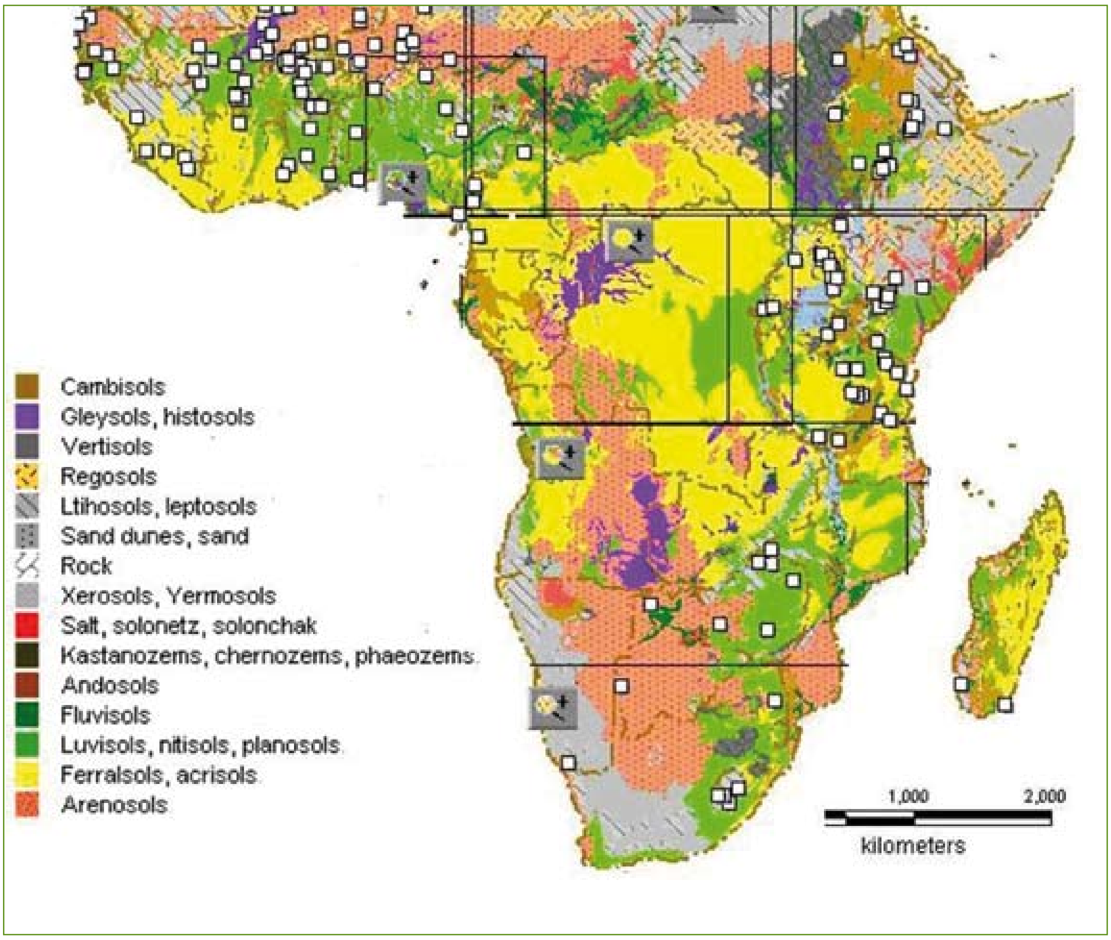

Figure 2. Soil map of Africa according to the FAO/Unesco classification.

4. Results

4.1. Variability in response

The distribution and summary statistics of mean yield differences are presented in Figure 3. The variability in yield difference was highest in natural fallows and lowest in continuously cropped and fertilized maize monoculture. Substantial differences between the mode and mean indicate distinct asymmetry in the distribution of effect size. The normal Q-Q plots also indicate the presence of asymmetry and, potentially, publication bias. In the Q-Q plot of the yield difference, the curve is slightly U-shaped, indicating that the data are skewed to the right (Figure 4). The plot of the response ratios (RR) is S-shaped and has one bump below and another bump above the straight line, suggesting that the studies come from two different populations.

4.2. Magnitude of response

Figure 5 presents the scatter plots of the relationship between the observed yield in the treatment (Y axis) and the yield of the respective control plot (X axis) for each study. Most of the data points from fertilized maize monoculture are above the Y = 2X line (RR > 2), showing that in most studies the sites are indeed responsive to soil fertility improvement, especially in that RR > 2 means a doubling of maize yield relative to control. The same is true for coppicing fallows and, to a lesser extent, non-coppicing fallows. In the case of herbaceous green manure and natural vegetation fallows, most of the data points fall below the Y = 2X line. In all treatments, a doubling of yields over the control was achieved where the control plots yield less than 4 t ha^{-1}. A tripling of yield over the control (Y = 3X) occurred only where the control plots yield less than 2 t ha^{-1}.

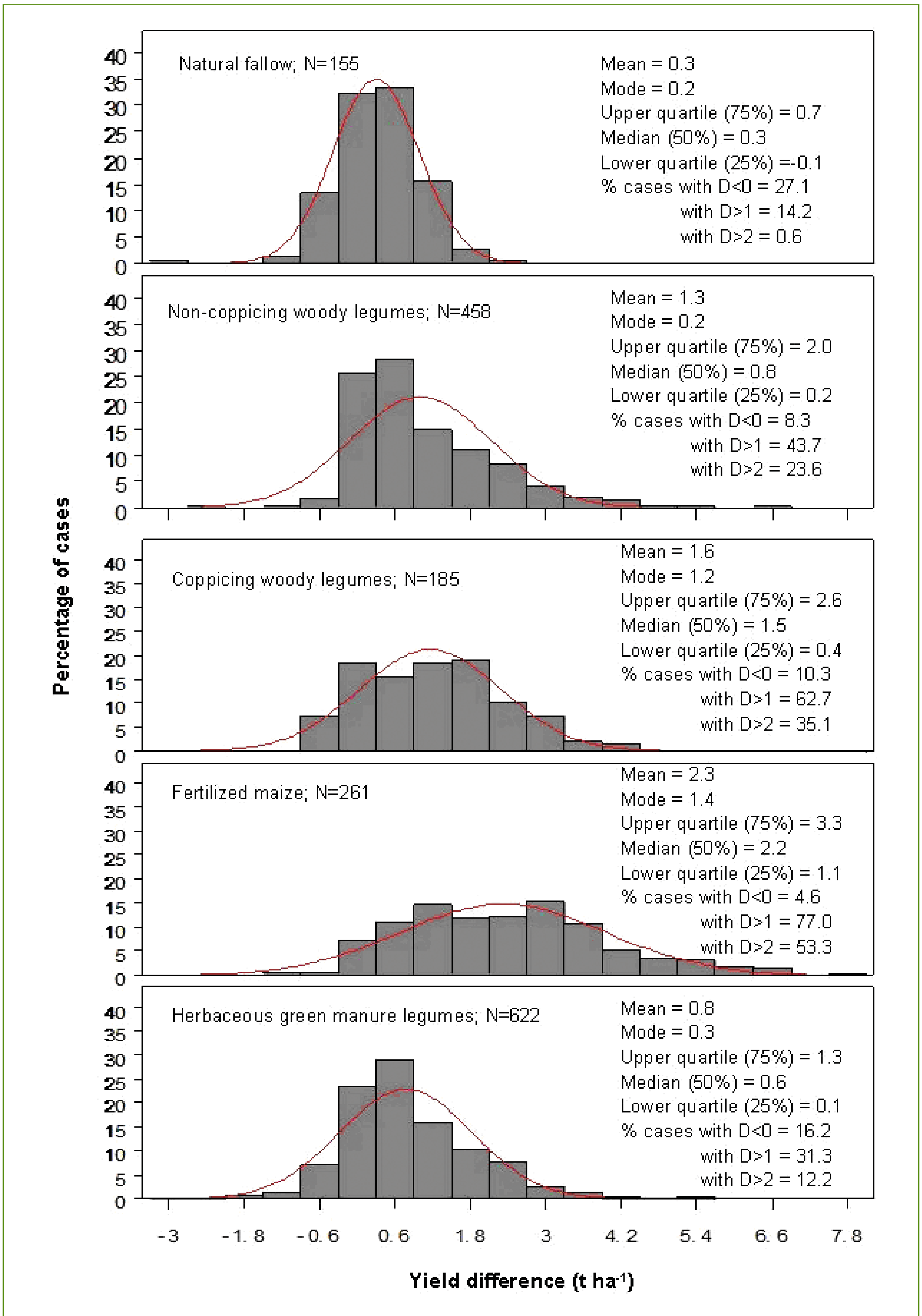

Figure 3. Distribution of maize yield differences in the various treatments, shown as bars, with the smooth line representing a normal distribution.

