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REVIEW ARTICLE

Current knowledge on practices targeting soil fertility and agricultural land rehabilitation in the Sahel. A review

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Abstract

Implementing sustainable production practices to rehabilitate soils is a grand challenge of our day, particularly for resource-poor farmers. The West African Sahel requires attention to balancing the need for increasing agricultural production against harsh environmental conditions. While there is much research documenting technologies for soil regeneration in the Sahel, there has been limited focus on how agricultural practices contribute or exacerbate these efforts. Previous assessments of agricultural practices in this region have been largely descriptive, and some soil ameliorating practices have been promoted with little empirical evidence on their effectiveness. Here we systematically review the literature on soil fertility and conservation practices that have been studied within West African Sahelian agricultural systems. We identified practices in the West African Sahel that have been tested to improve soil fertility and reduce land degradation, and summarized the outcomes of these practices. A unique contribution of this review is the assessment of site-specific conditions and contexts under which practices are most effective in studies which recorded these specific characteristics. We found that research in this area is dominated by chemical fertilizer and organic amendment practices, with moderate to few studies focused on soil and water conservation, crop diversification, or agroforestry. Additionally, most studies consisted of single practices rather than combining practices that target the range of biophysical limitations farmers face in agricultural production. These limitations highlight the need for increased research testing combinations of practices across long-term on-farm studies to generate stronger evidence of conditions under which practices best perform. These findings provide key lessons for research and extension on sustainable agricultural management under the challenging conditions of the Sahel.

Keywords Agroforestry · Chemical fertilizer · Crop diversification · Land conservation · Organic amendments · Sahel · Smallholder agriculture · Soil and water conservation · Soil fertility

Contents

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1 Introduction

Agricultural systems in the West African Sahel face low, erratic rainfall, low soil nutrient levels, and poor soil structure that present many challenges to crop growth. Crop-livestock integration is often a key strategy used to mitigate risks associated with agriculture in this region (Mertz et al. 2011). At the same time, this region also has rapid population growth particularly among the rural population heavily dependent on agriculture (La Rovere et al. 2005). Given these challenges, there is a large need for supporting agricultural production in this region that is focused on improving agricultural land conditions as well as crop production so that agricultural systems are resilient to future climate shocks and able to meet population demands.

Under Sahelian pedoclimatic conditions, improving agricultural production requires reducing land degradation and improving soil fertility. Land degradation can broadly refer to the decline in biological and economic productivity of land, encompassing many biophysical processes (Biancalani et al. 2013). This includes desertification, whereby fertile land is reduced to desert, and is of particular concern in the Sahel. Soil fertility encompasses the biological and physical as well as chemical properties of soil and is the ability of soil to maintain favorable conditions within these properties in order to facilitate sustained plant growth (Power and Prasad 1997). Both land degradation and soil fertility include short- and long-term processes that can be difficult to measure or observe. As such, research involving trials over different time frames and locations is needed to fully understand the effects of agricultural practices on the land. Furthermore, collectively reviewing studies that have specifically measured these conditions may provide important insight into key trends and support future research directions.

Challenging environmental conditions exacerbate land degradation and nutritional depletion of soil in the Sahel, which has led to an array of research on practices to mitigate these conditions (Schlecht et al. 2006). Whether from agricultural research or project-based nongovernmental organizations (NGOs), various improved practices have been trialed and evaluated (Akponikpè et al. 2010; Bayala et al. 2015; Bado et al. 2016). While some cite low adoption rates of these practices as reasons for declining agricultural productivity, the situation for improving agriculture in the region is more complex (Loeffen et al. 2008). Investigation of recommendations given to farmers often reveals conflicting, broad-scale advice that may prevent farmers from utilizing improved practices, as illustrated by a recent Tanzania example (Nord et al. 2021). In the Sahel, disconnects between research and extension have been identified that led to promotion of agricultural practices incompatible with local farming systems (Adesina et al. 1988; Feil et al. 1995). Given these long-standing concerns, there is value in taking stock of agricultural practices being promoted to improve soil fertility and reduce land degradation.

Regionally, there has been evidence of improved land conditions across the Sahel, referred to as the "re-greening of the Sahel" (Dardel et al. 2014; Ouedraogo et al. 2014). This effort is focused primarily on reforestation and natural resource management and has at times overlooked management practices for cultivated fields (Goffner et al. 2019). As crop production is an important land use in the region, assessment is needed of the full array of conservation management, inclusive of farmer managed tree regeneration and soil rehabilitation practices. We seek to fill this gap with this review.

Conservation of agricultural land includes soil and water conservation (SWC) practices, which in the Sahel include: zai pits, contour ridges, semi-circular bunds, and stone lines (Fig. 1). While adoption of these practices is often low, many involve modifications to traditional farmer practices and have been widely promoted (Lindskog and Mando 1992; Bado et al. 2016). One way for improving the usability of conservation practices, such as those that fall under SWC, would be to identify the site-specific conditions under which they may work best. These practices are often considered labor intensive, and farmers may not be able to risk investing in them unless they have greater certainty in their ability to improve their specific land conditions. One review has previously identified site-specific recommendations as a form of precision farming in semi-arid West Africa that may facilitate increased land productivity, but their conclusions of specific practices are limited (Aune et al. 2017). A systematic review of the current literature is therefore needed to identify site-specific conditions that may have already been identified in the research to compile a more comprehensive understanding of opportunities and limitations of studied practices.

