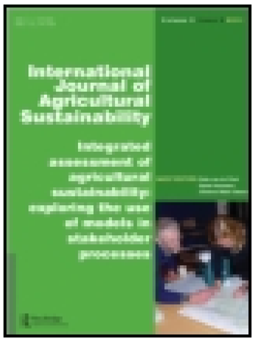

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Effectiveness of agricultural water management technologies on rainfed cereals crop yield and runoff in semi-arid catchment: a meta-analysis

M. S. Magombeyi[a,b], A. E. Taigbenu[a] and J. Barron[b,c]

[a]School of Civil and Environmental Engineering, Witwatersrand University, Johannesburg, South Africa; [b]International Water Management Institute, Colombo Sri Lanka; [c]Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

ABSTRACT

Multiple agricultural water management (AWM) technologies are being promoted worldwide in rainfed agro-ecological production systems, such as the Limpopo River Basin, to close the yield gap, enhance food security and reduce poverty, but evidences on yield gains and environmental impacts are varied. This paper conducts a review of the performance of AWM technologies against conventional farmer practices to produce adequate evidence on cereal yield and field runoff changes. With the interrogation of literature from 1980 to 2013 using seven AWM groupings, enough evidence was found that AWM technologies can deliver substantial benefits of increased crop yield and water productivity with reduced environmental impacts. Using random effects model, the standardized mean difference (SMD) of yield between AWM and control was 0.27, while SMD of water productivity was 0.46, indicating the effectiveness of the technologies (SMD > 0). Subgroup analyses showed greatest yield responses on silty-clay-loam, clay-loam and sandy soils compared to clay and loam-sandy soils, and higher yield increase under low rainfall regime (200–500 mm) than under high rainfall regime (500–800 mm). Large yield change variations for different AWM technologies present a huge opportunity for meeting the existing yield gaps and enhancing coping capacity in dry years and under climate change.

KEYWORDS

Agricultural water management; climate smart agriculture; Limpopo; rainfed; smallholder farmers; sustainable intensification; systematic review; yield gap

1. Introduction

Currently, Africa is experiencing an annual decrease in agricultural production of 3% due to soil erosion, land and environmental degradation (FAO, 2009; Owenya et al., 2012), whereas an annual increase of 6% was required to achieve the Millennium Development Goals by 2015 and now the Sustainable Development Goals set for 2030 (Bayala et al., 2012; United Nations, 2015). Further inherent risks to production are associated with seasonal variability of the amount and distribution of rainfall (Cooper et al., 2008; Magombeyi, Taigbenu, & Barron, 2016) and climate change. Climate change projections indicate a decrease in rainfall (5–15% per century) and hotter climate (temperature rise of 2–5°C by 2050) in southern Africa, where the Limpopo River Basin (LRB) is located (IPCC, 2012; World Bank, 2012). A combination of increased temperatures with increased rainfall variability due to climate change (Lobell et al., 2008) is likely to erode production capacity by about 50% (Müller, Cramer, Hare, & Lotze-Campen, 2011; Schlenker & Lobell, 2010) and constrain beneficial investment. Hence, climate change will exacerbate the current sub-optimal yield levels of 0.50–1.00 t ha^{-1} from smallholder farming in Sub-Saharan Africa (SSA) (FAO and DWFI., 2015; Rockström et al., 2009; van Ittersum et al., 2016), well below the attainable yields of 6.00–12.00 t ha^{-1}, typical under commercial farming (Tittonell & Giller, 2013; van Ittersum et al., 2013). The yield gap is particularly large for key staples such as maize, sorghum and millet in rainfed agro-ecological production systems (Guilpart, Grassini, Sadras,

CONTACT M. S. Magombeyi manumagomb@yahoo.com
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Timsina, & Cassman, 2017). Hence, sustainable intensification of agriculture to increasing crop yields, enhancing efficient use of rainfall and preserving the quality of the soil, is paramount not only for smallholder farmers in SSA but also at national and global levels (Alemaw & Simalenga, 2015; Carberry et al., 2013; Milgroom & Giller, 2013; Zhou et al., 2010). However, the required changes to management practices to close yield gaps vary considerably by region and production intensity levels (Mueller et al., 2012; Tilman, Balzer, Hill, & Befort, 2011).

Agricultural research and development innovations in SSA, including LRB have for decades focused on smallholder rainfed farming systems with the aim of increasing the value and productivity of land, water, labour and capital so as to achieve both local and national food security (Benin, Nin Pratt, Wood, & Guo, 2011; CAWM, 2007; Magombeyi et al., 2016). The smallholder farming system mainly produces crops for subsistence purposes and is characterized by low inputs and technology uses. The rainfall distribution in the LRB also presents a huge production risk as it is highly variable (20–45%) in space and time, with a basin annual mean of 530 mm (Mupangwa, 2009; Sullivan & Sibanda, 2010). Furthermore, the basin is affected by recurring droughts that occur at least once in every four years (Meinke et al., 2006; Twomlow et al., 2009) and lengthy dry spells (Magombeyi & Taigbenu, 2008; Mupangwa, 2009), which often cause crop failures and livestock deaths, thereby negatively affecting smallholder rural livelihoods.

To reduce the risks of production capacity, food insecurity and livelihoods in SSA, governments and the private sector have encouraged the implementation of improved AWM technologies in smallholder farming systems (Jat, Wani, & Sahrawat, 2012). These AWM technologies are applicable across diverse geographical, agro-ecological zones, soil types, plot sizes, and crops throughout Africa (IIRR and ACT, 2005; Vohland & Barry, 2009). AWM constitutes a set of key technologies which are aligned with the pillars of agriculture, market access, water management and the environment that are championed by the New Partnership for Africa's Development (NEPAD), and the Comprehensive Africa Agricultural Development Program (CAADP) (Owenya et al., 2012). AWM is therefore well positioned in the development agendas to achieving multiple objectives of climate change adaptation and mitigation as well as poverty alleviation and agro-ecosystem biodiversity conservation (Milder, Majanen, & Scherr, 2011).

Despite most studies in Africa generally reporting positive effects of AWM technologies on soil fertility and crop productivity (e.g. Bayala et al., 2012; IMAWESA, 2009; Munamati & Nyagumbo, 2010; Owenya et al., 2012), crop yields, rainfall partitioning and soil conservation in smallholder farming system have consistently remained below those achieved by large-scale producers in the same agro-ecological settings (Munamati & Nyagumbo, 2010; Mupangwa, Twomlow, & Walker, 2008). These results suggest that the conditions for optimum performance of the AWM technologies are yet to be fully context defined (Bulcock & Jewitt, 2013). Hence, blanket statements about the performance of AWM technologies are often inappropriate and misplaced because of the interplay of many climatic, environmental, policy, institutional and farming factors which impact on their adoption (Farooq, Flower, Jabran, Wahid, & Siddique, 2011). Furthermore, the complexity, time-bound and site-specific interactions between the components of AWM technology on yield performance requires long-term experiments for better understanding (Rusinamhodzi et al., 2011). By applying a meta-analysis, valuable synthesized information on the processes that make for the success or failure of AWM technology can be obtained and used to empower farmers on a suite of technologies appropriate for their context (Bayala et al., 2012; Marongwe et al., 2011). Hence, this paper is aimed at identifying and quantifying opportunities for AWM technologies to increase cereal crop yield and reduce field runoff, compared to conventional/traditional farmer soil and water management practices in arid and semi-arid areas across diverse experimental set up (on-farm or on-station), and agro-ecological conditions in the LRB.

2. Materials and methods

2.1. Study area

The case studies for this review were from the LRB (Figure 1), located in southern Africa between latitudes 20°S and 26°S and longitudes 25°E and 35°E, with a total land area of 430,000 km^2 (LBFP, 2010). The proportions of area in each country are Botswana (20%), Mozambique (21%), South Africa (44%) and Zimbabwe (15%). The altitude of the area ranges between 11 and 2330 m (mean 796 m). According to Magombeyi et al. (2016), the average poverty levels, based on US$1.25/capita/day, were 20% for Botswana (2009/2010), 56% for South Africa (2010), 68% for

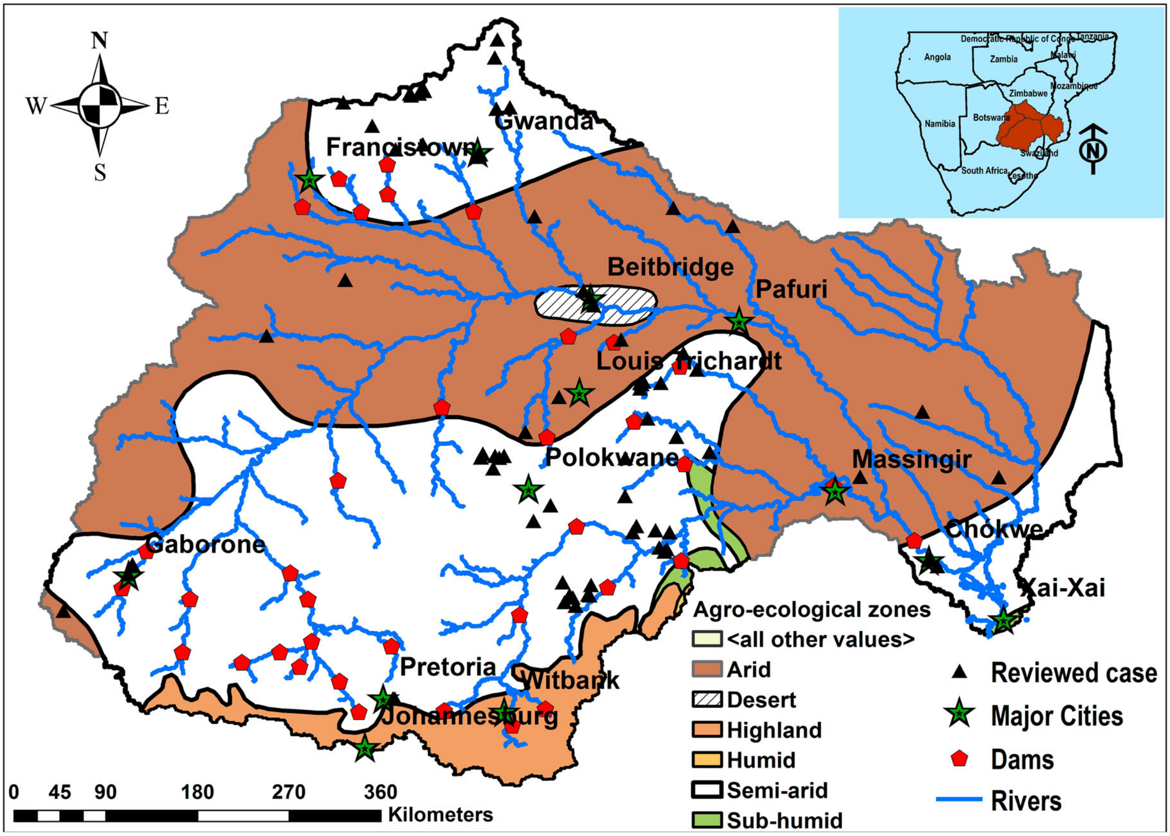

Figure 1. Reviewed case studies and the agro-ecological zones in the Limpopo Basin. Adapted after IIASA/FAO (2012).