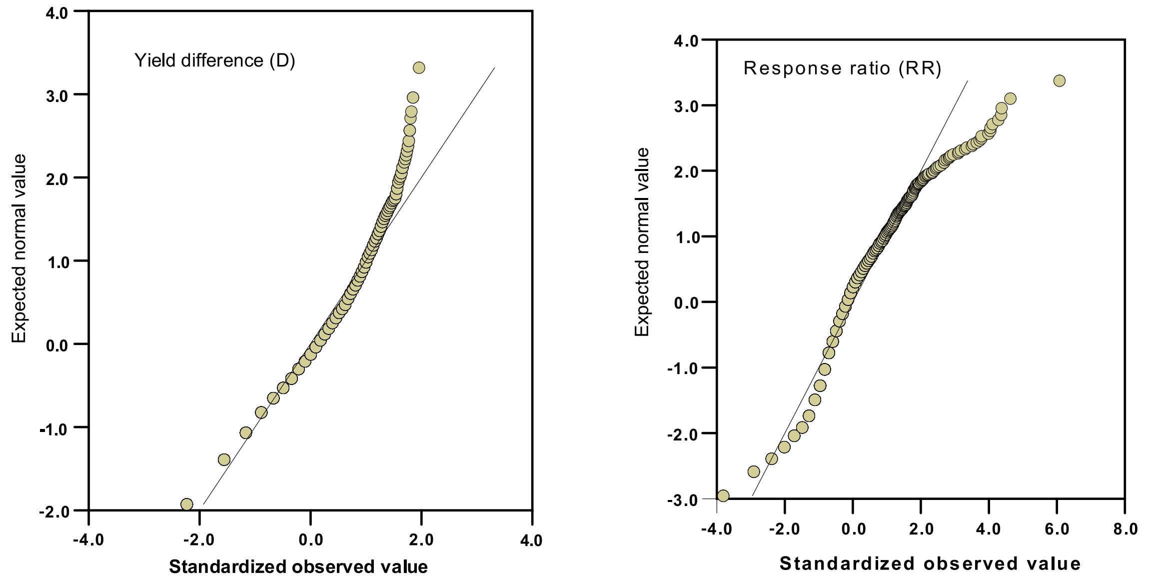

Figure 4. Normal quantile-quantile plots of the yield differences and log-transformed response ratios for exploring the normality assumption and publication bias. The circles represent individual observations, while the solid line (Y = X) shows the standard normal distribution.

Figure 6 presents the cumulative proportion of cases in each yield difference (D) category. Average D was highest at 2.3 t ha^{-1} in fully fertilized maize and was lowest at 0.3 t ha^{-1} following natural fallow. The probability of achieving D > 1.0 t ha^{-1} in fertilized maize monoculture was 0.77 but only 0.14 in natural fallow. In over 84% of the cases, herbaceous green manure, non-coppicing and coppicing legumes had a positive effect (i.e., D > 0) on maize yield. Mean D was 1.6 t ha^{-1} in coppicing woody legumes, 1.3 t ha^{-1} in non-coppicing woody legumes and 0.8 t ha^{-1} in HGMLs (Figure 3).

Maize yield was more than double that of the control (RR > 2) in 67% of the observations in coppicing woody fallows. Doubling of yield was observed in 45% of non-coppicing woody legume fallows, 16% of HGMLs and 19% of natural fallows. Yield increase was higher on sites where the control plot achieved less than 2 t ha^{-1} (low-to-medium potential) than on sites with high potential (Figure 7). All treatments except natural fallow showed maximum yield increases on sites with medium potential. In all cases except HGMLs, the yield difference from the control became narrower as site productivity increased (Figure 7).

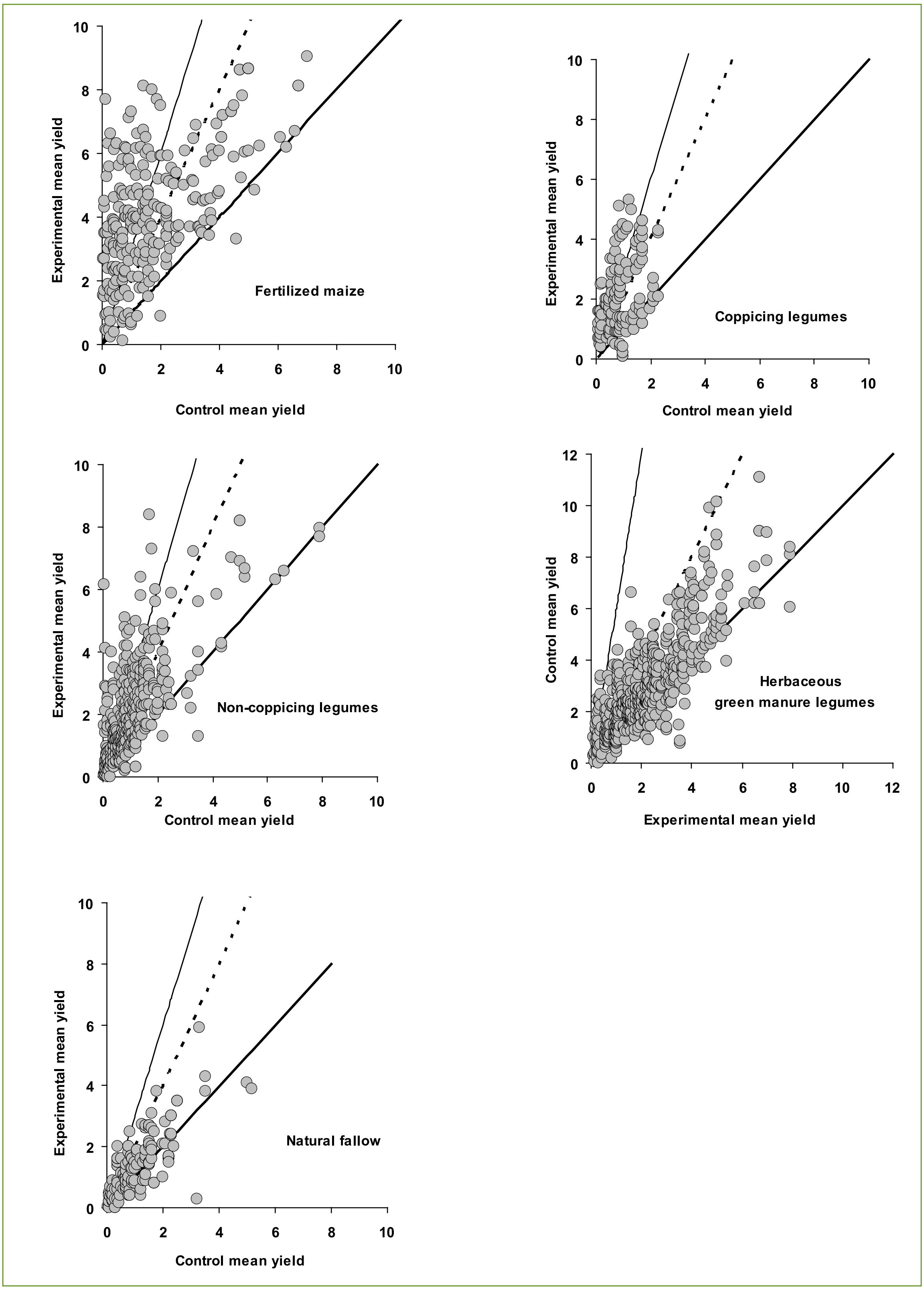

Figure 5. Scatter plots of treatment yields against control yields (t ha-1). The solid line shows where the treatment and control yield are the same (Y = X, RR = 1 and D = 0). The broken line (Y = 2X) shows where the treatment plots yield twice as much (RR = 2), and light line (Y = 3X) three times as much (RR = 3).