The aim of this study is to conduct a systematic review of soil fertility and conservation research in West African Sahel agricultural systems. Previous reviews to date in this region have focused more narrowly on specific conservation practices for review and have largely been descriptive and non-systematic in their review processes (Bayala et al. 2011; Zougmoré et al. 2014; Bayala et al. 2015; Bado et al. 2016; Aune et al. 2017). To limit biases in the literature reviewed and conduct a wider search for research in this area, this review aims to systematically identify research trends and assess where more focused research is needed. To the best of the authors' knowledge, this is the first review to systematically assess the literature on soil fertility and land degradation in this region to more comprehensively assess practices that have been studied. The objectives of this paper are to (1) identify practices, (2) summarize outcomes of on-farm and on research station trials to improve soil fertility and reduce land degradation of agricultural lands in the West African Sahel, and (3) assess site specificity of practices and specific contexts within which practices were effective. We considered conditions related to agroecology as well as socio-economic context. This review provides insights into the patterns of research

Fig. 1 Examples of practices studied to improve soil fertility and rehabilitate land in West African Sahel. Clockwise from top left—ridge planting (Photo by S. Snapp), agroforestry and crop residue retention (Photo by Krista Isaacs), manure application (Photo by S. Snapp), and zai/tassa pits (Photo by Mohammed Irshad Ahmed).

conducted and gaps in understanding of practice outcomes to guide future research.

2 Methods

2.1 Scope of review

We focused our review on the West African countries that cover the Sahel region, specifically Burkina Faso, Mali, Mauritania, Niger, and Senegal, to identify research studies with similar agro-ecological conditions. Additionally, studies of interest were those related to smallholder agricultural systems focused on crop production, with studies integrating crop-livestock production also considered given the importance of agro-pastoral systems in this region. Within these systems, this review targeted research that aimed to address soil fertility, soil conservation, or land degradation issues through the use of particular practices or groups of practices. Since these issues may be assessed with a range of measurements, this review did not limit studies to specific metrics and instead captured the range of metrics that have been used to assess these issues within this study area.

2.2 Search strategy

Literature was retrieved from databases that captured a wide range of sources with the major literature of interest. This included the Web of Science Core Collection, CABI, Agricola (FAO), AGRIS (USDA), and GARDIAN (CGIAR) databases. Search strings were used that included key terms identifying literature from the West African Sahel region of interest focused on practices that targeted soil fertility or land degradation practices within smallholder agricultural systems. Searches were conducted within each database and modified to meet the search functionality of each database (Table S1). Searches were refined to publications in the English language but were not limited by publication year or publication type. From these databases, 1,558 unique citations were identified and reviewed for adherence to inclusion criteria. Articles included in this review were studies located in part or in whole of the West African Sahel countries (Burkina Faso, Mali, Mauritania, Niger, Senegal), focused on agricultural systems, at least in part involving crop production, and tested specific practices to addressing soil fertility, soil conservation, or physical land degradation. Articles not meeting all criteria were excluded. This resulted in 109 relevant articles included in this review (Fig. 2).

2.3 Review of the selected literature

Articles were reviewed around the specific practices that were studied and descriptive information of the study was recorded. This included information on study design (field trial, survey, model, etc.) and whether field trials were conducted on a research station or on-farm. Duration of the research included in the article was noted based on the first and last years of data collection. Within each study all practices tested were documented and control treatments were noted (Table 1). For every practice that was studied, general outcomes of the practice (positive, negative, neutral) were recorded compared to the study control, with a focus on outcomes related to crop production (yield and biomass), soil fertility, erosion mitigation, water regulation, and socio-economic conditions (Table 2). In the case of multi-year or multi-location trials, if outcomes were mixed across years or locations, the overall outcome of the practice was recorded as neutral. If a study mentioned specific conditions under which a practice was observed to perform better or worse than controls, this information was recorded and noted as site-specific findings of the study. Practices included in studies were categorized by overall functionalities of practices building upon previous classifications used for diversified farming practices (Tamburini et al. 2020). This resulted in six practice categories, referred to as crop diversity (CD), non-crop diversity (NCD), inorganic amendments (IA), organic amendments (OA), soil and water conservation (SWC), and targeted nutrient placement (TNP). TNP was an additional category created to reflect the local adaptation common in this region of applying inputs at planting