Mozambique (2008/2009) and 69% for Zimbabwe (2011). It is projected that water stress to absolute water scarcity as a result of both natural and human-made phenomenon will be experienced in the basin by 2025 (Sulser et al., 2009). Water stress for an area is when annual water supplies drop below 1700 m^3 per person, while absolute water scarcity is when the water supplies drop below 500 m^3 per person (FAO, 2007).

2.1.1. Climate

According to Köppen-Geiger's five major Climate Classification system (A–E) most of the LRB falls in category B (potential evaporation and transpiration exceed precipitation, and rainfall is relatively low), with a small eastern portion of the basin in category C (warm and humid summers, with mild winters) (Hatfield Consultants, 2008). The basin rainfall is unimodal with the wet season from October/November to March/April, followed by a long dry spell in the winter (Willcocks & Twomlow, 1993). The annual rainfall ranges per country in the Limpopo Basin are: Botswana, 250–555 mm (mean 425 mm); Mozambique, 355–865 mm (mean 535 mm); South Africa, 290–1050 mm (mean 590 mm); and Zimbabwe, 300–635 mm (mean 465 mm), while the basin mean is 530 mm (CGIAR, 2003). Generally, rainfall should exceed 20–30 mm in a single event to trigger runoff, due to the basin's flat terrain, high temperatures and low humidity (LBPTC, 2010). While droughts are a common occurrence – 1980, 1982–1983, 1987, 1992–1993, 1994–1995, 1999, 2002–2004, 2005 and 2006–2007 (DEWFORA, 2011; SARDC, 2002), floods with devastating consequences from heavy rains do sometimes occur over Mozambique, South Africa and Zimbabwe as in the 2013/2014 and 2016/2017 (Shewmake, 2008).

Temperatures follow a seasonal variation and altitude levels, with the coolest months (0°C at night) experienced in winter (June–August) and the highest temperatures (above 40°C) experienced in early summer (late November to early December). With the predicted average increase in temperature of 0.7°C in the past 100 years, future regional air masses, basin climate and crop production and productivity are likely to be impacted (IPCC 2007). Annual evaporation rates are between 1600 and 1700 mm yr^{-1} in the cooler mountainous regions in the south-eastern part of the basin, with the highest values of 2600–3100 mm yr^{-1} in its warmer western and central regions.

2.1.2. Soils

The two dominant soil types in the basin are older soils that were formed from deep weathering of parent material during a time of higher temperatures and rainfall, such as the soils of highveld plateaus of South Africa and Zimbabwe, and considerably younger, shallower sediments from more recent erosional or depositional activities under drier climates, such as soils of the lowveld and coastal plains of Mozambique (Limpopo River Awareness Kit, 2011). Extreme soil degradation was noted in three areas in Limpopo Province of South Africa, corresponding with densely populated communal areas (former homelands of Venda) and Lebowa (south of Polokwane).

2.2. Farming systems for cereal production in the basin

The prevailing crop farming systems (subsistence, semi-commercial or emerging and commercial) in the LRB reflect its cultural, socio-economic conditions, agro-ecological potential and agricultural policies.

2.2.1. Conventional farming system

A mix of farming systems exists under conventional farming practice. However, greater attention is paid to smallholder or subsistence farming system, which engages the largest proportion of farmers in the basin. The smallholder, subsistence and conventional farming systems are primarily low-input-productivity systems, characterized by low level of management (e.g. water and nutrients) and intensive natural resources utilization that result in irreversible land degradation (Feed the Future, 2013; Munamati, 2009). Land preparation involves ploughing to a depth of about 0.10–0.20 m using animal or mechanical power or hoeing and planting on the levelled field (e.g. conventional tillage). Ploughing destroys soil structure and weakens soil aggregation by exposing soil organic carbon to microbial oxidation.

2.2.2. Crop production under subsistence farming system

The subsistence agriculture is typically a low-input–output system adopted by local communities to minimize risks from climate variability. Sorghum, millet, groundnuts, beans/pulses and oilseeds such as sunflower tend to perform better than maize, which is the most widely grown crop (FAO, 2004; ReSAKSS, 2017). Average grain yields of maize in the traditional (communal) farming system are of the order of 0.25 t ha^{-1} in Botswana, 0.80 t ha^{-1} in Mozambique and Zimbabwe, and 0.70 t ha^{-1} in South Africa, while the basin average yields for maize, grain sorghum and groundnuts are about 0.64, 0.60 and 0.40 t ha^{-1}, respectively (FAO, 2004). In contrast, large-scale rainfed commercial farming in the basin produces maize yields between 3.00 and 8.00 t ha^{-1} (BFAP, 2014; LBFP, 2010).

The area cultivated per family is about 4.00 ha in Botswana, 1.50–3.00 ha in Mozambique and Zimbabwe, and about 0.75 ha in South Africa. Late and poor land preparations are a common feature of the basin due to limited access to draught power, thereby making less labour intensive AWM technologies more attractive to farmers (Mupangwa, Dimes, Walker, & Twomlow, 2011; Rockström et al., 2009; Rusinamhodzi et al., 2011; Schlenker & Lobell, 2010). The use of improved seed for genetic diversity is limited, with approximately 90% of the seed obtained from previous harvest or local sources (Feed the Future, 2013; Netnou-Nkoana, Jaftha, Dibiloane, & Eloff, 2015; Progressio, 2009; The African Centre for Biodiversity, 2016), with an exception of Zimbabwe with well-developed seed distribution facilities (Friis-Hansen, 1992).

2.3. Benefits of AWM technologies

The benefits associated with AWM technologies include higher plant-water availability, redistribution of labour for land preparation to dry season, higher productivity and income and reduced vulnerability to erratic rainfall distribution and droughts (IPCC, 2007; Owenya et al., 2012). Furthermore, there is potential for enhanced sequestration of carbon, when combining AWM with cover crops and mulch practises and reduction in runoff soil erosion, which is a major cause of soil degradation in semi-arid (Oyedele & Aina, 2006).

2.4. Data search, collection and analysis

2.4.1. Literature Search

A comprehensive literature search provided cases of impacts of AWM technologies, obtained from peer-reviewed journals and non-peer reviewed conference proceedings, theses and project reports in the LRB from 1980 to 2013 (Figure 2). The sources searched for cases through the end of April 2013 were: AGRIS, CABDirect, ProQuest, EconLit, Text WebPublisher from INMAGIC, Science direct, Database of Abstracts of Reviews of Effects (DARE) and other databases (e.g. Scopus, ISI Web of Knowledge and Google Scholar).

2.4.2. Search strategy

The literature search used the following keywords and their combinations: maize, sorghum, millet, rainfed, reduced tillage, no-tillage, ripper, ridges, tied ridges, conservation agriculture, minimum tillage, zero tillage, infiltration pits, fanya juu, planting basins, bunds, terraces, contours, inter-cropping, agroforestry, rotation, grain yield, runoff, nutrient and water harvesting. Other words used were storage, retention, water storage, supplemental irrigation, irrigation, crop residues, mulch, residue, organic, inorganic, manure, fertilizer, Africa, Sub-Sahara Africa, Botswana, Mozambique, South Africa, Zimbabwe, Limpopo, Olifants, Mzingwane, Gwanda, Notwane, Chokwe and Xai Xai.

2.4.3. Eligibility criteria

All the identified studies were screened for relevance first on title, then on abstract and full-text paper, and further screening of the full papers that satisfied all the specified eligibility checks. The schematic overview of the decision tree (Figure 2) shows the selection process of the case studies used in the meta-analysis. Both published and unpublished studies were included in the meta-analysis to avoid publication bias, as studies with significant results tend to be published more often than those without significant results (Wang, 2009).

The study's empirical findings, which include dependent variables of cereal crop yield, water productivity and field runoff, were converted to an effect size. An effect size represents the numerical way of expressing the strength or magnitude of a reported relationship of various technologies (Higgins, Altman, & Sterne, 2011). An effect size near zero indicates homogenous result from control and experimental groups, while a high effect size indicates an effective technology. An effect size below zero indicates that the technology had a negative or reverse effect compared to the control group (Higgins et al., 2011).

2.5. Data synthesis and subgroup analyses

Meta-analysis using Review Manager (RevMan) 5.3 software (The Cochrane Collaboration, 2014) was used to determine the overall effect size of standardized mean difference (SMD) and to impose a 95% confidence limits on the means. SMD is the difference in mean effects from the AWM experimental treatment and control groups in relation to the pooled standard deviation of participants' outcomes. SMD is a summary statistic used when the studies in a meta-analysis assess the same outcome (e.g. yield) but measure it in different ways. SMD is not tied to any specific unit of measurement, but SMD > 0 means the intervention is effective. The rule of thumb used for SMD effect size from Schünemann et al. (2011) was: SMD < 0.4, small effect, SMD 0.4–0.7, moderate and SMD > 0.70, large effect.

The median and 25th and 75th percentiles were used for synthesizing the field runoff, as the mean is sensitive to extreme values. The random-effects model (Schünemann et al., 2011) was used because its estimate assumes there is a distribution of effects which, with its confidence interval (CI), addresses the question 'what is the best estimate of the average effect?' In contrast, the fixed effect model addresses the question 'what is the best (single) estimate of the effect? A funnel plot, which is a scatter plot of the effect estimate (SMD) in relation to the size or precision of each study, standard error (SE), was used for the assessment of risk of bias that may affect the cumulative evidence, such as publication bias and selective reporting within studies.

Factors such as soil texture, location and climate have well-known effects on grain yield and field runoff and may play a role in the observed yield patterns. Factors used as covariates for the response of crop grain yield to AWM technologies included: long-term rainfall, altitude, soil texture and field slope.