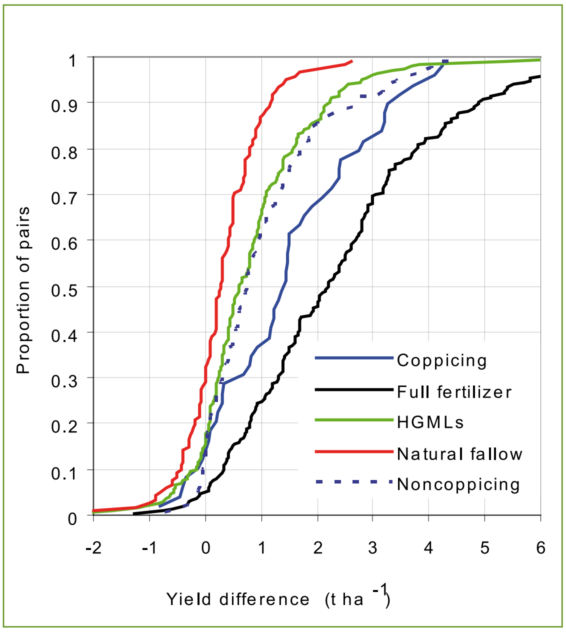

Figure 6. Plots of cumulative proportion of pairs against change in yield.

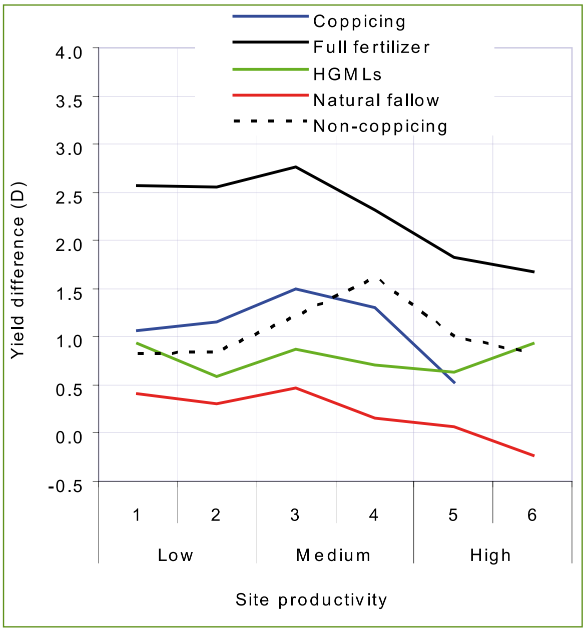

Figure 7. Plots of change in yield against site productivity class.

The 95% confidence intervals of response ratios and yield differences (Figure 8) show similar patterns. In all systems except natural fallow, the average response ratio is clearly above 1. The average differences are clearly above 0 for all the systems including natural fallow, indicating significant increase in response to legumes over the control.

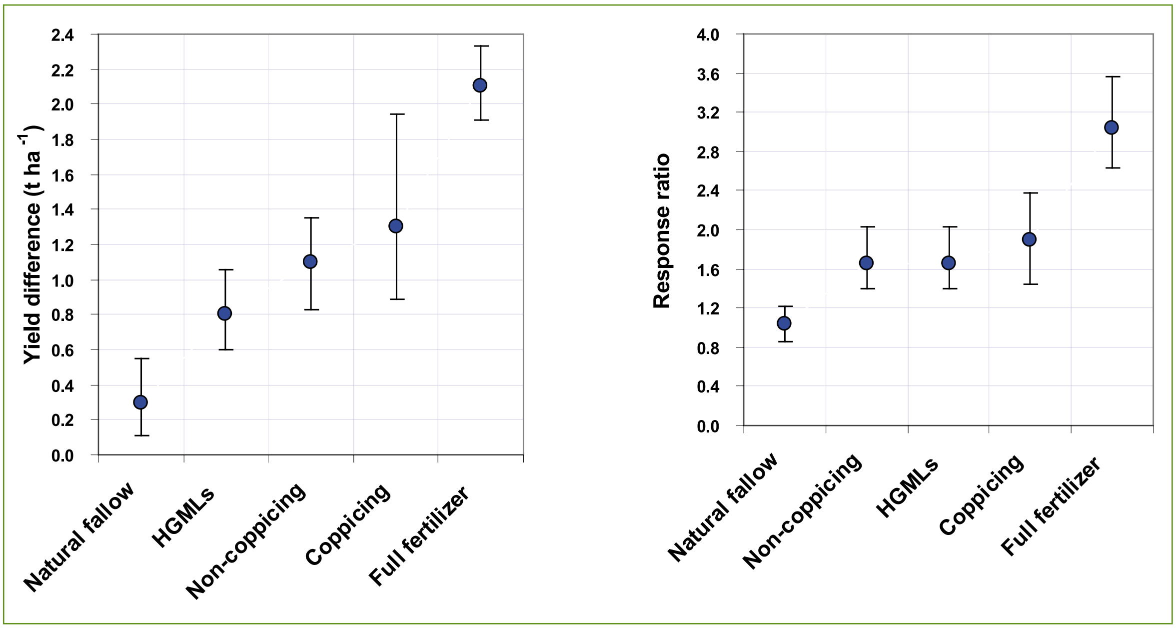

Figure 8. Means and 95% confidence intervals of yield differences and response ratios in the various treatments excluding legume fallows amended with fertilizer. Means (circles) are not significantly different from one another if their 95% confidence intervals (error bars) overlap. The means and 95% confidence intervals of the response ratios are in the original (back-transformed) scale.

4.3. Compensation for yield forgone during fallow phase

A 1-year or 2-year fallow-maize rotation is said to compensate for the yield forgone during the fallow phase if the response ratio is greater than or equal to 2 (RR ≥ 2). A 3-year fallow compensates when RR ≥ 3. In only 22% of the cases with 1-year fallows of HGMLs is RR ≥ 2. Some 65% of the cases with 2-year herbaceous legume fallows had RR ≥ 2, indicating compensation for the yield forgone during the fallow period (Figure 9). With non-coppicing woody legumes, 56% of the 1-year rotations and 51% of the 2-year rotations compensated for the yield foregone. In 3-year rotations, compensation for the forgone yield (RR ≥ 3) was noted in only 45% of the cases (Figure 10).

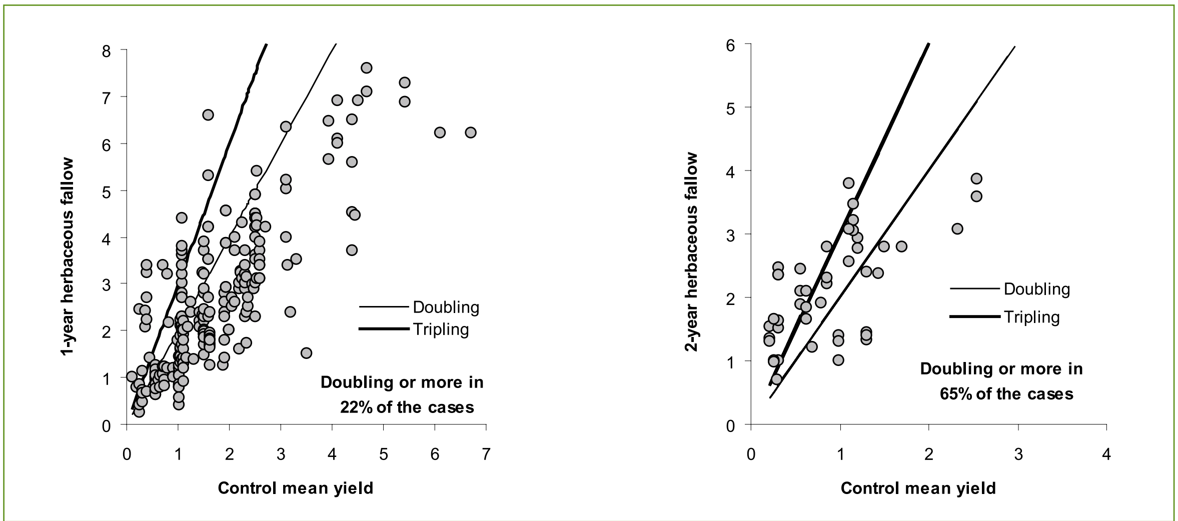

Figure 9. Compensation for yield forgone during fallowing for 1 and 2 years with herbaceous green manure legumes.

