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PEARL MILLET PRODUCTION PRACTICES IN SEMI-ARID WEST AFRICA: A REVIEW

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SUMMARY

Pearl millet (*Pennisetum glaucum* L.) is an important grain crop for millions of poor farmers and consumers in the semi-arid region of West Africa. During the past 40 years, much research on pearl millet production practices and adoption in this region has been conducted, but an attempt to summarize these results has not been previously completed and these research results are not readily available to many West African scientists. This review was completed to address this need and integrate knowledge, and at the same time identify research needs for the future and extension priorities for semi-arid West African agro-ecological zones. Research has shown that selection of improved varieties and cropping systems, appropriate cultural practices, and recommended integrated soil, nutrient, residue and pest management can greatly increase grain and stover yields of pearl millet. However, adoption by farmers has been minimal due to limited profitability, high risk and labour demand, limited input supply, market availability and appropriate public policy. This review has 196 articles included as in-text citations (Table 1) compared to 149 articles in the reference list, indicating that only one in four articles integrated two or more topics in the research. The obvious conclusion is that most of the past research has not addressed the 'system' but rather one or two management practices. In addition, most studies have interpreted responses in terms of yield without addressing other important considerations for farmer adoption. Recent conservation agriculture research moves closer to addressing the larger integrative types of research needed. Such research is complex and requires sustained funding for field and laboratory activities, but also for computer simulation modelling and economic assessment.

INTRODUCTION

Pearl millet (*P. glaucum* (L.) R. Br.) is an important food crop widely produced in Africa and India. Estimated world area of pearl millet is 24.2 million ha with approximately 45% of the world's production in West Africa where it is of major importance in 17 countries (FAO, 2014). Pearl millet is ranked as the sixth most important cereal crop in the world.

Pearl millet is grown in semi-arid to arid zones where soils predominately have sandy textures, low organic matter and nutrient levels; rainfall is limited and erratic; air and soil temperatures are high; and the growing season length is short and varies greatly across years. In West Africa, pearl millet is grown primarily for grain used for human

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Table 1. Summary of article citations in this review based upon title and citation in this review.

Section	Number of citations
Introduction	1
Variety selection and pest management	10
Pest management	19
Annual cropping systems	28
Agroforestry	10
Cultural practices	17
Crop residue management	23
Tillage and water harvesting	21
Nutrient management	40
Conservation agriculture	10
Adoption	17
Total	196

consumption, but the stover is also of great economic importance for livestock feed, building materials and fuel. Average pearl millet yields worldwide are lower than for other cereal crops (FAO, 2014), but improved production practices and cultivars result in more efficient use of photosynthetically active radiation (PAR), water, and nutrients and can greatly increase grain and stover yields. Research and demonstrations clearly indicate that adoption of improved production practices increase pearl millet grain yields and affords opportunities to use grain for value-added human food and livestock feed. The goals of this review were to provide a comprehensive review of the research literature on crop, soil and pest management research on pearl millet production in West Africa during the past 40 years, with emphasis on the Sahelien agro-ecological zone in Burkina Faso, Mali and Niger. Research citations from Senegal, Ghana, Nigeria, Cameron and Chad are also included. Variety selection, improved cropping systems and crop, soil, nutrient and pest management have been shown to increase yield, but have not been widely adopted, thus a short review on reasons for limited adoption of ‘improved practices’ is included. From this information, some general suggestions for future research and policy needed to increase adoption of improved practices and yields of pearl millet are provided.

VARIETY SELECTION

Pearl millet is a highly cross-pollinated species exhibiting a high-level of heterosis, ability to adapt to seasonal climatic differences, evolve with changes in biotic and abiotic factors (Rai and Andrews, personal communication), and adapt to climate change (Jat *et al.*, 2012). Varieties range from short oasis types that mature in two months to highly photoperiod-sensitive types that grow 4.5 m tall and have a five-month life cycle. Most pearl millet varieties are short-day photoperiod sensitive (Bilquez, 1963). Pearl millet varieties need to survive soil surface temperatures up to 55 °C, tolerate water and heat stress while responding through tillering to favourable conditions (Bidinger and Hash, 2004; Winkle *et al.*, 1997). Varieties should be planted

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with the first significant rainfall, survive early season water and heat stress and sand blasting in order to capture the flush of nutrients present after early-season rains, but also must mature late enough to efficiently utilize seasonal rainfall, PAR, and nutrients to optimize growth and crop yield, and to produce the highest quality grain (Rai and Andrews, personal communication). Yield potential and maturity classification are important variety selection criteria, as water use efficiency of pearl millet is closely related to yield (Payne *et al.*, 1990) and seasonal water use (Dancette, 1983). Disease and insect resistance is also important, and tolerance to the parasitic weed *Striga* (*Striga hermonthica* (Del.) Benth) is desired.