The subgroup analyses examined whether the subgroups reduce any heterogeneity in each AWM main group. Subgroups analyses of low (200–500 mm) and medium (500–800 mm) seasonal rainfall regimes, manure, nitrogen fertilizer input, categorized

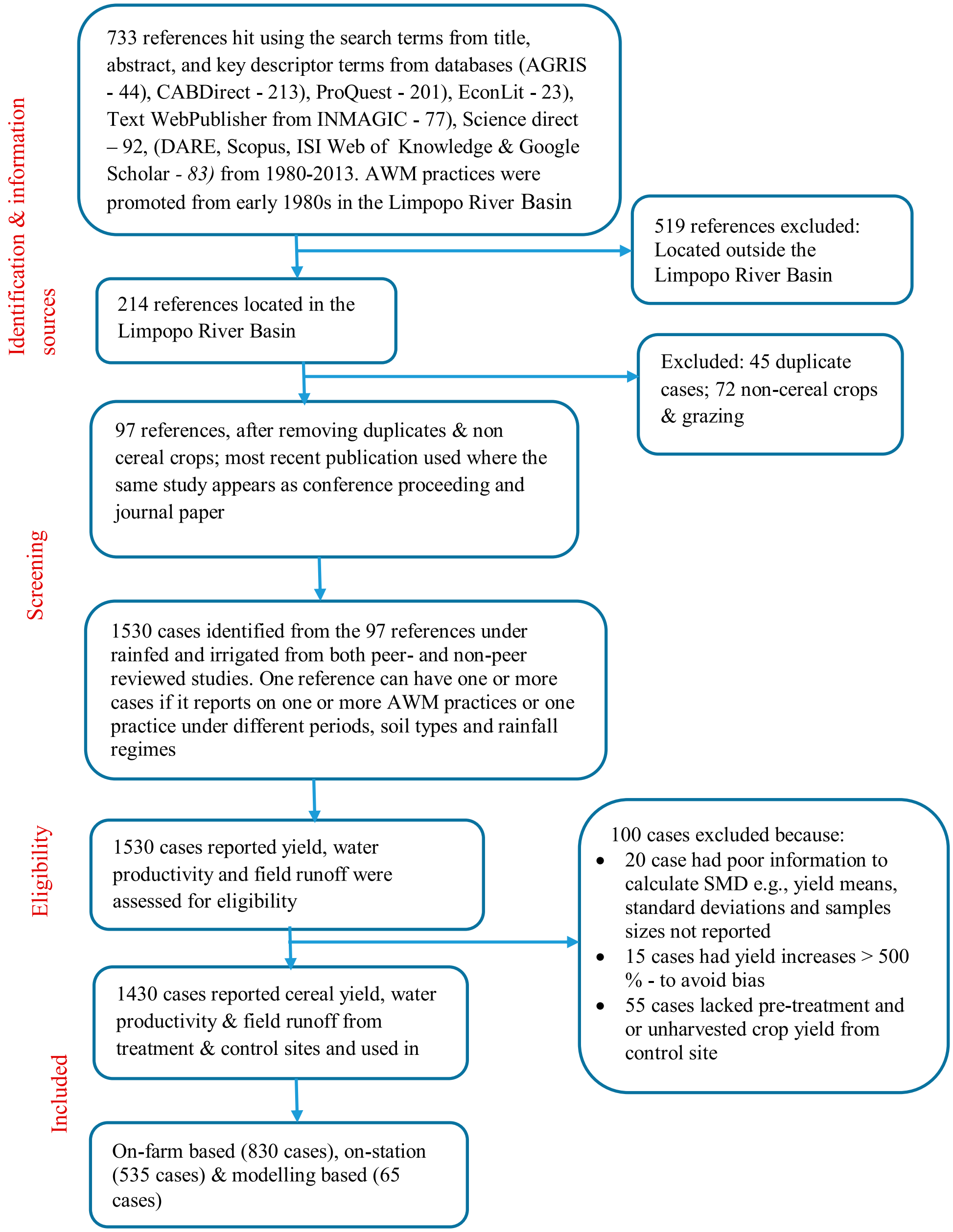

Figure 2. Schematic overview of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) process flow diagram for the search result modified from Moher, Liberati, Tetzlaff, and Altman (2009).

as low (<35 kg ha^{-1}) and high (36–300 kg ha^{-1}) and soil texture of clayey soil, sandy soil and loamy soil were considered.

2.6. Interpretation of results

Results from both individual references and meta-analyses are reported with a point estimate together with an associated 95% CI. The point estimate is the best guess of the magnitude and direction of the AWM experimental intervention's effect compared with the control one.

The *p*-value used in this study relates to the summary effect in a meta-analysis and is from a *Z*-test of the null hypothesis that there is no effect of the technology. In this paper the *Z*-test is reported, where $p < 0.05$ indicate statistical significant results (Higgins & Green, 2008; Rücker, Schwarzer, Carpenter, & Schumacher, 2008).

Consistence of results was measured by I^2 statistic, which is the percentage of observed total variation across studies as a result of real heterogeneity rather than chance or sampling error. Negative values of I^2 are set to zero, with a value of 0% indicating no observed heterogeneity. The following rule-of thumb was used to classify I^2 statistic (Cohen, 1988; Higgins & Green, 2008): <40% is low; 30–60% is moderate; 50–90% is substantial and 75–100% is considerable heterogeneity.

2.7. Rainfall classification

Partly based on FAO (2007) guidelines, long-term mean annual and season rainfall were categorized into four classes as very low (<200 mm), low (200–500 mm), medium (500–800 mm) and high (>800 mm). Each season was analysed as a separate case due to the differences in rainfall amount and distribution experienced during each growing season over several years considered in the study.

2.8. Classification of AWM technologies

The AWM technologies were classified into seven groups from consultation with other researchers and extension officers in the basin and partly based on Bayala et al. (2012), FAO (2009) and IPCC (2007). These groups are: Group A – Reduced tillage (minimum or zero tillage, ripper), Group B – *in situ* water retention (tied ridges, planting basins, bunds, terraces, contours), Group C – Evaporation suppressants (crop residues, mulching), Group D – Nutrient only (organic – manure and inorganic – fertilizer), Group E – Water harvesting with storage (full or supplemental irrigation), Group F – Cropping system and Agroforestry (trees and crops: crop rotations and intercropping) and Group G – Combination of two or more technologies (ripper or planting basin or ridges combined with fertility treatment (fertilizer and/ or manure), planting basins or crop rotation with mulch) (see Table 1). The conventional farming system is taken as the control against which the experimental AWM technology groups are compared.

2.9. Risk of crop yield to AWM technologies

The relative frequency of positive or negative effects on crop yield for each soil texture was estimated. The level of performance of each AWM technology was assessed by the cumulative probability distributions of first and second order stochastic dominance of yield. An alternative to conventional practice dominates if it has a smaller area under the distribution plot at every outcome level (Uaiene, 2004).

2.10. Assessment of certainty of the evidence from reviewed studies

The GRADE (Grading of Recommendations Assessment, Development and Evaluation) approach, using the GRADEpro GDT software (Schünemann, 2008) was used to assess the strength of evidence for or against AWM technology and develop recommendations on the use of AWM technologies (Andrews et al., 2013; Schünemann et al., 2011). GRADE is a well-developed formal process to rate the quality of scientific evidence in systematic reviews and to develop evidence-based recommendations.

2.11. Assumptions of the study

The assumptions of the study are:

- Plant population across technologies may vary but remain the same within each case study
- The management of crops was assumed to be similar in the experiment and control plots.
- Crop species, variety and treatment effects were similar, i.e. in each study the same crop species or varieties were used in the experiment and control groups.

A limitation of the current approach is that field soil fertility and management prior to the initiation of the experiment or observation, which could affect performance of experimental trials in the subsequent year, was not revealed in most of the case studies.

3. Results and discussions

3.1. Descriptive statistics of AWM cases

Ninety-seven (97) references from 1980 to 2013 were identified. They consisted of cases from on-station (37%), on-farm (58%) and modelling (5%). A total of 1430 AWM paired cases (experimental and control) stemmed from the 97 references and 50.1% were

Table 1. Current farm practices and AWM Technologies.

AWM technology class	Group	No. of paired cases	Water soil nutrient feature	Typical names	Management feature
Reduced tillage	A	83	Increase infiltration/soil carbon	Minimum or zero tillage; ripping (no soil inversion)	Reduced and energy-efficient manual, mechanized and animal draft power
In-situ water retention	B	284	Slow down and trap runoff and enhance infiltration rates, guard against erosion, and help keep soil fertility in place	Zai pit/ planting basins, planting/infiltration pit, fanyaa juu, tied ridges, bunds, terraces, contour ridges	Manual, mechanized and animal draft power for creating and managing soil structures
Evaporation suppress	C	115	Reduce runoff, increase infiltration, reduce evaporation, promote decompose to provide humus, protect soil from rain and wind erosion. May cause water logging under continuous rainfall	Organic and inorganic materials, e.g. wild grass, crop residues or tree biomass, either leguminous or not), plastic sheeting, rock	Residues/mulch must provide at least 30% soil cover (Unger, Stewart, Parr, & Singh, 1991); conflict between livestock feed and mulch from crop residues
Nutrient only	D	263	Improve soil nutrient, and water holding and cation exchange capacities. Crop response to nutrients depends primarily on available moisture and is poor under low seasonal rainfall	Organic (manure) and inorganic nutrient components	Collect/ buy fertilizer or manure. Station nutrient placement method increases nutrient use efficiency under smallholder farming
Water harvesting with storage	E	73	Improve water supply for the plant, livestock and domestic use. Can bridge and smoothen seasonal water supply variability	Full or supplemental irrigation	Manual and mechanical capture of rainfall in surface and subsurface reservoirs, soil profile, and groundwater aquifers for irrigation application
Cropping system and agroforestry	F	237	Improve soil fertility, regulate nutrient cycling, reduce soil erosion, increase labour productivity and reduce the risk of complete crop failure due to water stress and pest and disease	Trees and crops: crop rotations & intercropping e.g. Sorghum-cowpea, millet-cowpea, maize-cowpea, and sorghum-groundnuts associations	The practise of intercropping of annual and perennial crops with trees and/or bushes with beneficial use for crop-livestock farming systems and infertile soils prone to erosion (Van Duivenboodew et al., 2000)
Combination of two or more interventions	G	445	Promote infiltration, conserve moisture, enhance soil micro flora and fauna in soil	Planting basin + fertility treatment, reduced tillage + mulch (conservation agriculture)	Manual, mechanized and animal draft power
Farmer/ conventional practise		1485	Low input requirement, promotes infiltration, conserve moisture in soil, organic matter mineralization and destroy soil micro flora and fauna, resulting in poor soil structure and enhanced sheet and wind erosion	Planting on flat ploughed surface or on-line planting; no use or minimal use of nutrients	Manual, mechanized and animal draft power

peer-reviewed studies, 34.6% project reports, 8.5% conference papers and 6.8% were theses (Figure 3). The highest number of cases were from Group G – combination of two or more AWM technologies. The proportion of cases based on publication period were 1980–1990 (0.2%), 1991–2000 (11.8%), 2001–2010 (55.1%) and 2011–2013 (32.9%). The references of the reviewed cases for the different AWM groups and the highest number of consecutive years of implementing the AWM technology or modelling are presented in supplementary material.