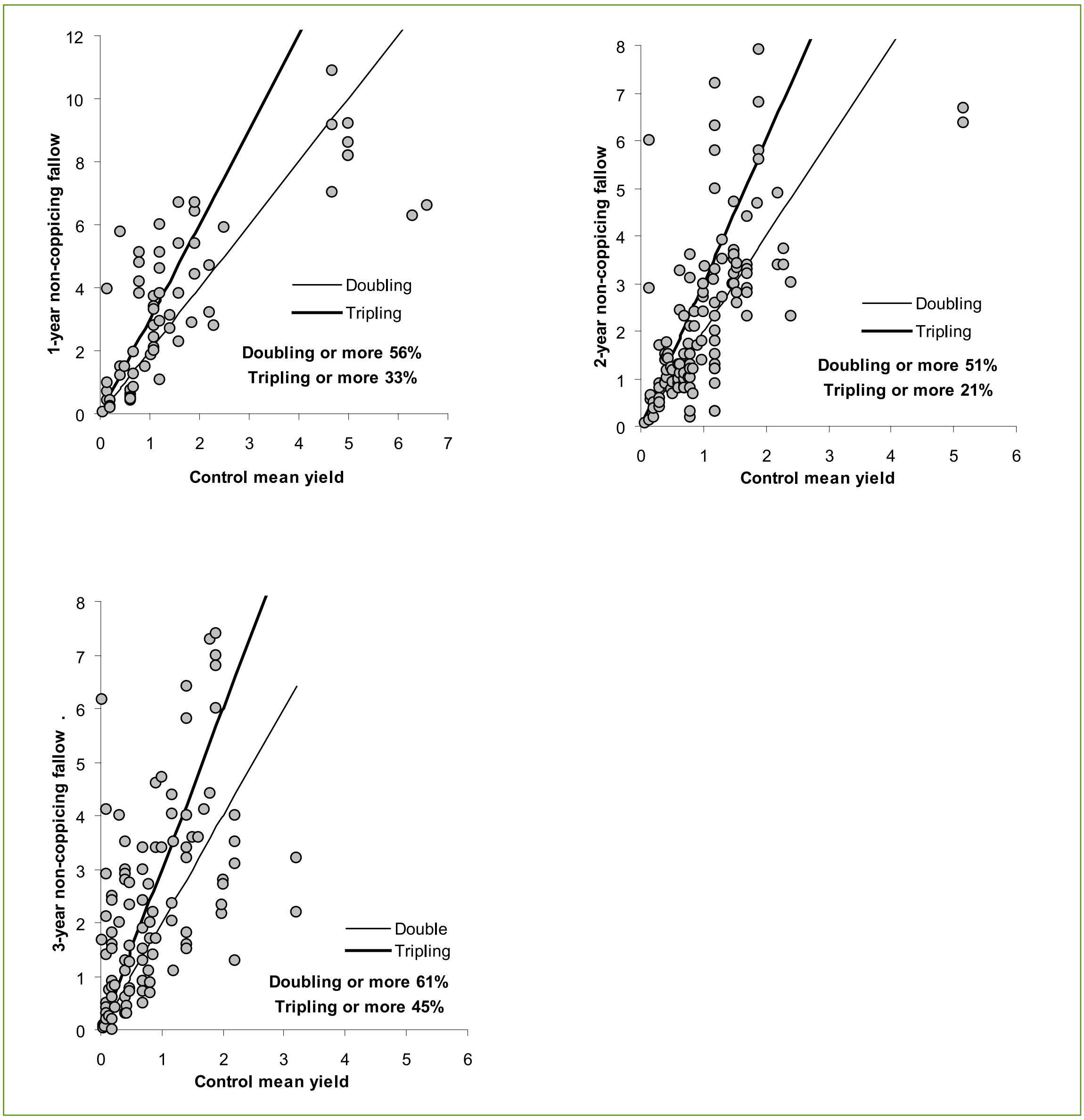

Figure 10. Compensation for yield foregone during fallowing for 1,2 & 3 years with non-coppicing woody legumes.

4.4. Moderators of response

4.4.1. Fallow length and management

Response to HGMLs managed as pure fallows was higher than to those managed as relay intercrops. The 95% confidence interval of the mean RR in rotational fallows (1.49–1.90) did not overlap with those in relay intercrops (1.12–1.43). Neither did the 95% confidence interval of mean D in rotational fallows (0.8–1.2 t ha^{-1}) overlap with that of relay intercropping (0.4–0.6 t ha^{-1}).

To compare non-coppicing species used in relay intercropping with their use in improved rotational fallows, 48 publications, with a total of 391 pairs of observations, were included. Improved fallows constituted 70.6% of the

cases and relay intercrops the remaining 29.4%. Although the 95% confidence intervals overlapped, response was higher in rotational fallows than in relay intercrops. The 95% confidence interval for RR was 1.27-1.43 in rotational fallows and 1.11–1.30 for relay intercrops. The 95% confidence interval of mean D in rotational fallows, at 0.88–1.41, overlapped with that of relay intercrops, at 0.34–1.01.

Rotational fallows of non-coppicing species were managed as 1-year fallows in 21.6% of the cases, 2-year in 44.4%, and 3-year in 34.0%. The 3-year rotation gave higher RR than the 1- and 2-year fallows (Figure 11, left). However, the 95% confidence intervals of mean D in 3-year fallows (1.1–1.8 t ha^{-1}) overlapped with those of the 1-year fallows (0.9–1.7 t ha^{-1}) and 2-year fallows (0.8–1.3 t ha^{-1}).

After clearing non-coppicing legume fallows, postfallow maize was cropped for 1 season in 65.0% of the cases, for 2 seasons in 24.5% and for 3 seasons in 10.5%. There was no difference in RR between the 1- and 2-season and 1- and 3-season postfallow crops (Figure 11, right). Variability in response increased with postfallow cropping. However, the 95% confidence intervals of D indicate that response is higher in the first postfallow crop, at 1.3–1.9 t ha^{-1}, than in the third, at 1.0-1.2 t ha^{-1}.

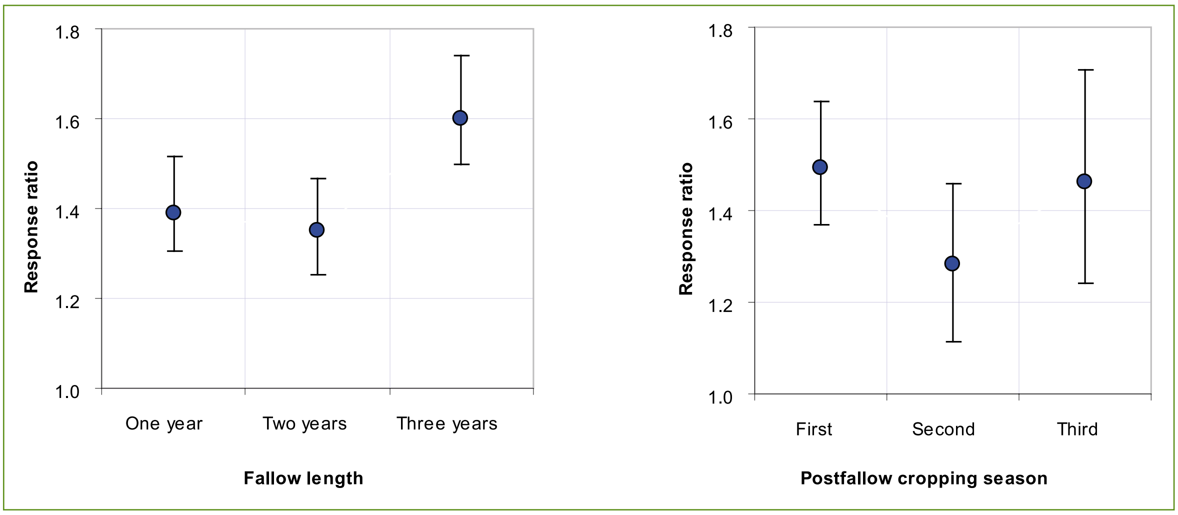

Figure 11. Changes in response ratio with fallow length and postfallow cropping. Means (circles) are not significantly different from one another if their 95% confidence intervals (error bars) overlap. The means and 95% confidence intervals are in the original (back-transformed) scale.