Traditional varieties are tall, and produce low, but relatively stable, grain yield and harvest indices. Research has developed shorter maturity varieties with high-grain yield potential and harvest index, allow greater light penetration through the canopy to afford higher yields of intercropped species, and minimize risk from the short, variable length rainy seasons of semi-arid West Africa. However, the increased yield potential of these varieties is often not realized in farmer's fields due to water and nutrient stress, and sub-optimal plant populations (Maman *et al.*, 2000a; Payne, 1997). The best variety varies with location, farm situation and end-use. FAO (2008) has catalogued over 70 of the most common pearl millet varieties in West Africa for genetic background, maturity, height, ability to tiller, panicle length, kernel weight and yield potential.

INTEGRATED PEST MANAGEMENT (IPM)

The most serious pest problem of West Africa is the parasitic weed *Striga* (*S. hermonthica)*. Host plant resistance has been identified for grain sorghum (*Sorghum bicolor* (L.) Moench), but not for cultivated pearl millet (Tesso and Ejeta, 2011), thus production practices remain the only way to manage *Striga*. Infestation with *Striga* increases with low soil fertility, drought, and continuous planting of pearl millet and other host cereals (Andrews and Brammel-Cox, 1993). Historically, build-up of *Striga* seed in the soil has been minimized by long fallow periods. Multiple-year crop rotation eliminates the host plant from the field, and is effective in controlling *Striga*. Late planting (Gworgwor *et al.*, 1998), minimum tillage, recommended fertilizer application rates (Andrews and Brammel-Cox, 1993; Hess and Ejeta, 1987), and intercropping with legumes (Carsky *et al.*, 1994; Carson, 1988) have been shown to reduce *Striga* infestation. None of these methods are completely effective, but integration of these practices improves control (Gworgwor *et al.*, 1998). Physical control by timely hand weeding, promoting pearl millet growth in order to be more competitive, and intercropping are commonly used to control other weed problems (Hatcher and Melander, 2003).

Downy mildew (*Sclerospora graminicola*) is the most serious pearl millet disease in West Africa with reported yield losses of 20–30% (Ndiaye, 2002). This disease can be effectively controlled by use of resistant varieties (Hess *et al.*, 2002; Thakur *et al.*, 2011), seed treatments of Apron Star (metalaxyl fungicide plus furathiocarb insecticide) (Scheuring *et al.*, 2002; Thakur *et al.*, 2011), and rouging of disease plants (Mbaye, 1992). Apron Star produces an average pearl millet yield increase

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of 30% (Scheuring *et al.*, 2002), but is effective for only the first 35 days of growth (Hess *et al.*, 2002). Since most serious infestation of downy mildew occurs in the seedling stage, Apron Star reduces 80+% of crop yield losses (Andrews, personal communication). Other economically important diseases are rust (*Puccinia substriata*), smut (*Moesziomyces penicillariae*), ergot (*Claviceps fusiformis*) and leaf spot (*Pyricularia grisea*), and when available, resistant or tolerant varieties are the best means of control (Hess *et al.*, 2002).

Major insect pests include pearl millet leaf miner (*Heliocheilus albipunctella* de Joannis), stem borer (*Coniesta ignesfusalis*), armyworms (*Spodoptera exempta*), and grasshoppers (several species). Recently, a biological control method for pearl millet leaf miner has been implemented in West Africa through the release of the wasp *Habrobracon hebstor* Say which parasitizes the larvae (Payne *et al.*, 2011). Production practices of crop rotation, intercropping, adjusting planting date and harvest time, field selection and mechanical control minimizes losses from insect pests (van Huis and Meerman, 1997), but insect problems increase with intensification of production (Abate *et al.*, 2000). Crop rotation can reduce problems for insects that have a limited number of hosts and are not mobile, and is especially effective for reducing nematode infestations (Bagayoko *et al.*, 2000a). Intercropping can reduce insect infestations by increasing diversity present in the field, but the use of pesticides (Buntin *et al.*, 2007) or pesticidal plant extracts (Anaso *et al.*, 1998) are often the most effective means of control. Pearl millet has a high level of tolerance to insects (Buntin *et al.*, 2007), and insecticides are expensive and have safety issues, thus are not commonly used in pearl millet production in West Africa (Abate *et al.*, 2000).

Birds are a major pest problem for pearl millet in West Africa. Pearl millet varieties are not bristled and unlike grain sorghum, grain does not contain tannins. Thus, bird tolerance is not available. This likely contributes to farmer decisions to plant similar maturing varieties at the same time, as earlier or later maturing varieties in the field suffer more bird damage.

ANNUAL CROP SYSTEMS

Pearl millet in West Africa is most widely grown in intercropping systems with cowpea (*Vigna unguiculata* (L.) Walp) (Reddy *et al.*, 1992), and often in agroforestry systems (Reij and Smaling, 2008). Pearl millet is also grown as a sole crop, or intercropped with groundnut (*Arachis hypogaea* L.), grain sorghum, or maize (*Zea mays* L.).

Bush fallow systems

Bush fallow has traditionally been a key component of West African cropping systems to improve soil organic matter and nutrient levels at low cost to farmers. These systems traditionally produced crops for 3–5 years then 7–15 years in bush fallow to replenish soils. Due to increased population growth, soil degradation, and economic development, bush fallow cannot currently meet crop nutrient needs (Schlecht and Buerkert, 2004) and is presently used by only 2% of pearl millet producers in West Africa.