The number of case studies for each crop type were: maize (1085: 76%), sorghum (208: 15%) and millet (38: 2.7%), while cowpea (58: 4%) and groundnut (41: 2.9%) were used in some of the intercropping cases. The proportion of paired cases based on

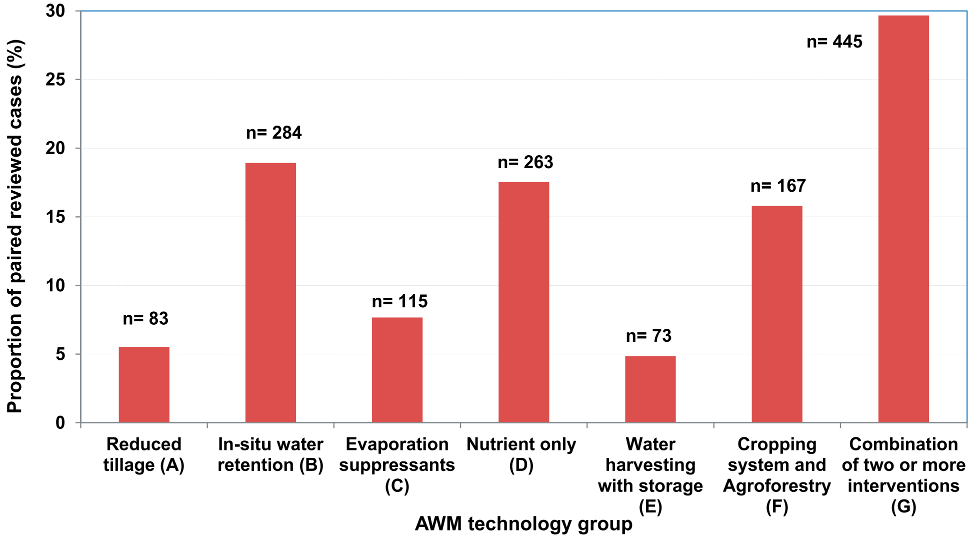

Figure 3. Paired case studies identified for each AWM technology group.

duration of study were 1 year (17%: 256), 2 years (22%: 332), 3 years (27%: 404), 4 years (29%: 435), 5 years (3.5%: 53) and above 5 years (1.3%: 11), indicating that more than 80% of the paired cases had been tested for more than two years. The proportion of on-farm cases were highest with 870 cases (57%), followed by on-station with 555 cases (37%) and modelling with 70 cases (5%).

3.2. Yield response for different AWM technology groups

The overall value of SMD for yield was 0.27 with a 95% CI of 0.18–0.35, indicates an opportunity to enhance crop production with AWM technologies in the basin (Figure 4). The efficacy of AWM technologies was highest for water harvesting with storage – group E (SMD = 0.53), followed by *in situ* water retention – group B (SMD = 0.38) and a combination of two or more AWM technologies – group G (SMD = 0.31). This result indicates the critical aspect of securing water for improved crop yield and production in the Limpopo agro-ecological landscapes. The widest variation in yield observed for group E is indicative of the huge potential of yield gains that can be realized from this technology. Evaporation suppressants alone (group C) had the least effect on the improvement of crop yield (SMD = 0.07). Negative yield impacts were observed for groups A, C and F (Figure 4), indicating unstable performance of some AWM technologies because of the complex relationship between farm management practices and the soil–rainfall–crop system. The median yield gains (t ha^{-1}) and their marginal changes in relation to conventional practise confirm the performance ranking of AWM groups (Table 2).

Overall, yield performance comparison showed that technologies implemented on-station (511 cases) performed better than those from on-farm (758 cases). The median yield gains from on-station were 63% (control of 1.23 t ha^{-1} and experiment of 2 t ha^{-1}), while yield gains from on-farm were 29%, with control of 1 t ha^{-1}and experiment of 1.29 t ha^{-1}. Water productivity improvement was also higher under technologies implemented on-station. This result showed reduced crop yield and productivity performance due to poor replication of on-station conditions at the farm level.

The low value of I^2 (Figure 4) suggest low heterogeneity among the seven AWM groups, while the *p*-value indicates statistically insignificant results (Higgins & Green, 2008; Rücker et al., 2008). However, Rücker et al. (2008) argue that I^2 is generally limited in assessing clinically relevant heterogeneity and it is good practice to also look at efficacy and covariate sizes.

The yield increase from AWM technologies compared to the control (figures given in brackets) and rainfall regimes are presented in Table 2. Median yield increase ranged 9–95% (mean 34%), with an absolute median yield range of 1.40–2.20 t ha^{-1} (not shown). Table 2 indicates that although group E and group A produced the highest absolute median

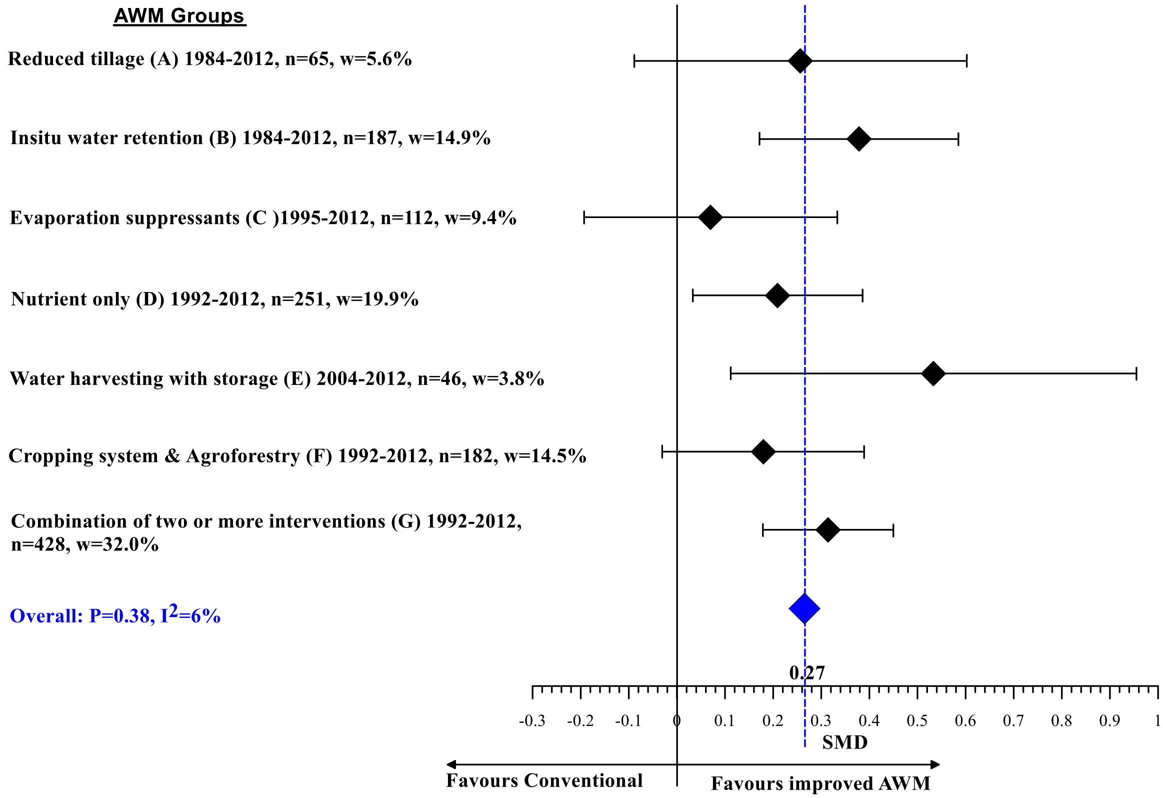

Figure 4. Synthesized grain yield (t·ha^{-1}) change for 7 AWM technology groups in the Limpopo Basin. The diamond symbol represents the mean, the horizontal axis of the diamond represent the 95% CI.

yields of 2.20 t ha^{-1} (control 1.00 t ha^{-1}) and 1.78 t ha^{-1} (control yield 1.58 t ha^{-1}), respectively, the range of yield gains of the latter from low to medium rainfall regimes is marginal compared to the former. This result indicates that group E technology achieves higher yield gains when annual rainfall is low, and this is particularly significant in the semi-arid environment of the basin. The nutrient only (D) and in-situ water retention (B) groups seemed to perform equally in both low and medium rainfall regimes.

The funnel plot of standard error (SE) against the SMD in yield is presented in Figure 5, and it indicates a symmetric scatter for the seven AWM groups about the overall SMD of 0.27. This result suggests considerable strength of evidence that the number of cases included for the analysis of the crop yield is comprehensive enough to ensure less chance of bias and between group heterogeneity (Schünemann et al., 2011).

3.3. Water productivity for different AWM groups

The total water (rainfall and rainfall plus supplemental irrigation) crop productivity variation for the seven

Table 2. Summary of AWM technologies and expected yields increase across all crops and rainfall regimes.

AWM technology groups	Median yield (control) (t ha^{-1})	Median yield increase (%)	Median yield increase per rainfall regime 200–500 mm (501–800 mm) (%)
Water harvesting with storage: E ($n = 58$)	2.2 (1.0)	95	28 (129)
Cropping system and agroforestry: F ($n = 167$)	1.42 (0.95)	34	50 (11)
In-situ water retention: B ($n = 190$)	1.44 (1.11)	33	32 (35)
Combination of two or more interventions: G ($n = 428$)	1.59 (1.06)	25	42 (18)
Nutrient only: D ($n = 247$)	1.36 (1.1)	31	21 (23)
Reduced tillage: A ($n = 83$)	1.78 (1.5)	12	7 (18)
Evaporation suppressants: C ($n = 115$)	1.4 (1.29)	9	16 (30)

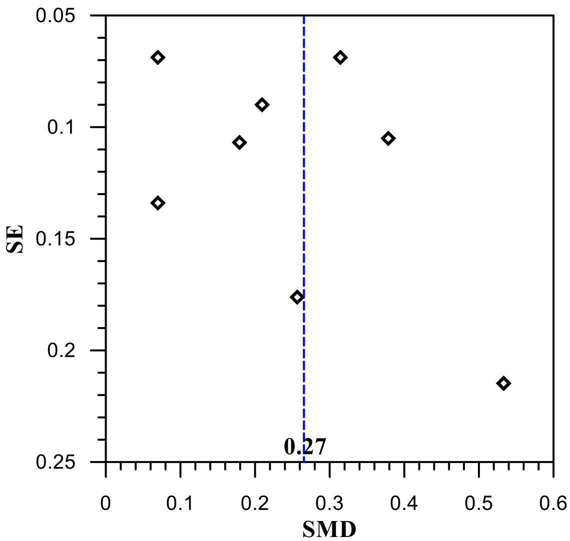

Figure 5. Funnel plot from the seven AWM intervention groups on cereal crop yield.