4.4.2. Fertilizer amendment

Where maize cropped after non-coppicing species was amended with fertilizer, the data for rotational fallows and relay intercrops were analyzed separately. Forty-eight peer-reviewed publications with a total of 456 pairs of means were included in this analysis. In analysing the effect of fertilizer amendment in rotational fallows, fallow length and postfallow cropping were used as covariates. However, neither their main nor their interaction effects were significant. When postfallow plots were amended with half of the recommended dose of fertilizer, response in rotational fallows of non-coppicing legumes was 28% higher than in similar plots that were not amended (Figure 12). Although amendment with the

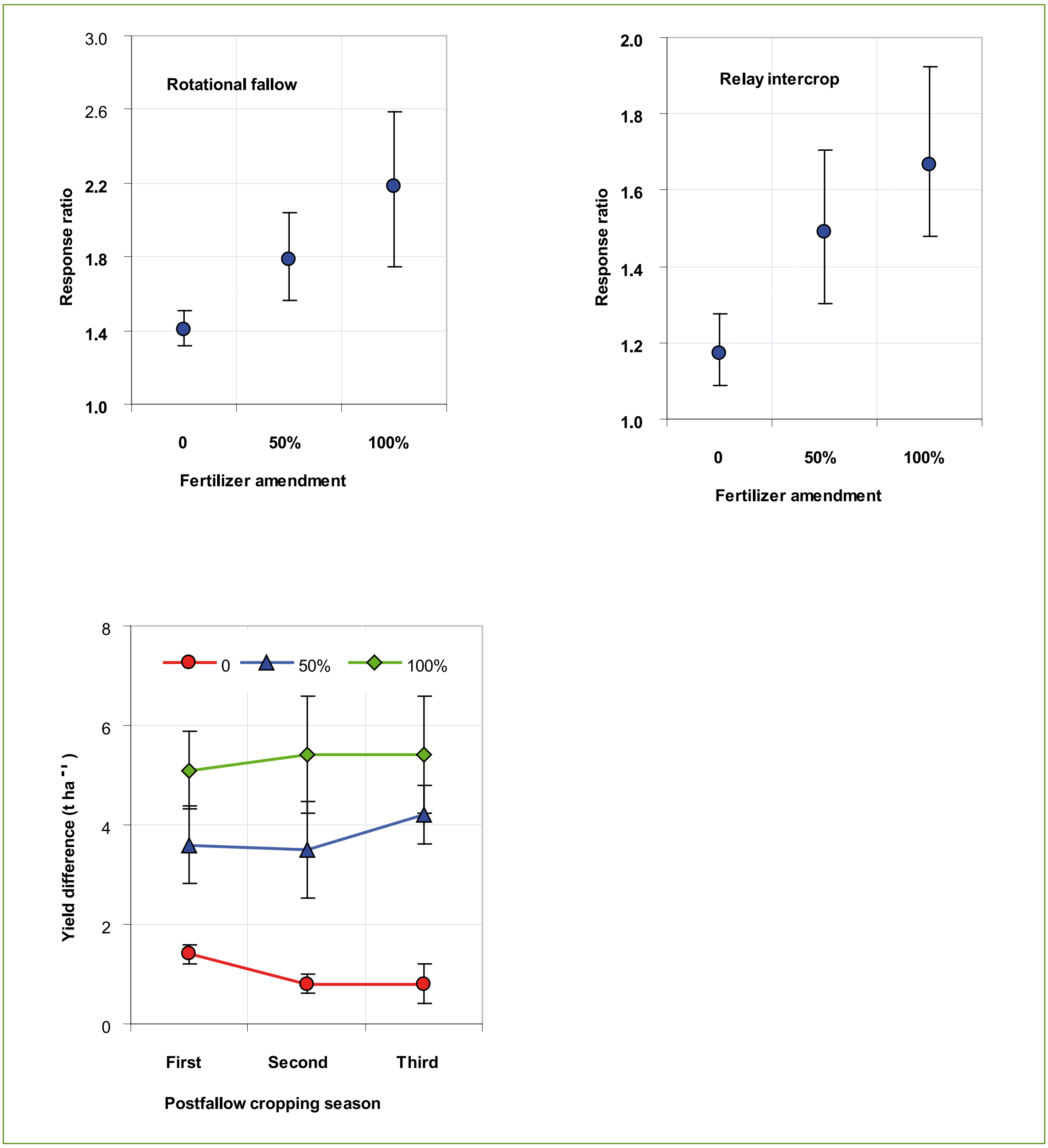

Figure 12. Changes in response ratio and yield differences with fertilizer amendment in rotational fallows and relay intercrops and changes in yield differences with postfallow cropping and fertilizer amendment in non-coppicing legumes. The amendments are 0%, 50% and 100% of the recommended fertilizer dose for maize grown postfallow. Means (circles) are not significantly different from one another if their 95% confidence intervals (error bars) overlap. The means and 95% confidence intervals are in the original (back-transformed) scale.

full recommended dose of fertilizer increased yields by 56%, response was highly variable. In postfallow plots not amended with fertilizer, yield declined with the length of cropping.

In relay intercropping with non-coppicing legumes, amending the soil with half of the recommended fertilizer dose increased yield by 27% over similar plots not amended with fertilizer (Figure 12). Amending with the full recommendation increased yield by 42%. For maize intercropped with coppicing woody species, response was higher by 38% when half of the recommended dose of fertilizer was applied, and by 32% when the full recommendation was applied, than on plots without fertilizer amendment. In all cases, amendment with the full recommended dose of fertilizer did not significantly differ from the 50% amendment.

4.4.3. Altitude, rainfall and soil type

Yield response ratio was higher in middle altitudes of 700–1400 masl than in high altitudes >1400 and in low altitudes <700 masl (Table 3). It was higher in areas with high rainfall >1400 mm than in those that receive medium-to-low rainfall <1400. Response was higher on Lixisols than on Ferralsols and Nitisols. In fully fertilized maize, response was higher on Acrisols than on Nitisols (Table 4). The effect of soil type on response ratio was unclear in coppicing, non-coppicing and herbaceous green manure legumes, though response was generally higher on Lixisols.

Table 3. Effect of altitude, rainfall and soil type on maize yield response across all treatments

Effect	Class	Number of pairs[a]	RR	LCI	UCI
Altitude (masl)	Mid (700–1400)	871	1.8	1.4	2.2
	High (>1400)	418	1.2	0.9	1.6
	Low (<700)	244	1.2	0.9	1.6
Rainfall (mm y^{-1})	High (>1400)	344	2.9	2.4	3.6
	Medium (700–1400)	1171	1.4	1.3	1.6
	Low (<700)	18	0.6	0.4	0.9
Soil type	Lixisol	146	1.8	1.4	2.5
	Cambisol	30	1.7	1.2	2.5
	Luvisol	569	1.6	1.3	2.0
	Acrisol	121	1.5	1.2	2.0
	Ferralsol	314	1.0	0.8	1.3
	Nitisol	157	0.9	0.6	1.3

LCI = lower 95% confidence limit, masl = metres above sea level, mm y-1 = millimetres per year, RR = response ratio, UCL = upper 95% confidence limit.