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Crop rotation systems

Rotation of pearl millet with other crops in West Africa has been promoted for decades to enhance yields (Bagayoko *et al.,* 1996, 2000a; Bationo *et al.*, 1996; Buerkert *et al.*, 2002; Mason *et al.*, 2014; Nicou, 1978; Subbarao *et al.*, 2000), reduced pest infestations (Abdou *et al.*, 2012; Buerkert *et al.*, 2002; van Huis and Meerman, 1997), improve soil physical properties (Kadi *et al.*, 1990), increase infestation with beneficial arbuscular mycorrhizae (Bagayoko *et al.*, 2000a; Buerkert *et al.*, 2001), promote more efficient nutrient cycling (Bagayoko *et al.*, 1996, 2000a; Bationo *et al.*, 1996; Buerkert *et al.*, 2002) and increase productivity, stability and sustainability (Peter and Runge-Metzger, 1994; Sauerborn *et al.*, 2000).

Intercropping systems

Intercropping is widely practiced to maximize return from the most limiting production factors, to reduce risk, and to take advantage of the beneficial effects of legumes on other crops (Bationo *et al.*, 2011; Norman, 1977). In Niger, traditional pearl millet intercropping systems involve hill planting of seed of tall, late-maturing pearl millet varieties following the first 10–20 mm rain of the growing season (Reddy, 1988; Reddy *et al.*, 1990). Photoperiod sensitive, indeterminate cowpea varieties (Reddy *et al.*, 1990) are planted two to six weeks later depending on completion of pearl millet planting on the entire farm, first hand weeding, and seasonal rainfall (Reddy, 1988). Pearl millet plant population is typically low (approximately 5000 hills ha^{-1} or 15,000 plants ha^{-1}) and the cowpea population is commonly 1000–5000 plants ha^{-1} (Ntare and Williams, 1992; Reddy *et al.*, 1990) but varies depending upon cowpea growth habit and climatic conditions. In Niger, the recommendation is for pearl millet row spacing of 1.5 m with two rows of an indeterminate cowpea variety planted between the pearl millet rows at the time of first weeding (Reddy, 1988). Pearl millet matures before cowpea, which is dependent upon residual soil water or late season rains to produce reasonable yields (Fussell and Serafini, 1985). In general, grain legume yields are very low (Singh and Emechebe, 1998) and influenced by the degree of competition for PAR and water from pearl millet (Ndunguru and Williams, 1993). In this system, pearl millet dominates cowpeas for sunlight, water, and nutrients, and the goal of farmers is full production of pearl millet grain and stover, while cowpea grain or stover production is of secondary importance.

Research has shown that the pearl millet/cowpea and pearl millet/groundnut intercrop system productivity can be increased by choosing appropriate pearl millet (Reddy *et al.*, 1990) and cowpea cultivars (Ntare, 1990); adjusting plating date, populations, and spacings (Ntare and Williams, 1992, Reddy *et al.*, 1992); and application of fertilizer (Ntare and Bationo, 1992). Shorter, early maturing pearl millet varieties combined with indeterminate, spreading cowpea genotypes result in the highest yields and land use ratios (Reddy *et al.*, 1990). Relative number of rows and spacing of pearl millet and intercropped grain legumes varies greatly depending upon location, rainfall and rainfall distribution during the growing season (Odo and Bibinu, 1998). In general, pearl millet intercropping systems are site specific, and

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production practices vary greatly depending upon soil, climate, input availability and crop varieties available. Published recommendations for intercropping in West Africa of pearl millet are largely for Niger, and 20 years old, thus updating recommendations for use of new improved varieties and other production practices is needed.

AGROFORESTRY SYSTEMS

Production of pearl millet together with trees, especially *Faidherbia albida* (Del.) A. Chev., is common in West Africa (Garrity *et al.*, 2010). *F. albida* is a multipurpose, deep-rooted, leguminous tree species with reverse phenology, as it has leaves present during the dry season then drops the leaves during the growing season (Roupsard *et al.*, 1999). Pearl millet growth and yields are dramatically greater under the *F. albida* trees, with reports of 36–169% increase (Mokgolodi *et al.*, 2011; Reij *et al.*, 2009) attributed to higher soil nutrient levels, higher water availability, improved microclimate, and better soil physical properties (Breman and Kessler, 1997; Kho *et al.*, 2001). Zaï pits, rock bunds and manure application have synergistic effects on yields when planting pearl millet into stands of *F. albida* (Reij *et al.*, 2009). Gnankambary *et al.* (2008) found that N and P applications increased the rate of *F. albida* and *Vitellaria paradoxa* litter decomposition and nutrient release, which contributed to late season growth stimulation under trees. Mokgolodi *et al.* (2011) reported that a dense stand of *F. albida* ha^{-1} added the equivalent of 50 t ha^{-1} of manure to soil. Greater early-season pearl millet growth has been associated with lower soil temperature (Vanderbeldt and Williams, 1992) and/or greater water availability (Kho *et al.*, 2001). Payne *et al.* (1998) found that soil fertility and fine-particle content decreased with distance from the tree centres, and that maize and sorghum produced 50% greater yields near the tree centres, while pearl millet yielded more near the edge of the tree canopy. They suggested that variation in soil water, nutrient levels and temperature between the tree centre and perimeter could be used to diversify cropping systems and increase grain yields. Studies with other parkland tree species without reverse phenology (*V. paradoxa* and *Parkia biglobosa*) indicate that soil nutrient levels are higher but crop yields are reduced under trees due to shading and less interception of PAR by crops (Boffa *et al.*, 2000). Given the need for higher pearl millet grain and stover yields, and value of fire wood and other tree products, increased adoption of pearl millet production in stands of *F. Albida* is merited.