AWM groups is presented in Figure 6. The best performing AWM technology in terms of water productivity is nutrient only – group D (SMD = 0.9) followed by *in situ* water retention – group B (SMD = 0.71) and a combination of two or more technologies – group G (SMD = 0.29). Group G showed the largest variations, indicating a wide opportunity to increase productivity by this technology. The evaporation suppressants (Group C) had too few water productivity data to do any statistical analysis, and water harvesting with storage – group E (SMD = 0.21) resulted in marginal enhancement of water productivity. It can be conjectured that there could be untapped water productivity potential with some AWM technologies that showed large water productivity variations, while others could be already performing in their optimum range in the basin. The overall water productivity efficacy of SMD = 0.46 indicates that AWM technologies (experiment) are more effective than control treatment.

The funnel plot of SE against the SMD from water productivity is presented in Figure 7 for the six AWM groups (Figure 6) which had sufficient data for the analysis. It is observed that there is asymmetry in the scatter for these AWM technologies about the overall SMD of 0.46, reflecting a

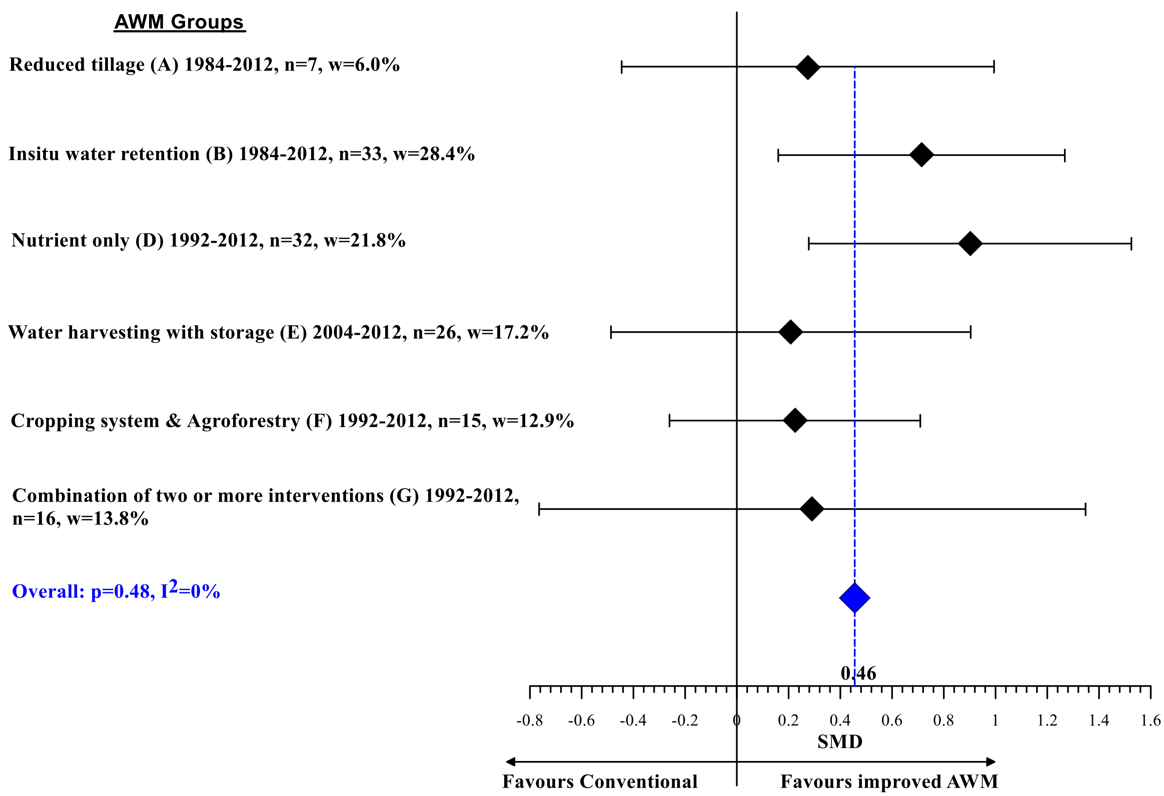

Figure 6. Water productivity (kg mm^{-1}) variations for the seven AWM technology groups. The diamond symbol represents the summary effect measure, the vertical axis of the diamond represents the point estimate and the horizontal axis of the diamond represents the 95% CI.

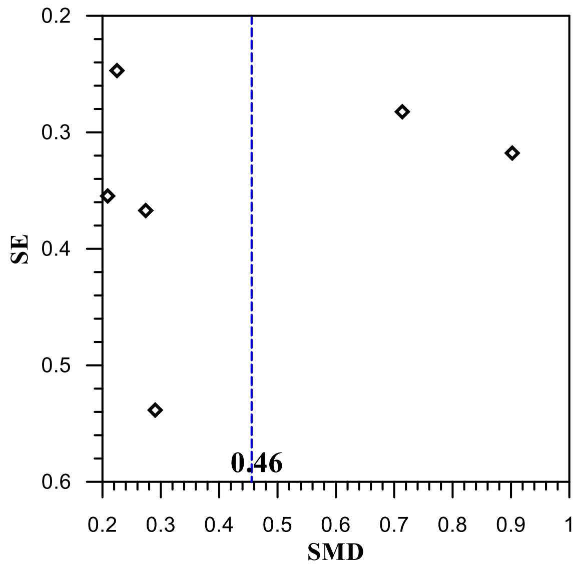

Figure 7. Funnel plot from the six AWM intervention groups on water productivity.

reduced strength of evidence that the cases included for the analysis are not comprehensive enough, thereby warranting additional studies in the future to support the efficacy of AWM technologies on crop water productivity.

3.4. Yield responses from AWM groups under different rainfall regimes

The performances of various sub-groupings of AWM technologies in low and medium rainfall regimes are presented in Figure 8. The I^2 (Figure 8) showed substantial technological heterogeneity, while the *p*-value indicated statistically significant results (Higgins & Green, 2008; Rücker et al., 2008). The subgroup of crop rotation plus mulch from group G performed best in both low (SMD = 2.01) and medium (SMD = 3.7) rainfall regimes, followed by planting basin plus fertilizer. This suggests the importance of crop rotation in providing a balanced soil nutrient for the following crop unlike application of inorganic fertilizer. There are no consistent trends in the performances of other AWM sub-groups from the low to medium rainfall regimes. This result indicates that the yield potentials for some AWM technologies could be substantial (SMD = 5.1) and marginal (SMD = −1) for others, depending on the complex soil–rainfall–crop system that has to be understood by farmers/researchers in applying these technologies. There is marginal increase in effectiveness of AWM technologies to improving yields in low rainfall regime (SMD = 0.51) compared to the medium rainfall regime with an overall SMD value of 0.39. These results concur with Rusinamhodzi et al. (2011) who reported significant yield increases under reduced tillage for a lower rainfall regime of less than 600 mm compared to a higher rainfall regime of 600–1000 mm. Hussain, Olson, and Ebelhar (1999) also reported yield decreases of 5–20% in wet years and 10–100% increases in relatively dry years under conservation agriculture compared to conventional tillage practices. To strengthen the evidence of the influence of rainfall in AWM technologies, intra-season or crop season rainfall distribution should be collected in future studies.

3.5. Yield performance of individual technologies within groups D and F

The analysis breaks down the average performance of an AWM group to an individual technology within that group. A comparison of efficiency of fertilizer alone with SMD of 0.20 in yield to intercropping with leguminous crops with SMD of 0.03, indicates that intercropping has little effect on yield (Table 3). The efficiency of organic manure only was better (SMD = 0.30) compared to different levels of application of inorganic fertilizers which produced values of SMD between 0.18 and 0.21. Microdosing of inorganic fertilizers that did not exceed 35 kg ha^{-1} performed better (SMD = 0.21) than large quantities of fertilizer of 36–300 kg ha^{-1} with SMD of 0.18. This result underscores the significance of adequate soil-water availability in order to realize the efficiency of fertilizer on crop yield. The results in Table 3 also indicate a considerable increase in yield when the frequency of weeding per growing season is increased, as weeds compete with crops for nutrients and water.

The effect of evaporation suppressants (Group C) on yield showed that large quantities of mulch of 4.00–10.00 t ha^{-1} (125 cases) enhance yield (SMD = 0.15) compared to less mulch of between 0.50 and 3.00 t ha^{-1} (102 cases), which gave a value of SMD of 0.02. For water harvesting with storage (Group E) based on 170 cases, the efficacy of supplemental irrigation was highest (SMD = 1.17) compared to full sprinkler (SMD = 0.71) and full furrow (SMD = 0.36) irrigation types. This result suggests that it is not only the irrigation infrastructure that is important