[a] The pairs reported here exclude sites with missing altitude, rainfall or soil type data.

Table 4. RRs and their LCLs and UCLs for the treatments on different soil types

Treatment	Soil type [a]	Number of pairs [b]	RR	LCL	UCL
Fully fertilized	Acrisol	(13)	5.6	3.7	8.6
	Luvisol	95	4.5	3.6	5.6
	Lixisol	31	3.6	2.4	5.5
	Ferralsol	49	2.2	1.6	3.1
	Cambisol	(12)	1.4	0.9	2.4
	Nitisol	38	1.4	0.9	2.2
Coppicing fallow	Lixisol	26	2.9	1.5	5.8
	Luvisol	123	2.1	1.3	3.4
Non-coppicing fallow	Acrisol	41	2.0	1.5	2.7
	Lixisol	67	1.9	1.5	2.4
	Luvisol	174	1.8	1.5	2.2
	Ferralsol	60	1.5	1.2	2.0
	Cambisol	(23)	1.4	0.9	2.2
HGML	Lixisol	(14)	1.7	0.9	3.0
	Luvisol	105	1.6	1.3	1.9
	Nitisol	119	1.4	1.1	1.8
	Acrisol	54	1.3	1.1	1.7
	Ferralsol	177	1.3	1.1	1.5

HGML = herbaceous green manure legume, LCI = lower 95% confidence limit, RR = response ratio, UCL = upper 95% confidence limit.
[a] Food and Agriculture Organization classification.
[b] Excluding sites with missing soil type data. Parentheses indicate small sample size.

5. Discussion

Although publication bias cannot be ruled out in meta-analysis, the studies included in this analysis have adequately captured the diversity of environments, legume fallow systems and maize genotypes under smallholder agriculture. If the mode is indeed a better estimate of average effects than the mean, then the benefits from legumes are more modest than those indicated by the mean in most cases. The asymmetry in Figure 3 is probably because studies with insignificant results are less likely to be published. Distinct asymmetry in the effect distribution suggests the type of publication bias that exists when the population effect differs from zero (Wang and Bushman 1998). The bias may not be simply due to unpublished insignificant results. Some studies could have been deemed to be failures because the legumes did not become properly establish (R. Coe personal communication). The difficulty in capturing such studies is one of the weaknesses of this analysis.

Publication selection bias arising from the exclusion of studies for reasons outlined under data retrieval criteria is believed to have minor effect. Most of the studies excluded from the analysis compared maize yields from treatments with those from natural fallows but not from continuously unfertilized maize, which was our control. Some studies compared legume fallows with natural fallows that were previously cropped during the growth of the managed fallow. Our decision to exclude those studies was based on the following logic. Firstly, using natural fallows as the control in cross-regional syntheses would be invalid because the species composition of natural fallows varies from region to region and from site to site. Secondly, using a natural fallow as the control is valid only where continuous cropping without fertilizer is not the norm, as in the humid tropics of West Africa (Hauser et al. 2006). In parts of East and Southern Africa where continuous cropping is the norm, using a natural fallow as the control would bias the results.

In the first part of the analysis, treatments with fertilizer amendment were separated. The analysis of data on organic inputs and fertilizer amendment was restricted only to those studies that specifically assessed the interaction. Our analysis, based on the dataset that satisfied these minimum requirements, clearly shows that fertilizer gives the best response, followed by coppicing woody legumes. Response ratios did not differ among the coppicing and non-coppicing woody legumes and HGMLs. However, yield response in the legumes was significantly higher than in natural fallows and unfertilized continuous maize.

Maize yield response varied with (1) legume establishment and management practices, which affect the primary productivity of the legumes, and by (2) site productivity, which is moderated by soil type and climatic factors such as altitude and rainfall. Clearly, yield response was higher when herbaceous and woody legumes were managed as rotational fallows than when managed as relay intercrops. Although response ratio was highest in maize grown after 3-year fallows of non-coppicing legumes, a 3-year fallow has no clear advantage over a 2- or 1-year fallow in terms of yield.

Amending the postfallow plots with half of the recommended fertilizer dose further increased yields by more than 25% over those of similar plots that were not amended. However, amendment with the full recommended dose did not significantly increase yields beyond that. This indicates that legumes can play an important role in raising fertilizer use efficiency (Vanlauwe et al. 2001) and so reduce fertilizer requirements. Positive interactions between nutrients from legumes and mineral fertilizer have been demonstrated. However, the interaction is complex (Vanlauwe et al. 2001), and little is known about its mechanisms. Future research needs to focus on analyzing the impact of legumes on fertilizer use efficiency and their prospects for reducing fertilizer requirements for a given yield target.

In addition to legumes, inherent site productivity appeared to influence the performance of maize. Tripling of yields over the control is not achievable on sites with high potential, where control plots yield more than 2 t ha^{-1}. Response ratios were lower on sites with low potential than on those with medium potential. Response was low on sites that receive low or moderate rainfall and have fertile soils. Response was highest on Lixisols, which have few plant nutrients and permit agriculture only with frequent fertilizer applications. In fully fertilized maize, response was generally higher on Acrisols. These soils are inherently infertile and become degraded very quickly when cultivated (Stocking and Murnaghan 2001). Response to fertilizer was poorest on Nitisols, which are among the most fertile soils of the tropics. Maize cropped after non-coppicing and herbaceous green manure legume species also responded poorly on Ferralsols, which are strongly acidic and have few plant nutrients, especially available phosphorus (Stocking and Murnaghan 2001). As legumes and biological nitrogen fixation are particularly sensitive to these constraints, poor legume growth and nitrogen fixation would be expected (Giller et al. 1997).

This analysis has investigated the aggregate effect of factors that contribute to variability in response at the macro level. Despite the huge variation, the mean effects of legumes on maize yield are positive. The studies reviewed here have attributed this to various factors. The most common explanation was improvement in nutrient availability as a result of

1. nitrogen (N) input by biological N_2 fixation (Adu-Gyamfi et al. 2007, Chikowo et al. 2004, Kaizzi et al. 2004, Ojiem et al. 2007, Wortmann and Kaizzi 2000),
2. retrieval of nutrients from below the maize rooting zone (Chintu et al. 2004, Mekonnen et al. 1997),
3. reduced nutrient losses to leaching, runoff and erosion (Hartemink et al. 1996, Phiri et al. 2003), and
4. improved soil water conditions (Vanlauwe et al. 2001).

Legumes accumulate large amounts of N, up to 99% of which is derived from the atmosphere (Adu-Gyamfi et al. 2007, Kaizzi et al. 2004). For example, the amount of N fixed by pigeon pea in maize intercrops was estimated at 37.5–117.2 kg N ha^{-1} yr^{-1} in Malawi and 6.3–71.5 kg N ha^{-1} yr^{-1} in Tanzania (Adu-Gyamfi et al. 2007). In Uganda, Mucuna accumulated 170–350 kg N ha^{-1} yr^{-1}, up to 97% of which is released over a period of 25 weeks (Kaizzi et al. 2004). Some 8–19% of the N released is taken up by the subsequent maize crop, fuelling a yield increase of 25–68% (Kaizzi et al. 2004). For example, the fertilizer-replacement value of total N was estimated to exceed 50 kg N ha^{-1} at Tanga in Tanzania and 69 kg N ha^{-1} at Jimma in Ethiopia (Bogale et al. 2001). Some legumes more effectively improved soil productivity and maize yield than did others, probably because of differences in biomass production, N_2 fixation and recovery of leached nutrients. In Uganda, *Sesbania sesban* and *Tephrosia vogelii* fallows contributed more to soil N balance than did *Mucuna* and *Cajanus cajan* fallows (Wortmann and Kaizzi 2000).

Rotating maize with legume fallows can use subsoil nitrate and water more effectively than can maize monoculture (Hartemink et al. 1996, Chirwa et al. 2007, Nyamadzawo et al. 2007, Phiri et al. 2003). Legumes have other beneficial effects on crop yield, as they can improve the availability and uptake of nutrients such as phosphorus (Akinnifesi et al. 2007, LeMare et al. 1987, Randhawa et al. 2005).