CULTURAL PRACTICES

Planting date

The pearl millet growing season in West Africa ranges from 60 days in the north to 150 days in the south. Yearly variation in length of growing season is largely due to onset date of the rainy season (Sivakumar, 1988). The traditional photoperiod sensitive, late-maturing varieties produce the highest yields, and yields are highest when planted following the first major growing season rain of 10–20 mm (Reddy, 1988; Reddy and Visser, 1993; Reddy *et al.*, 1990). Pearl millet is always the first planted crop, often 10 days earlier than other crops (Andrews, personal communication) which then

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benefits from the nutrient flush that follows early season rains. The fact that pearl millet has a large early season root-to-shoot ratio, tolerates high soil temperatures (Bidinger and Hash, 2004), and tolerates sand blasting (Buerkert and Stern, 1995; Buerkert *et al.*, 2000a; Michels *et al.*, 1995b, c) makes early planting a viable option. The optimum planting date range for pearl millet is only 10–14 days, which is a major constraint to using soil tillage with animal traction (Grema and Odo, 1998).

Plant population and spacing

West African pearl millet farmers traditionally plant low plant populations of approximately 5000 hills ha^{-1} (2–5 plants hill^{-1}) in order to reduce risk of yield loss from water stress (Bationo *et al.*, 1990, 1992) and allows plants to scavenge large soil volumes for the limited amount of nutrients available (Charreau and Nicou, 1971). Increased plant populations, combined with use of improved varieties and recommended fertilizer application, have been found to increase pearl millet grain yields. Bationo *et al.* (1990) found that increasing population from 5000 to 40,000 hills ha^{-1} increased yields in years with normal and above average rainfall, with only a slight yield decrease in drought years in Niger. Payne (1997) reported that even in dry years, higher grain yield and water use efficiency are possible using a plant population of 20,000 hills ha^{-1} with application of 40 kg N ha^{-1} and 18 kg P ha^{-1}. Maman *et al.* (2000a, b) confirmed these results, while de Rouw (2004) reported that higher plant populations increased the risk of crop failure.

Pearl millet recommendations for plant population and spacing vary with anticipated seasonal rainfall and soil water holding capacity. Hill planting ranges from 45 × 45 cm to 100 × 100 cm, and seedlings are thinned to 2–5 plants hill^{-1} when approximately 15 cm tall, thus giving a final plant population between 10,000 and 50,000 plants ha^{-1}. Some producers keep plant populations low to enhance intercropped cowpea yield in intercropping systems (Grema and Odo, 1998) but increased pearl millet yields can be produced by plant populations that are two to four times greater than traditionally used (Bationo *et al.*, 1990; Maman *et al.*, 2000a, b; Payne, 1997).

CROP RESIDUE MANAGEMENT

Crop residue management is important to reduce runoff and increase infiltration of water into the soil (Nicou and Charreau, 1985), capturing Aeolian material with higher nutrient levels (Drees *et al.*, 1993; Geiger *et al.*, 1992; Michels *et al.*, 1995a), increase soil organic matter content (Klaij and Hoogmoed, 1993), lower soil temperature and reduce soil evaporation (Buerkert *et al.*, 2000a; Stroosnijder *et al.*, 2001), reduce sandblasting damage and stand variability of young pearl millet seedlings (Buerkert and Stern, 1995; Buerkert *et al.*, 2000a; Michels *et al.*, 1995b, c), minimize soil crusting effect on crop emergence; enhance nutrient recycling and crust remediation through termite and microbial decomposition (Geiger *et al.*, 1992; Mando and Stroosnijder, 1999), stimulate early season root and shoot growth (Muehlig-Versen *et al.*, 1997; Rebafka *et al.*, 1994), increase soil pH and nutrient levels (Bationo *et al.*, 1993; Coulibaly

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et al., 2000; Michels *et al.*, 1995a), increase yield and fertilizer response (Bationo and Mokwunye, 1991; Bationo *et al.*, 1993; Coulibaly *et al.*, 2000), and increase biological N fixation by rotated or intercropped legumes (Rebafka *et al.*, 1994). Most studies show yield increases (Mason *et al.*, 2014) from leaving residue on the soil surface, but some report greater yield with residue incorporation into the soil (Coulibaly *et al.*, 2000; Rebafka *et al.*, 1994) due to improved microbial activity, increased rate of crop residue decomposition, and reduced soil bulk density promoting root proliferation and penetration. Most soils in semi-arid West Africa have low water holding capacities and organic matter, but it should be remembered that on poorly drained, high water holding capacities in high rainfall areas or in landscape position where water may accumulate, leaving crop residues can actually lower crop (Baudron *et al.*, 2014).