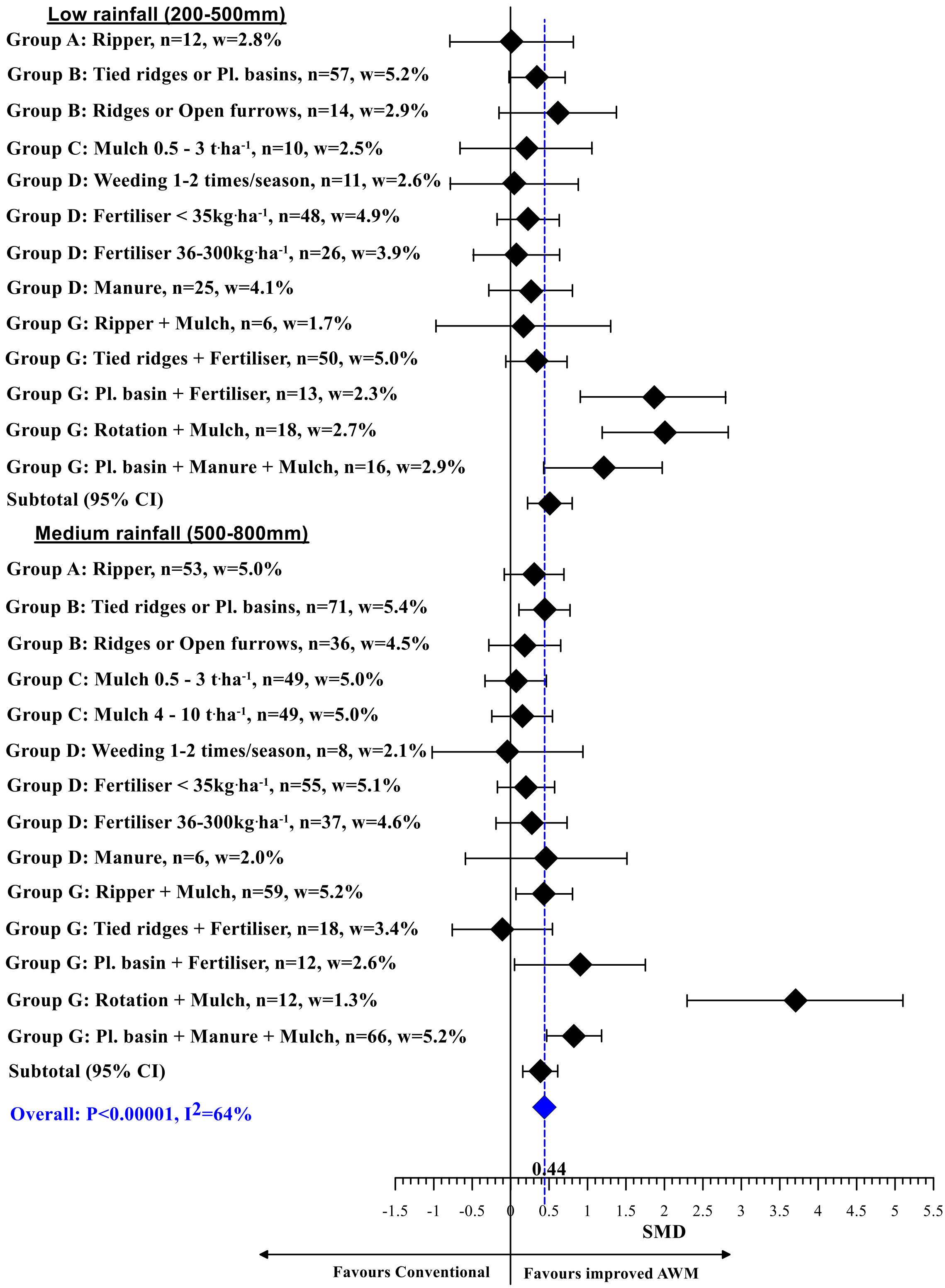

Figure 8. Standardized yield difference for all AWM technologies in different rainfall regimes.

Table 3. SMD effect size for individual AWM technologies from groups D and F.

Subgroup	Type of AWM	Number of cases	Effect Estimate SMD [95% CI]
Nutrient only (Group D)	6	818	0.21 [0.07, 0.35]
Fertilizer only	1	342	0.20 [−0.01, 0.41]
Fertilizer less or equal to 35kg·ha^{-1}	1	212	0.21 [−0.06, 0.48]
Fertilizer 36 – 300 kg·ha^{-1}	1	126	0.18 [−0.17, 0.53]
Manure only	1	62	0.30 [−0.21, 0.80]
Weeding once per season	1	38	0.01 [−0.62, 0.65]
Weeding 2–3 times per season	1	38	0.50 [−0.15, 1.14]
Cropping system (Group F)	2	112	0.14 [−0.23, 0.51]
Intercropping	1	52	0.03 [−0.52, 0.57]
Improved seed variety	1	60	0.23 [−0.27, 0.74]

Note: CI is confidence interval; SMD: <0.4 represents a small effect, 0.4–0.7 moderate and >0.70 a large effect.

but the availability and effective management of soil–water during critical long dry spells of the cropping season.

3.6. Yield responses in different soil textures

AWM technologies have the highest likelihood of producing good yields in silty clay loam soils which are part of the cultivated basin area of 2,20,000 km^2 (53% of basin area) as reported in Limpopo River Awareness Kit (2011) than in other soils (e.g. clay loam, loamy sandy and sandy) with clay soils presenting the greatest challenge to these technologies. Silty clay loam soils cover an approximate area of 46,000 km^2 (11%) of the basin area (Bangira & Manyevere, 2009) and present great potential for expansion and intensification of crop production to the areas that are currently uncultivated. These results agree with Rusinamhodzi et al. (2011) who reported mostly negative yield changes for clay soils but positive yield changes in both loam and sandy soils when conventional tillage and reduced tillage plus mulch were compared. The yield change frequency histogram for different soil textures for the combined AWM technology, group G is shown in Figure 9. For sandy soil, the modal frequency of 25% is observed for the yield change classes of 0–25% and – (0–25%), while for sandy loam, the modal frequency of 19% is for yield change classes of 26–50%, 0–25% and – (0–25%). For clay, the modal frequency of 37% is for yield change class of – (0–25%) and for silty clay loam, the modal frequency of 97% is for yield change class of >75%.

3.7. Effect of site potential on yield responses

The SMD for yield changes for all AWM technologies in relation to crop production potential at control sites is presented in Figure 10. The I^2 (Figure 10) shows moderate heterogeneity among the AWM technologies, while the *p*-value indicates statistically significant results (Rücker et al., 2008). Using the mean yield categories at control sites of low (<0.50 t ha^{-1}), medium (0.50–2.00 t ha^{-1}) and high (>2.00 t ha^{-1}), there is greater yield increase at low control yield sites than at sites with medium and high control yields. The high yield gains from AWM technologies at low yield control sites indicate that AWM technologies increase yields in large areas of low-yielding environments occupied by smallholder farmers in the basin. For maize crop, the control produced low category mean yield of 0.35 t ha^{-1}, while AWM technologies produced a mean yield of 0.75 t ha^{-1}. For the medium yield category, the control was 1.10 t ha^{-1}, while for AWM technologies it was 1.64 t ha^{-1}, and in the high yield category, the control was 3.30 t ha^{-1}, while for AWM technologies it was 3.2 t ha^{-1}. Similarly for sorghum, in the low, medium and high categories, the control was 0.30, 1.21, 2.78 t ha^{-1}, respectively, while for AWM technologies it was 0.45, 1.52 and 2.77 t ha^{-1}, respectively. For millet, reviewed cases were only obtained for the low and medium categories which for the control was 0.31 and 0.60 t ha^{-1}, respectively, while for AWM technologies it was 0.60 and 0.80 t ha^{-1}, respectively. There are generally little benefits from AWM technologies when conventional practice produced high yields of greater than 2.00 t ha^{-1} (SMD = –0.05).

3.8. Risk to yield response for different AWM technologies

Essentially, all AWM technologies provide a 90% chance to increasing yields in the 1.00–3.00 t ha^{-1} yield range. Only AWM technology groups of

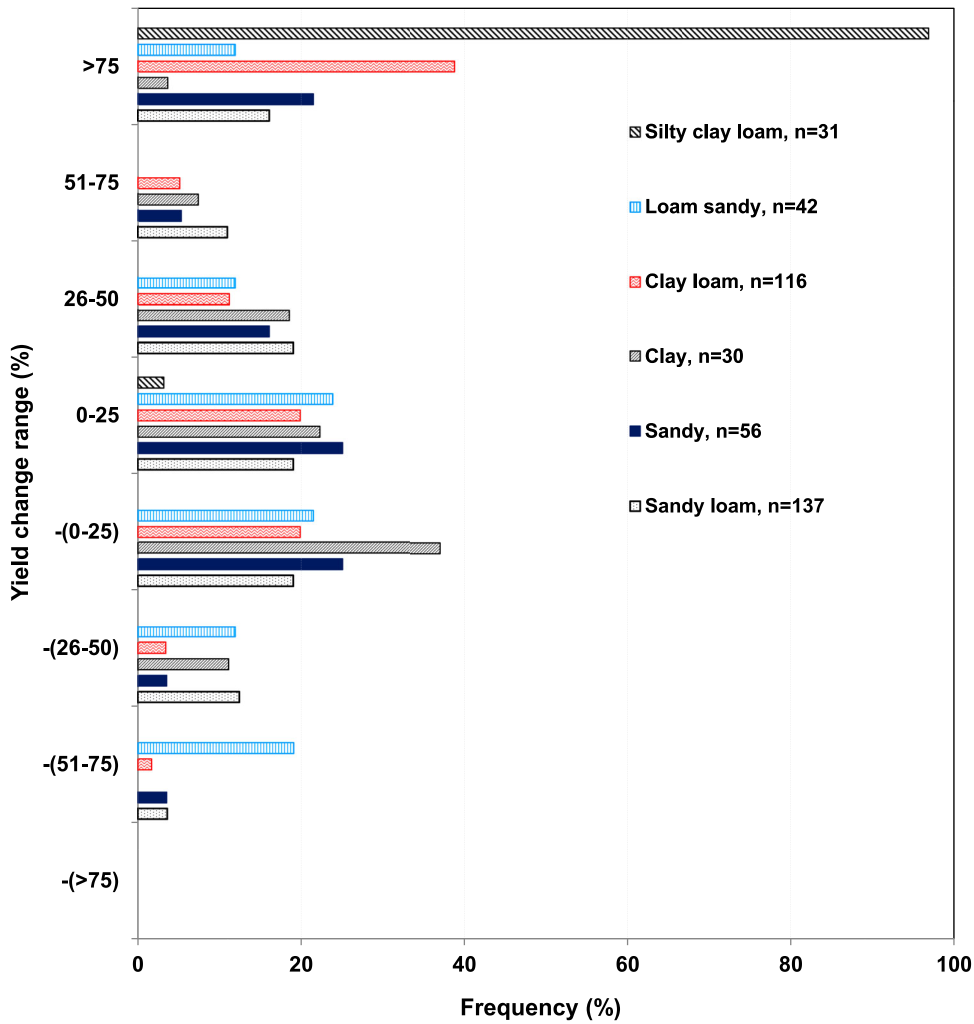

Figure 9. Yield change frequencies in different soil textures for combined AWM technology, group G.

intercropping and agroforestry (F) and water harvesting with storage (E) provide higher reliability of yield gains than conventional practice for all yield levels. These results are deduced from the plot of the cumulative probability distribution for the seven AWM technology groups and the controls for all 1430 paired cases presented in Figure 11. The probability of obtaining grain yields lower or equal to the control constitutes a risk to farmers if the performance of a technology, on average, across a wide range of conditions, is used to give recommendations. The curve of water harvesting with storage (Group E) is farthest to the right of the control cumulative distribution curve and, therefore, represents the most resilient AWM technology that exposes the least risk of yield failure to farmers (Figure 11). However, it is important to note that all the AWM technologies reduce yield failure risk to some extent for yield ranges of 0.50–2.50 t ha^{-1}.