Increased maize yield response has also been attributed to pest suppression (Sileshi et al. 2007). The studies included in this analysis reveal that legumes reduce

1. infestation by arable and parasitic weeds (Akobundu et al., 2000, Gacheru and Rao 2005, Khan et al. 2006, Mureithi et al. 2003, Sileshi and Mafongoya 2003, Sileshi et al. 2006),
2. damage to maize by soil insects (Sileshi and Mafongoya 2003, Sileshi et al. 2005) and
3. plant parasitic nematodes (Arim et al. 2006).

Rotational fallows of *S. sesban* have consistently reduced *Striga* infestation of maize in Kenya (Gacheru and Rao 2005) and Zambia (Sileshi et al. 2006). Intercropping maize with *Desmodium* spp. has also reduced *Striga* and stemborer problems (Khan et al. 2006). When intercropped with maize in Kenya, *Canavalia*, *Crotalaria* and *Mucuna* reduced damage to maize from the lesion nematode *Pratylenchus zea* compared with maize monoculture (Arim et al. 2006). Intercrops may favour the build-up of nematode antagonists and enhance plant resistance to nematodes through improved nutrient status and plant vigour (Wang et al. 2003), thus increasing the nutrients available for plant uptake.

The discussion above indicates that the positive effect of legumes on maize yield arises from a number of interrelated factors. In absolute economic terms, the discounted net benefit of agroforestry-based soil fertility enhancement is higher than that of continuous maize production without external fertilization (the de facto farmers' practice) but lower than that of chemically fertilized fields. But, in terms of the benefit/cost ratio, improved woody fallow options perform better than both, as they yield higher returns per unit of investment cost than does continuous maize production with or without fertilizer. The explanation is that the higher gross income recorded for the mineral fertilizer option was achieved at higher cost, and a much lower cost is required to achieve the relatively modest benefits realized through improved woody fallow options (Ajayi et al 2007b).

Although we did not attempt to quantify farmers' adoption of woody or herbaceous legume fallows in Africa, the potential impacts of these technologies have been generally unrealized because of slow adoption. It is evident that a farmer's decision to plant woody or herbaceous legume fallows is not based exclusively on technological characteristics but is a matrix of several factors such as the farmer's perceptions, resource endowment and household size; input and crop prices; land tenure and property rights; the location of the village; soil type; and other biophysical conditions (Ajayi et al, 2007a).

6. Conclusion and recommendations

The key conclusion from this analysis is that the effect of herbaceous and woody legumes on maize is positive and significant, albeit with considerable residual variation. Maize yield response to woody legumes is higher than to HGMLs. The study established that maize yield was at least doubled than the control, in coppicing woody species in 67% of the cases and with non-coppicing woody legumes in 45%. In contrast, doubled yield response was only occasional in HGMLs, at 16%. The yield response was higher in rotational fallows than in relay intercropping. Three-year fallows of non-coppicing species had no significant yield advantage over 2- or 1-year fallows. While the choice of legume species and management may have major effects on maize yield, this analysis could not confirm the superiority of a particular species across all locations.

The strong point of this analysis is its ability to generalize conclusions across many published studies. The analysis clearly reveals that legumes had high impact on yield in certain situations—in middle altitudes and areas with high rainfall and on Lixisols—and could reduce the fertilizer requirement by half. The general picture is that maize yield is influenced not only by legumes but by many site and management factors (which explains the wide variability in yield especially following natural fallows) and that the increase in maize yield using legumes was highest in areas with medium potential. Projects that promote legumes for soil fertility improvement therefore need to encourage farmer experimentation with several options rather than rely on the wholesale promotion of a single option.

The analysis suggests that amending legume fallows with mineral fertilizer may be important if high yield productivity must be sustained over several years, as yields normally fall as the postfallow cropping period lengthens. Amending postfallow plots with half of the recommended fertilizer dose can increase yields by over 25%, indicating that legume rotations may reduce fertilizer requirements by half, and that a positive synergy can be expected by combining organic and inorganic fertilizers.

Where both soil organic matter and phosphorous (P) content is very poor, legumes may not accumulate significant amounts of biomass and will fix little N. To maintain positive nutrient balances for N and P in these environments, organic resources need to be combined with low rates of mineral fertilizer amendment. As mineral fertilizers and green manure legumes do different things and often have complementary effects on maize yield, one approach should not be promoted as a replacement for the other. To achieve impact, technologies that improve legume establishment and growth on degraded soils, as well as recover applied mineral fertilizers more efficiently, need to be further refined.

This study has demonstrated that woody and herbaceous legumes can substantially increase

maize production. We have provided evidence of the potential contribution of woody and herbaceous legumes to maize productivity that can now be harnessed for sustainable smallholder agriculture in Africa. Rather than apply a blanket recommendation, we urge that the most promising indicative woody and herbaceous green manure options be evaluated under local conditions and scaled up appropriately.

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Appendix

Table A. Publications included in the meta-analysis and the treatments compared in each study

Author(s)	Source	Country	Treatment[a]
Abunyewa & Karbo 2005	Land Deg Dev 16:447–454	Ghana	2, 6
Agyare et al. 2002	Agroforestry Systems 54:197–202	Ghana	2, 6
Akinnifesi et al. 2006	Experimental Agriculture 42:441-457	Malawi	3, 5, 6
Akinnifesi et al. 2007	Plant and Soil 294:203-217	Malawi	3, 5, 6
Atusaye et al. 2003	CIMMYT grain legumes proceedings	Malawi	1, 2, 6
Ayuk and Mafongoya 2002	14th SADC-ICRAF proceedings	Zambia	2, 4, 5, 6
Boehringer and Leinher 1997	Expl Agr 33:301–312	Benin	2, 6
Boehringer et al. 1999	For Farm Com Tree Res 4:117–120	Malawi	2, 6
Bogale et al. 2001	CIMMYT maize proceedings	Ethiopia	1, 2, 6, 5
Carsky et al. 1999	Nutr Cycl Agroecosys 55:95–105	Nigeria	1, 5, 6
Carsky et al. 2001	Nutr Cycl Agroecosys 59:151–159	Nigeria	1,5, 6
Chamango 2001	CIMMYT 7th conference proceedings	Malawi	2, 6
Chibudu 1998	Trans Zim Sci Ass 72:88–92	Zimbabwe	2, 5, 6
Chikowo et al. 2006	Agric Ecosys Envir 102:119–131	Zimbabwe	1, 2, 3, 5, 6
Chikowo et al. 2006	Nutr Cycl Agroecosys 76: 219–231	Zimbabwe	2, 3, 6
Chintu et al. 2004	Experimental Agriculture 40:341–352	Zambia	3, 4, 5, 6
Chirwa et al. 2003	Agroforestry Systems 59:243–251	Zambia	2, 3, 4, 5, 6
Chirwa et al. 2004	Biol Fertil Soils 40:20–27	Zambia	2, 4, 5, 6
Cooper et al. 1996	Experimental Agriculture 32:235–290	Malawi	2,5, 6
Drechsel et al. 1996	Agroforestry Systems 33:109–136	Rwanda	1, 4, 6
Esilaba et al. 2004	Agricultural Systems 86:144–165	Uganda	1, 5, 6
Fischler and Wortman 1999	Agroforestry Systems 47:123–138	Uganda	1, 4, 6
Fischler et al. 1999	Field Crops Research 61:97–107	Uganda	1, 6
Fofana et al. 2004	Nutr Cycl Agroecosys 68:213–222	Togo	1, 5, 6
Franke et al. 2004	Experimental Agriculture 40:463–479	Nigeria	1, 5, 6
Friesen et al. 2003	CIMMYT grain legumes proceedings	Ethiopia, Tanzania	1, 2, 5, 6
Gachene et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Gacheru and Rao 2005	Int J Pest Manage 51:91–100	Kenya	1, 2, 4, 6
Gama et al. 2004	ICRAF conf proceedings	Tanzania	1, 2, 4, 6
Gichuru 1991	Plant and Soil 134:31–36	Nigeria	2, 6
Gitari et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Harawa et al. 2006	Nutr Cycl Agroecosys 75:271–284	Malawi	2, 3, 6
Haule et al. 2003	Malawi J Agr Sci 2:21–33	Malawi	2, 5, 6
Ikpe et al. 2003	Nutr Cycl Agroecosys 67:129–136	Nigeria	2, 6
Jama et al. 1998	Agronomy Journal 90:717–726	Kenya	2, 4, 6
Jatango 2003	DFID project report	Ghana	1, 2, 6
Jeranyama et al. 2000	Agronomy Journal 92:239–244	Zimbabwe	1, 6
Kaho et al. 2004	Tropicultura 22:49–55	Cameroon	1, 6