Although agronomic studies indicate that leaving (or incorporating) crop residues is important for soil maintenance and pearl millet yield (Coulibaly *et al.*, 2000; Mason *et al.*, 2014), residues are commonly removed from fields due to multiple uses, including livestock feed and fuel (Bationo and Mokwunye, 1991; Lamers and Bruentrup, 1996; Lamers *et al.*, 1998; Schlecht and Buerkert, 2004). The issue is further complicated by the low production level of residues associated with low grain yields resulting from the harsh production climate and degraded soils (Michels *et al.*, 1995b). In general, farmers prioritize crop residues for livestock feed (Giller *et al.*, 2011). Freely roaming animals, especially goats (*Capra* species), and rapid turnover of organic matter due to presence of termites and temperature induced microbial action (Bationo and Buerkert, 2001) complicate maintaining adequate levels of crop residues in fields. Termite decomposition of crop residues is a key factor in rehabilitating crusted soils (Mando and Stroosnijder, 1999). Farmers typically do not apply crop residues to entire fields, but rather to low producing micro-sites within fields or to fight wind erosion, and economic studies have shown this to be a rational practice from an agronomic and economic viewpoint (Lamers *et al.*, 1998; Schlecht and Buerkert, 2004). Even though there are large economic incentives for removal of crop residues from fields, leaving crop residues in the field is a key sustainable crop and soil management practice. However, it should be remembered that leaving crop residues on poorly drained soils can have an adverse effect on yield, in these cases, competition for crop residue use seldom exists (Baudron *et al.*, 2014)

TILLAGE AND WATER HARVESTING

West African soils have both physical and chemical limitations, which combined with the limited and erratic rainfall patterns, negatively impact plant growth (Nicou and Charreau, 1985). Practices to stimulate total root weight or root density positively correlate with plant growth (Nicou and Chopart, 1979). Tillage has been shown to increase plant growth and yield (Mason *et al.*, 2014) by increasing soil porosity, root density, depth of rooting, water storage and plant water use, and reduced evaporation (Nicou and Charreau, 1985). Tillage also speeds nutrient cycling from crop residues and soil organic matter. The combined effect of these factors is increased pearl millet yields by 17–25% for pearl millet. Klaij and Hoogmoed (1993) found that pre-plant

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tillage improved use of fertilizer and crop residues, stand establishment, and pearl millet yield, and water use efficiency. Adoption of tillage by farmers in West Africa has been limited due to lack of availability of a power source (especially due to poor condition of draft animals) and limited time to complete tillage between the first seasonal rains and planting (Grema and Odo, 1998; Nicou and Charreau, 1985).

Tillage options available include shallow cultivation with a harrow (tines), ridging and mounding, tied ridging and localized tillage to form micro-catchments termed zaï (Fatondji *et al.*, 2001; Nicou and Charreau, 1985). Harrow systems are performed during the dry season to increase water infiltration of early season rains, and have little effect on crop root growth with yield increases from 0 to 15% (Nicou and Charreau, 1985).

Formation of ridges attempts to trap water to prevent runoff and promote plant water use. This method works best when ridges are formed perpendicular to the slope in the field (Doraiswamy *et al.*, 2007; Doumbia *et al.*, 2009). They found that ridging increased grain yield 30–50% and soil C by 12–26% in Mali, Gambia and Senegal. Subbarao *et al.* (2000) likewise found a 35% pearl millet yield increase with ridging in Niger, while Nicou and Charreau (1985) and Mason *et al.* (2014) found approximately 20% grain yield increase. Often the yield increase of ridging interacts with fertilizer application (Doraiswamy *et al.*, 2007) but not always (Subbarao *et al.*, 2000). However, ridges deteriorate during the rainy season due to rainfall, wind translocation of soil, and weeding (Fryrear, 1984), and thus, in-season (Bielders *et al.*, 2000) and annual maintenance (Doumbia *et al.*, 2009) is required. Ridging also helps reduce wind erosion by creating a rough soil surface (Bielders *et al.*, 2000).

Ridges can be tied to hold water in place rather than to flow down the furrow. Tied ridging works best on heavier soils with tying occurring within one month of planting. Tied ridging does not work as well on sandy soils because of lower water holding capacity and ease of ridge destruction, but if used, later tying works best to make water available at the critical flowering growth stage. Tied ridging collects and stores surface water (van Duivenbooden *et al.*, 2000), which leads to more stable yield increases to fertilizer application (Ohm *et al.*, 1985) and greater length of the growing season (Stroosnijder, 2003). Sanders *et al.* (1990) found that tied ridges increased grain yield by 40%, fertilizer by 75%, and the combination of tied ridges and fertilizer by 132%.