3.9. Impacts of AWM technologies on runoff and sediment loss

The environmental impacts of AWM technologies from groups A (Reduced tillage), B (*In situ* water retention), and G (a combination of two or more technologies) are represented by the median sediment loss reduction of 78% (65 cases) and runoff reduction of 62% (51 cases), compared to conventional farmer practise (Figure 12). The influences of rainfall regime

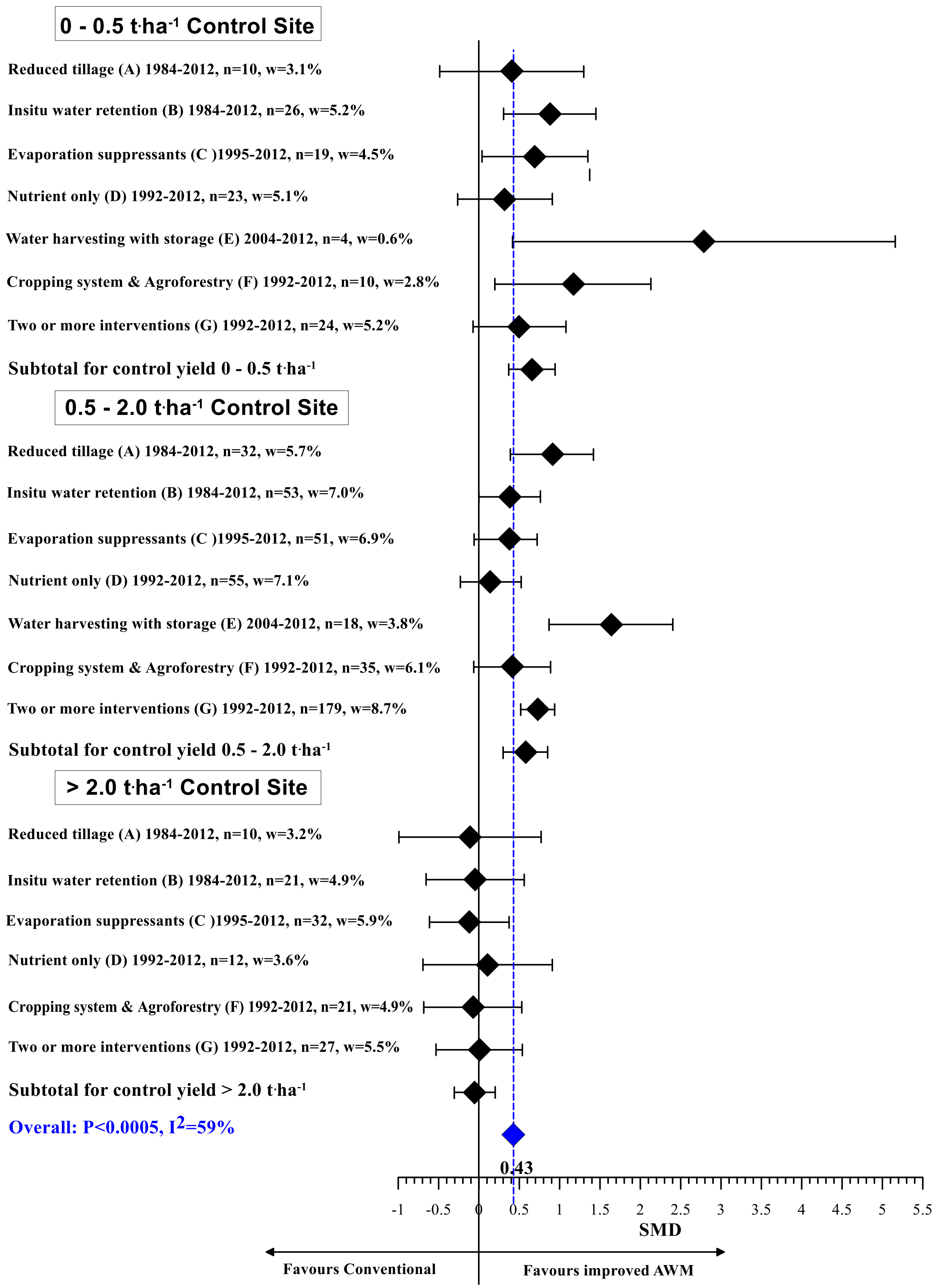

Figure 10. Yield changes under all AWM intervention groups for control sites with different yield potentials. The diamond symbol represents the summary effect measure, the vertical axis of the diamond represents the point estimate and the horizontal axis of the diamond represents the 95% CI.

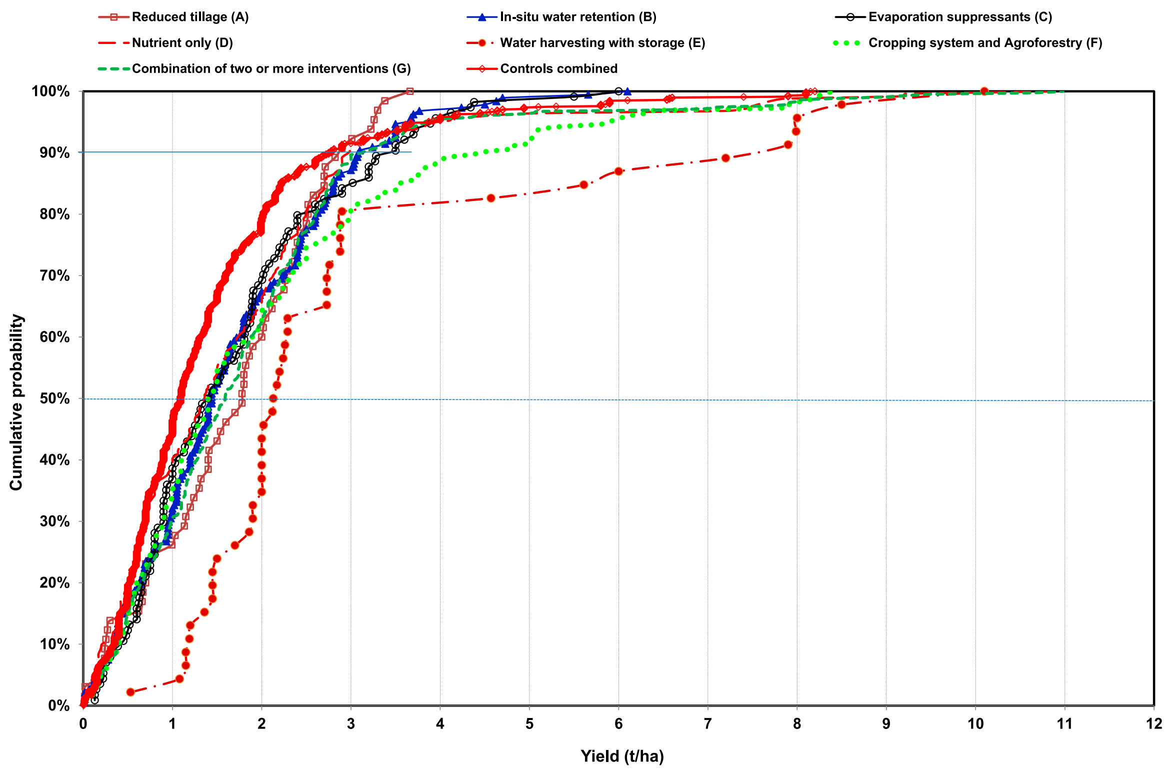

Figure 11. Cumulative distributions of yield under seven AWM technology groups and control across all crops.

on the environmental impacts of these three AWM technologies are presented in Figure 13. The median runoff reduction is higher with higher rainfall, whereas the median sediment reduction is about the same for both rainfall regimes, suggesting a limit to the effectiveness of sediment reduction.

3.10. Summary of findings

The results presented in Table 4 from the GRADEpro GDT software show high strength of evidence that the SMD of yield between conventional and AWM technologies is 0.27, while there is moderate strength of evidence to support water productivity, with SMD of 0.46. This confirms the results of the funnel plots for yield and water productivity presented earlier.

3.11. Discussions

The results presented from 97 references with 1430 paired cases of AWM technologies in the Limpopo Basin provide some indication of their relative performances and major consistent trends without any attempt to explain each individual variation. Of significance to smallholder farmers is the improvement in production, measured by crop yield and water productivity, and environmental protection, assessed by reduced sediment and field runoff losses.

The AWM technologies can enhance regional and local food security through adaptation to expected climate change and maximization of crop water productivity. An overall assessment of the seven AWM technologies, based on crop yield and water productivity, showed that water harvesting with storage (E) and *in situ* water retention (B) out-perform the others, although intercropping and agroforestry (F) and a combination of two or more AWM technologies (G) gave consistently good yield results because of the synergy effect. However, in spite of the synergy, G performed lower than *in situ* water retention (B) and nutrient management (D) (Figure 6). The synergy in this group G is masked by other low yielding AWM technology combinations found in this group such as ripper plus mulch or crop rotation plus mulch. The reduced tillage improved median yield by 0.24 t ha^{-1} and *in situ* water retention by 0.33 t ha^{-1} when compared with the control (Table 2). This result is

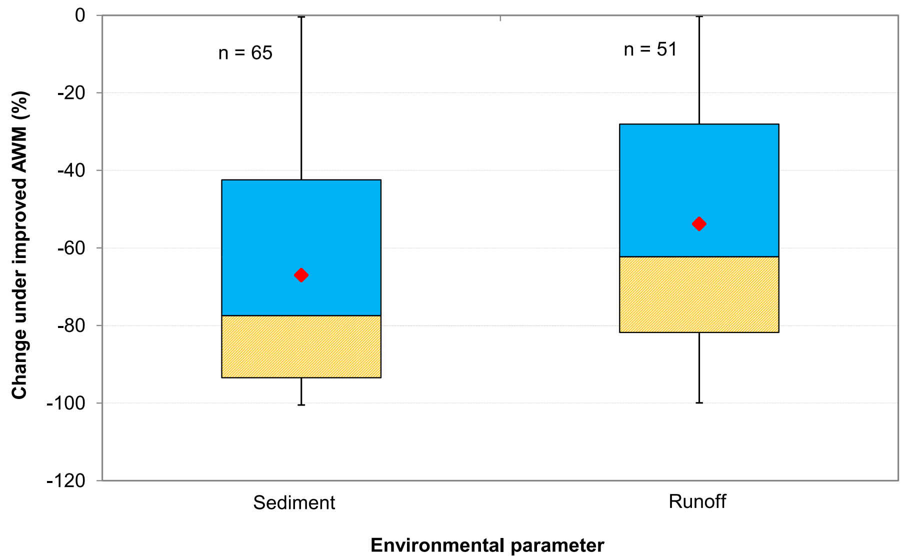

Figure 12. Change in runoff and sediment generated for the combined AWM technology group. The diamond symbol represents the mean, the horizontal line in the box the median, the upper and lower boundaries of the box are the 25th and 75th percentiles, and the upper and lower ends of the extended lines represent the minimum and maximum values of the data.

consistent with Mafongoya et al. (2016) who reported yield increases from direct seeding, rip-line seeding and seeding into planting basins by 0.445, 0.258 and 0.241 t ha^{-1}, respectively.