Table A. continued

Author(s)	Source	Country	Treatment[a]
Kaizzi et al. 2004	Nutr Cycl Agroecosys 68:59–72	Uganda	1, 5, 6
Kamanga 2002	CIMMYT working paper	Malawi	2, 6
Kamanga et al. 1999	Afr Crop Sci J 7:355–363	Malawi	2, 6
Kamidi et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Kirungu et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Kwesiga and Coe 1994	For Ecol Manage 64:199–208	Zambia	2, 4, 5, 6
Kwesiga et al. 1999	Agroforestry Systems 47:49–66	Zambia	2, 4, 5, 6
MacColl 1990	Experimental Agriculture 26:263–271	Malawi	1, 5, 6
Mafongoya and Dzowela 1999	Agroforestry Systems 47:139–151	Zimbabwe	2, 4, 5, 6
Mafongoya et al. 2004	ICRAF conf proceedings	Zambia	2, 4, 5, 6
Mafongoya et al. 2006	Nutr Cycl Agroecosys 76:137–151	Zambia	2, 4, 5, 6
Makumba and Maghembe 1999	13th SADC-ICRAF proceedings	Malawi	2,4, 5, 6
Makumba et al. 2000	DARS Ann. Sci. Proc.	Malawi	2, 6
Maobe et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Maroko et al. 1999	Soil Sci Soc Amer 63:320–326	Kenya	2, 4, 6
Mekuria 2003	CIMMYT grain legumes proceedings	Malawi	1, 6
Meliyo et al. 2007	Advances in ISFM in sub-Saharan	Tanzania	3, 6
Morse & McNamara 2003	Experimental Agriculture 39:81–97	Nigeria	1, 5, 6
Muleba 1999	J Agric Sci 132:61–70	Burkina Faso	1, 5, 6
Mupangwa 2003	CIMMYT grain legumes proceedings	Zimbabwe	1, 4, 6
Mureithi et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Mureithi et al. 2003	Trop Subtrop Agroecosys 1:57–70	Kenya	1, 5, 6
Muza 1998	IDRC Covercrops in West Africa	Zimbabwe	1, 2, 6
Muza 2003	CIMMYT grain legumes proceedings	Zimbabwe	1, 5, 6
Mwale 2003	CIMMYT grain legumes proceedings	Zambia	1, 4, 5, 6
Mwenye 2003	CIMMYT grain legumes proceedings	Zimbabwe	1, 6
Niang et al. 2002	Agroforestry Systems 56:145–154	Kenya	1, 2, 4, 6
Njunie and Wagger 2003	East Afr Agr For J 69:49–61	Kenya	1, 5, 6
Nyadzi et al. 2003	Agroforestry Systems 59:253–263	Tanzania	2, 6
Nyakanda 2004	ICRAF conf proceeding	Zimbabwe	2, 4, 6
Nyambati 2002	PhD thesis	Kenya	1, 5, 6
Obaga et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 5, 6
Okapara et al. 2005	Global J Agr Sci 4:113–118	Nigeria	1, 5, 6
Onim et al. 1990	Agroforestry Systems 12:197–215	Kenya	1, 4, 6
Onyango et al. 2000	KARI 2nd science conf proceedings	Kenya	1, 6
Onyango et al. 2001	7th East South Africa Maize Conf	Kenya	1, 5, 6
Phiri 1999	13th SADC-ICRAF proceedings	Malawi	2, 6
Phiri et al. 1999	Agroforestry Systems 47:153–162	Malawi	2, 5, 6
Phiri et al. 2003	Agroforestry Systems 59:197–205	Zambia	2, 5, 6
Rao et al. 2002	Experimental Agriculture 38:223–236	Kenya	2, 5, 6
Saha and Muli 2000	KARI 2nd science conf proceedings	Kenya	1, 6
Sakala and Mhango 2003	CIMMYT grain legumes proceedings	Malawi	1, 6
Sakala et al. 2003	Malawi J Agr Sci 2:34–41	Malawi	1, 4, 5, 6

Table A. continued

Author(s)	Source	Country	Treatment[a]
Sakala et al. 2004	CIAT book	Malawi	1, 6
Shirima et al. 2000	Int J Nemat 10:49–54	Tanzania	2, 4, 6
Sileshi and Mafongoya 2003	Applied Soil Ecology 23:211–222	Zambia	1, 2, 4, 6, 5
Sileshi and Mafongoya 2006	Agric Ecosys Envir 115:69–78	Zambia	3, 4, 5, 6
Sileshi and Mafongoya 2006	Applied Soil Ecology 33:49–60	Zambia	3, 4, 5, 6
Sileshi et al. 2005	Agr Forest Entomol 7:61–69	Zambia	1, 2, 3, 4, 5, 6
Smestad et al. 2002	Agroforestry Systems 55:181–194	Kenya	1, 2, 4, 6
Sogbedji et al. 2006	Agronomy Journal 98:883–889	Togo	1, 2, 5, 6
Steinmaier and Ngoliya 2001	Agricultural Systems 37:297–307	Zambia	1, 6
Tian et al. 2000	Plant and Soil 224:287–296	Nigeria	1, 6
Tian et al. 2005	Nutr Cycl Agroecosys 71:139–150	Nigeria	1, 6
Torquebiau and Kwesiga 1996	Agroforestry Systems 34:193–211	Zambia	2, 5, 6
Whitebread et al. 2004	Nutr Cycl Agroecosys 69:59–71	Zimbabwe	1, 4, 5, 6

Afr Crop Sci J = African Crop Science Journal, Agr Forest Entomol = Agricultural and Forest Entomology, Agric Ecosys Envir = Agriculture, Ecosystems & Environment, Biol Fertil Soils = Biology and Fertility of Soils, CIAT = Centro Internacional de Agricultura Tropical (International Center for Tropical Agriculture), CIMMYT = Centro Internacional de Mejoramiento de Maiz y Trigo (International Maize and Wheat Improvement Center), conf = conference, DARS Ann. Sci. Proc. = Department of Agricultural Research Services Annual Scientific Proceedings, DFID = Department for International Development (United Kingdom), East Afr Agr For J = East African Agriculture and Forestry Journal, Expl Agr = Australian Journal of Experimental Agriculture, For Ecol Manage = Forest Ecology and Management, For Farm Com Tree Res = Forestry, farm and Community Tree Research, Global J Agr Sci = Global Journal of Agricultural Sciences, ICRAF = International Centre for Research in Agroforestry (World Agroforestry Centre), IDRC = International Development Research Center (Canada), Int J Nemat = International Journal of Nematology, Int J Pest Manage = International Journal of Pest Management, ISFM = integrated soil fertility management, J Agric Sci = Journal of Agricultural Science, KARI = Kenya Agricultural Research Institute, Land Deg Dev = Land Degradation and Development, Malawi J Agr Sci = Malawi Journal of Agricultural Science, Nutr Cycl Agroecosys = Nutrient Cycling in Agroecosystems, SADC = Southern African Development Community, Soil Sci Soc Amer = Soil Science Society of America, Trans Zim Sci Ass = Transactions of the Zimbabwe Scientific Association, Trop Subtrop Agroecosys = Tropical and Subtropical Agroecosystems.
a 1= herbaceous green manure legume, 2 = non-coppicing legume, 3 = coppicing legume, 4 = natural fallow, 5 = fertilized maize, 6 = unfertilized monoculture maize (control).

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