Zaï is a traditional system in which small pits 20–30 cm in diameter and 10–20 cm deep are dug and in the bottom of the pit an organic matter source (manure, compost, crop residues) is placed and seeds planted (Fatondji *et al.*, 2001). This system combines the benefits of tillage, micro-catchments to capture water, and supplying nutrients needed to increase plant growth and yield. Yields have tripled and water use efficiency doubled with use of a zaï pit without an organic matter application (Fatondji *et al.*, 2006). With manure or crop residue application in combination with zaï, nutrient uptake has been increased by 43–87 and yield by 35–220% (Ouattara *et al.*, 1999). The zaï system has contributed to pearl millet grain yield increases (Mason *et al.*, 2014), restoration of degraded soils, and regeneration of indigenous herbaceous plants and trees in northwest Burkina Faso (Sawadogo, 2011; Sawadogo *et al.*, 2008a, b). Implementation of zaï has a high initial labour investment of 40–60

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days ha^{-1} and recurrent costs for maintenance, manure transport and/or compost production, but this had not impeded adoption in Burkina Faso and Niger (Riej and Smalling, 2008).

Bunds and barriers

Stone rows and vegetative barriers have been shown to increase soil water storage and reduce runoff by 20% and reduce soil carbon loss by reducing erosion (Stroosnijder and Hoogmeoed, 2004), but fertilizer application was required in order to obtain a yield response (Stroosnijder, 2003). Ouattara *et al.* (1999) and Reij and Smalling (2008) reported yield increases from stone rows of 35–65% in Burkina Faso.

NUTRIENT MANAGEMENT

Regional, national and individual experiment evaluation of soil nutrient status in West Africa, all indicate that crop nutrient removal is greater than nutrient additions (Bagayoko *et al.*, 1996; Bekunda *et al.*, 1997; Smalling *et al.*, 1993, 1997). Sanchez *et al.* (1997) reported an average of 660 kg N ha^{-1}, 75 kg P ha^{-1} and 450 kg K ha^{-1} loss during the past 30 years on 200 million ha of cultivated land in 37 African countries. Nutrient removal increases with increasing population density; increasing yields especially when both stover and grain are removed; and through runoff, leaching and gas emissions (Bekunda *et al.*, 1997). In a study in southern Mali, pearl millet was the biggest nutrient mining crop (−47 kg N, −3 kg P, −37 kg K ha^{-1} yr^{-1}) because no fertilizer is commonly applied and pearl millet has a high nutrient content per unit of harvested product (Smalling *et al.*, 1993). Nutrient depletion is complicated by the low nutrient status of many African soils, and has contributed to decreasing agricultural productivity in Africa during the past six decades (Sanchez *et al.*, 1997).

Generally phosphorus is considered to be the most limiting nutrient for pearl millet production in West Africa, with nitrogen being second most important (Bationo and Mokwunye, 1991). In some cases, low soil pH, potassium or micronutrients are important. Pearl millet yield responses to phosphorus and nitrogen applications are wide spread throughout West Africa, but fertilizer use is very low due to limited supply, high cost relative to pearl millet grain price, and lack of disposable income of poor farmers. The net result is that low application rates combined with methods to minimize cost and maximize nutrient use efficiency are used.

Traditional systems depended upon bush fallow to regenerate soil organic matter and nutrient supply as described earlier. Grazing animals recycle nutrients through faeces and urine deposition, but there is an inadequate manure production to meet crop needs and due to un-uniform distribution. Corralling animals facilitates composting manure and urine for field application to provide nutrients and improve soil physical properties (Bationo and Mokwunye, 1991), but compost has low nutrient concentrations (Sanchez *et al.*, 1997), is labour intensive, and manure supply is inadequate (Bationo *et al.*, 1998; Giller *et al.*, 1997). Application of good quality organic amendments increases pearl millet yields (Fatondji *et al.*, 2006; Maman and Mason, 2013). Site specific application of manure based upon micro-topography

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Table 2. Microdose, and N and P fertilizer application influence on pearl millet grain and stover yields on sandy soils in Burkina Faso, Mali and Niger, 2001–2005 (adapted from Bagayoko *et al.*, 2011).

	Grain		Stover	
	Yield	Increase over control	Yield	Increase over control
Treatments	kg ha^{-1}	%	kg ha^{-1}	%
Zero	447	–	1347	–
Microdose	721	61	2228	65
Microdose + 20 kg P_20_5 ha^{-1}	849	90	2657	97
Microdose + 40 kg P_20_5 ha^{-1}	906	103	2683	99
Microdose + 30 kg N ha^{-1}	739	65	2449	82
Microdose + 60 kg N ha^{-1}	777	74	2586	92
Microdose + 20 kg P_20_5 ha^{-1} + 30 kg N ha^{-1}	973	118	2832	110
Microdose + 40 kg P_20_5 ha^{-1} $_{+}$ 30 kg N ha^{-1}	1043	133	3259	142

has been shown to increase nutrient use efficiency (Brouwer and Powell, 1998). Several studies indicate that integrated nutrient management combining crop residue management, manure and/or compost application along with fertilizer affords the greatest opportunity to increase yields (Bationo and Buerkert, 2001; Michels and Bielders, 2005; Pieri, 1989; Stroosnijder and Hoogmoed, 2004) and to build soil organic C (Ouédraogo *et al.*, 2006, 2007). Fertilizer application rates for grain crops in West Africa are low, while fertilizer is widely applied to profitable cash crops (Buerkert *et al.*, 2000b).