Water harvesting with storage (E) that resulted in median yield increases of 34–95% provides the least risks to farmers in terms of coping with the inherent rainfall variability of the LRB. Some limitations of not

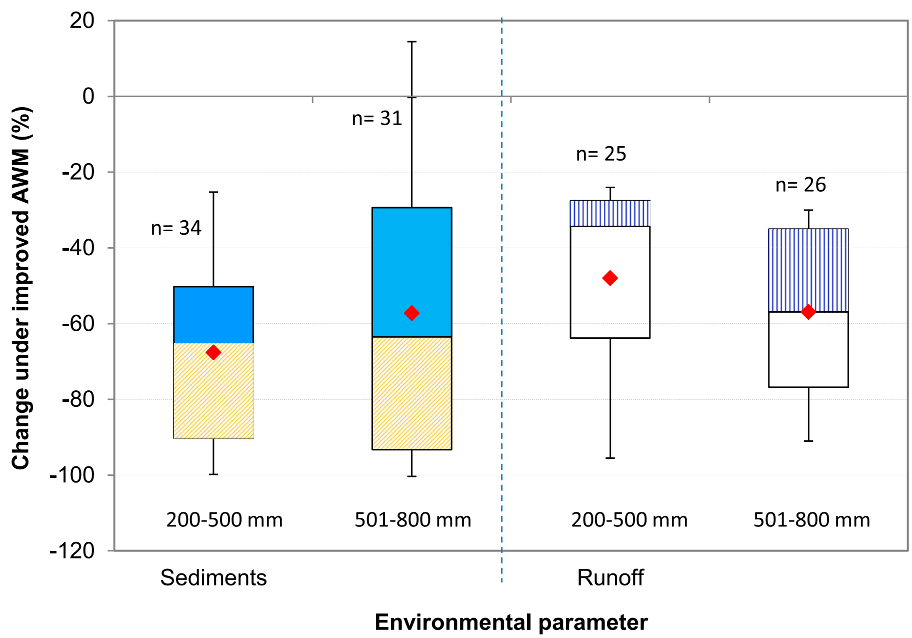

Figure 13. Sediment and runoff reduction for combined AWM technology group in different rainfall regimes. The diamond symbol represents the mean, the horizontal line in the box the median, the upper and lower boundaries of the box are the 25th and 75th percentiles, and the upper and lower ends of the extended lines represent the minimum and maximum values of the data.

Table 4. Summary of findings.

AWM technologies versus farmer practice for increasing crop yield and water productivity in semi-arid areas

Patient or population: Subsistence farming with increasing crop yield and water productivity in semi-arid areas
Settings: Arid and semi-arid subsistence farming
Intervention: Improved AWM technologies versus farmer practice

Outcomes	**Illustrative comparative risks* (95% CI)** Assumed risk	Corresponding risk	**Relative effect (95% CI)**	**No of Participants (AWM Groups)**	**Quality of the evidence (GRADE)**	**Comments**
	Control	**Improved agricultural water management technologies versus farmer practice**				
Cereal crop yield		SMD for yield in all technology groups was **0.27** indicating AWM had small effect on yield		2517 (7 groups)	⊕⊕⊕⊕ **high**	AWM technologies are recommended
Water productivity		SMD for water productivity in all technology groups was **0.46** indicating AWM had moderate effect on increasing water productivity		242 (7 groups)	⊕⊕⊕⊝ **moderate**	113 cases and 129 controls – control studies. AWM are recommended

*The basis for the **assumed risk** (e.g. the median control group risk across studies) is provided in footnotes. The **corresponding risk** (and its 95% CI) is based on the assumed risk in the comparison group and the **relative effect** of the intervention (and its 95% CI).
CI: Confidence interval; SMD: < 0.4 represents a small effect, 0.4–0.7 moderate and > 0.70 a large effect (Schünemann et al. (2011).
GRADE Working Group grades of evidence.
High quality: Further research is very unlikely to change our confidence in the estimate of effect.
Moderate quality: Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate.
Low quality: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate.
Very low quality: We are very uncertain about the estimate.

having actual seasonal rainfall data nor rainfall distribution to correlate to yield and water productivity, and quite low number of cases that measured erosion (67 cases) and runoff (51 cases) were considered to increase uncertainty of the results. This lack of data suggests the need for improved field monitoring to capture these aspects.

Understanding the bio-physical and socio-economic contexts of smallholder farmers is crucial in identifying the most appropriate suite of AWM technologies, as the results indicate that every technology has relative chances of success and failure depending on soils, rainfall regime, nutrient, water and farmer management practices. For instance, the decrease in median yields for cropping system and agroforestry (F) and combination of two or more technologies (G) with an increase in rainfall regime implies that farmers have to pay closer attention to the management of soil-water at higher rainfall to avoid waterlogging, crusting and leaching of nutrients and pesticides. Similarly, the challenges posed by clay soils imply that smallholder farmers need better management strategies to improve production and productivity. Hence, the onus is on researchers to make additional effort in understanding when and where AWM technologies work.

The assessment showed large yield variations with different AWM technologies, indicating that higher yield gains, which are attainable, present huge promise for meeting the substantial yield gaps that currently exist in conventional farming practice. It is expected that with further technology development, continued on-farm experiments of different technologies and appropriate knowledge transfer mechanisms and support including enabling market-policy conditions, these technologies can readily be adopted by smallholder farmers in the basin.

The reductions of runoff and sediment loss are important in partitioning the total precipitation, maintaining soil stability, and conserving the inherent and applied nutrients in agricultural fields in semi-arid areas (Mzezewa and van Rensburg 2011). Furthermore, AWM technologies partition rainfall in a way that increases soil–water infiltration and reduces evaporation rate to enhance crop soil–water availability to bridge the intra-seasonal dry spells for increased yields and water productivity (Moroke, Dikinya, & Patrick, 2009). Field runoff losses above 50% of the rainfall from untilled bare lands, which constitute an erosion hazard, have been reported in the basin (Mupangwa, Twomlow, & Walker, 2012), while comparable runoff losses up to 46% have been reported in Ethiopia (Zere, Hensley, & Van Huyssteen, 2006) and 25–30% under conventional tillage in SSA (Rockström, 2000). High soil losses ranging from 10.00–50.00 t ha^{-1} y^{-1} in both low and high rainfall zones have resulted in low productivity in over 25% of the smallholder areas in Zimbabwe (Nyamadzawo, Nyamugafata, Wuta, Nyamangara, & Chikowo, 2012; Vogel, 1992; Whitlow & Campbell, 1989). The added benefit of AWM technologies in climatic adaptation through the carbon sequestration requires further investigation.

We suggest that better institutional capacity and better context-specific advice to farmers could enable successful AWM up-scaling. Renewed efforts and commitment by CAADP (2017) and African Union (2014) through the Malabo Declaration have addressed the policy issues. However, the constraint to farmers to accessing affordable technologies that suit their context despite climatic variability still persist. This was also discussed in Bulcock and Jewitt (2013) who noted the need for a new set of guidelines that are broader than the current one for the uptake of water harvesting. There is a general weakness in documentation and communication of the experiences and lessons learned under AWM technologies in the basin. Hence, this paper contributes to share knowledge and best practices on AWM technologies, their capabilities and limitations under diverse conditions.

There is a need to support farmers with appropriate AWM technologies based on soil and rainfall regimes. Support to accessing appropriate credit facilities and micro-finance to invest and reduce economic risk in view of the prevailing climatic risk and variability is also needed. This support may include contract farming, crop insurance and farmers participating in inputs and/or outputs markets through farmer organizations to reduce transaction costs (Markelova, Meinzen-Dick, Hellin, & Dohrn, 2009; Nyagumbo, Mutsamba, Barrett, Dengu, & Thierfelder, 2012). Furthermore, provision of advice on seasonal rainfall regime forecast to provide early-warning systems to support implementation of appropriate AWM technologies such as planning for fertilizer and supplemental irrigation application (Van Duivenboodew, Paln, Studer, Bielders, & Beukes, 2000) is required.

4. Conclusions

This meta-analysis has captured for the first time the diversity of environments in which AWM technologies among smallholder farmers have taken place in the LRB, and helped to identify the potential biophysical zones where studied technologies are being researched and applied. The meta-analysis showed that the environment played an important role in determining the relative agricultural crop yield production level for AWM technologies. Overall there is moderate to high evidence that AWM technologies can deliver substantial benefits of climate-smart agriculture in terms of increased crop yield and water productivity to smallholder farmers, whilst attaining desired environmental impacts through retention of sediment and runoff. Yield stability analysis showed that under prolonged drought or very high rainfall conditions, no AWM technology, except water harvesting with storage (Group E) can offset the effects of these extreme conditions. Furthermore, no single AWM technology fits all circumstances to achieve sustainable smallholder agricultural production. Evidence suggests that a combination of two or more AWM technologies (G) and intercropping and agroforestry (F) demonstrate high yield opportunity in low rainfall regimes. The efficiency of organic manure only was better (SMD = 0.3) compared to different application levels of inorganic fertilizers which produced values of SMD between 0.18 and 0.21. Micro-dosing with inorganic fertilizers less than 35 kg ha^{-1} performed better than large quantities of fertilizer of 36–300 kg ha^{-1}, suggesting the need for adequate soil-water availability in order to realize the efficacy of fertilizer on crop yield.

Variations in reported yields within each AWM group suggest that there are still potential opportunities to increase yields beyond average values for enhanced food security and income generation. Attempts to replicate AWM successes at specific sites should be earnestly pursued and appropriately targeted to climatic and edaphic conditions with adequate inputs (fertilizers, seeds, and herbicides) and correct timing of farming operations for best results. Success of AWM technologies depends on the transformation of conventional practices through social learning and participatory approaches between farmers, donors, researchers, and practitioners in the public and private sectors. Given the negative implications of climate change on agricultural production in SSA including the Limpopo Basin (IPCC, 2014), AWM technologies can be implemented as a viable strategy to build resilience and food security for people living in high rainfall variability areas.

Disclosure statement

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