Phosphorus fertilizer can be applied to feed the crop, as a one-time investment to rapidly increase the soil level, or applied to gradually build soil levels while meeting crop needs (Buresh *et al.*, 1997). Applications can consist of low reactive rock phosphate, although partial acidulation is required to have immediate benefits (Bationo *et al.*, 1986, 1992; Buresh *et al.*, 1997); intermediate reactive rock phosphates which reduces phosphorus deficiencies, has long-term residual effects and does not acidify the soil (Gerner and Mokwunye, 1995); soluble phosphate fertilizers which are immediately available to meet crop needs; or some combination of the above. Point applications at planting (microdose) or to young seedling can reduce phosphorus fixation in the soil, and promote stand establishment and early season growth due to increased root and shoot growth, and enhance colonization with vesicular arbuscular mycorrhizae further increasing nutrient uptake (Bagayoko *et al.*, 2000b; Valluru *et al.*, 2010). This results in increased grain and stover yields (Table 2; Bagayoko *et al.*, 2011; Buerkert *et al.*, 2001; Muehlig-Versen *et al.*, 2003) and has been widely adopted (Abdoulaye and Sanders, 2005).

Due to high pearl millet plant demand, the multiple soil nitrogen transformations and potential nitrogen losses to leaching and volatilization, nitrogen is recommended to be applied based upon the soil level and expected grain yield. Application is usually split with partial application at planting or shortly thereafter, and the balance side-dress applied near pearl millet hills at the time of the first hand weeding. Nitrogen use

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efficiency has been shown to increase with split application (Uyovbisere and Lombin, 1991), greater soil water storage using tied ridges (Nyakatawa, 1996), leaving crop residues on the soil surface (Bationo *et al.*, 1993), presence of adequate soil phosphorus level (Fussell *et al.*, 1987), applying jointly with manure with fertilizer (Baidu-Forson and Bationo, 1992), and for pearl millet rotated with legumes (Bationo *et al.*, 1996; Bekunda *et al.*, 1997).

Deficiencies of other nutrients are not common in West Africa, presumably due to higher native soil levels; being supplied by bush fallow, crop residues and other organic amendments; or nutrients being present in other fertilizers products (Bekunda *et al.*, 1997). Acid soil reaction (pH) and aluminium toxicity are often a concern on low buffer capacity sandy soils with low organic matter. Small, but important, changes in soil pH occur as the soil organic matter content is raised (Buerkert *et al.*, 2000a; Geiger *et al.*, 1992) and/or ashes are added to fields (Rebafka *et al.*, 1994) which increase plant growth and soil nutrient availability.

It is commonly assumed that available water is the limiting factor in crop production in the semi-arid West African, but several studies (Bationo and Mokwunye, 1991; Maman *et al.*, 2000a; Payne, 1997, 2000; Payne *et al.*, 1990;) indicate that this is only true in the very driest northern part of the region and/or in the very driest years. Yield and water use efficiency can be increased in most situations by increasing plant population and applying recommended fertilizer rates, especially when combined with appropriate soil tillage, water harvesting methods, and leaving crop residues on the soil surface.

CONSERVATION AGRICULTURE

Conservation agriculture, the combination of minimal soil disturbance, residue cover for the entire year and crop rotation to promote crop diversity (Giller *et al.*, 2009; Kassam *et al.*, 2009), has contributed to reducing soil erosion and major improvements in crop yields in the Americas (Triplett and Warren, 2008), and has been promoted for Africa (Pretty *et al.*, 2006). Concerns exist about the level of crop residues produced and competing uses, lack of tradition for crop rotation, inputs of herbicides and fertilizers not being readily available, and that the components of conservation agriculture do not fit into the context of the majority of small farmers in West Africa (Giller *et al.*, 2009, 2011; Mason *et al.*, 2014). In addition, pearl millet yields during the first years of no tillage practice are often lower even when crop residues are applied (Ikpe *et al.*, 1999). Some scientists believe that no-till is not a viable option for West Africa due to the soil physical properties, the prolonged dry season, and the lack of crop residues, but intensive tillage reduces soil C and soil water holding capacity unless manure (Ouattara *et al.*, 2006; Stroosnijder and Hoogmoed, 2004) or other amendments are added. Creative approaches to adapt the conservation agriculture principles to different environmental and soil conditions, farmer resource levels, and build complex management skills will be important for wide-spread adoption in West African pearl millet production systems.

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ADOPTION

The literature on adoption of conservation agriculture or its components is quite limited both in quantity and quality, and it can be concluded that economic considerations are heterogeneous and site specific (Pannell *et al.*, 2014). Economic studies indicate that conservation agriculture and components are usually, but not always, more profitable which contrasts with low actual adoption. They found that the rotation maize yield increase was not adequate to offset the reduced benefits from sale from the legume crop. Bagayoko *et al.* (1996) concluded that limited adoption of grain sorghum or pearl millet – cowpea or groundnut rotation was due to tradition, need for use of expensive pesticides to control pests in monoculture cowpea and groundnut production systems, increased risk associated with fewer crops in a field during the growing season, and greater land use efficiency associated with intercropping.

Pannell *et al.* (2014) concluded that zero tillage (with or without crop residue mulching) was best suited to larger farmers with secure land property rights and fenced fields with less urgent food needs, and with access to credit with low interest rates. The adoption of crop residue mulching has received considerable attention, with the focus on competition, or opportunity cost, between crop residue mulching and use of crop residues for livestock feed (Bationo and Mokwunye, 1991; Baudron *et al.*, 2014; Giller *et al.*, 2011; Lamers and Bruentrup, 1996; Lamers *et al.*, 1998; Schlecht and Buerkert, 2004). Control of crop residue use is a key issue due to social norms. Pannel *et al.* (2014) found that the additional benefit to a farmer to exploit his/her own crop residues is not adequate to pay for fencing. Baudron *et al.* (2014) concluded that agricultural intensification in Africa will require practices that increase crop residue production adequate to 'feed' both the soil and livestock.

Low adoption of fertilizer recommendations for pearl millet has been attributed to risk, labour limitations, immediate cash needs, markets; failure to recognize variability of farmer objectives; availability and price of fertilizers; high fertilizer/grain price ratios, and a lack of demonstration trials (Abdoulaye and Sanders, 2005, 2006; Schlecth *et al.*, 2006; Vitale and Sanders, 2005). Increased grain prices due to storage and selling at times of the year with higher price, and increasing demand for grain as food or feed have been shown to promote adoption of fertilizer application (Vitale and Sanders, 2005).

Camara *et al.* (2006) studied adoption of improved sorghum and pearl millet varieties across semi-arid West Africa. They found that farmer's preferred early maturity, high food quality, productive and disease resistant varieties, and that adoption of varieties with these characteristics were limited by lack of available seed, fertilizer and information. de Rouw (2004) studied adoption of variety selection, plant population and fertilizer application, and concluded that lack of adoption was due to new, recommended practices not reducing the risk of yield loss and crop failure. They concluded that practices that reduced risk and easily adopted were low plant population without fertilizer, planting both early and late maturing varieties, and manure application. Pannell *et al.* (2014) also found that low uncertainty and risk, especially in initial years, contributed to adoption of conservation tillage and/or

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components. High farmer education level has also been shown to promote adoption of improved crop production methods (Alene and Manyong, 2007)

Aune and Bationo (2008) proposed a ladder approach for agricultural intensification, with the initial step being practices without cash costs based upon improved management of local resources such as application of organic fertilizer, seed priming, and water harvesting technologies, all of which require additional labour which may be limiting. They proposed a second step of microdose fertilizer application with low financial cost, then crop and livestock intensification terminating in development of commercial agriculture with agroforestry systems, cash crops, and dairy production. Abdoulaye and Lowenberg-DeBoer (2000) basically concluded this same process in studies of agricultural intensification in south central Niger.

RECOMMENDATIONS AND CONCLUSIONS

Pearl millet is an exceptionally adaptable crop in the harsh climatic and soil environment of semi-arid West Africa. Although grain and stover yields are currently low, it responds to use of improved, adapted varieties with resistance to major pests, appropriate cropping systems using recommended cultural practices, tillage and water harvesting/conservation practices, organic and inorganic fertilizer application, and IPM practices to control striga and downy mildew and other crop pests. There is a critical need to adopt an appropriate a suite of these management practices to overcome the difficulties of continuous cropping, since current population pressures on the land preclude the possibility of using the well-established bush-fallow systems that restored soil fertility and helped control some pests. Although these practices are well known and proven to increase yields, there is a long tradition of less-intensive management practices and substantial barriers to introduce change. Site specificity due to soil, climate, farm family priority, and/or market opportunities complicates developing a menu of practices with wide applicability. Most of the articles cited in this review were published between 1985 and 2005, a reflection that research funding has declined. Scientists need to become more actively involved in national agricultural policy development in order to provide an environment conducive to farmer adoption of improved practice. Of particular importance is utilization and marketing of pearl millet grain, and production input availability at economically reasonable prices. Additional funding of research that focus on the integration of pearl millet production practices, both on-farm and on-station, that can generate large data sets to combine with existing data sets would allow broader use of powerful computer simulation tools to increase our knowledge to increase pearl millet productivity in a sustainable and environmentally friendly manner. Pearl millet will continue to be one of the most important crops contributing to food security in semi-arid West Africa, a major crop that provides food to millions of poor people in this region, and stover as an animal feed and fuel source. However, improved policy and increase research efforts are needed to fully exploit this crops potential to produce much higher grain and stover yields, and to contribute to food security and economic growth.

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