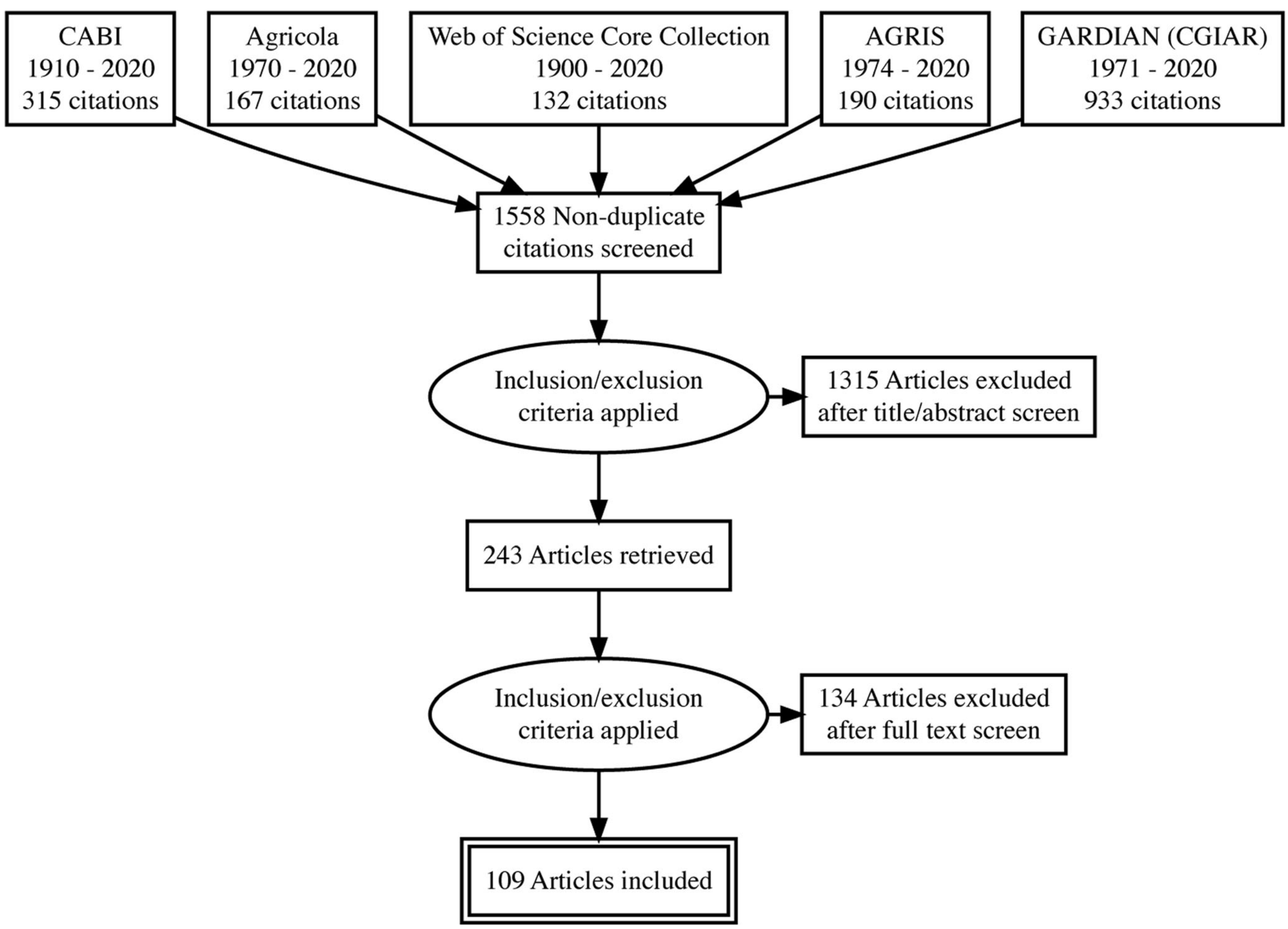

Fig. 2 Flow diagram of the literature review process showing databases included in search and number of studies that were included after the review process.

Table 1 Description of practices included in groupings and controls used by practice groups.

Groups	Practices	Controls
Crop diversity (CD)	Crop rotation, intercropping, planting density	Continuous monocropping, no inputs Intercropping with traditional varieties, no input Rotation with some inputs
Non-crop diversity (NCD)	Agroforestry (planting trees, farmer managed natural regeneration), fallow, tree belts	Continuous monocropping Plots without trees/perennial species and no inputs
Inorganic amendments (IA)	Chemical fertilizers	No amendments - removal of residue Low organic inputs - residue retained, some manure Moderate amount of N, P, or K addition (nutrient omission controls)
Organic amendments (OA)	Manure/animal waste application, residue retention, mulching (Acacia tumida, Neem)	No amendments - residue removed Some amendments - manure vs. crop residue Low application of manure or crop residue Chemical fertilizer application
Soil and water conservation (SWC)	Planting pits (zai/tassa), Half-moon, grass strips, stone bunds, tillage, ridges, irrigated water management	No SWC practices, flat planting Full to reduced tillage with low to no inputs
Targeted nutrient placement (TNP)	Micro-dosing fertilizer or manure, hill-placement of fertilizer or manure	No inputs applied

locations as opposed to broadcast application. Given the particular emphasis of this practice in the literature, we considered this type of input application separate from either the IA or OA categories. We defined TNP as application of inorganic fertilizer or manure by planting location, which was commonly noted in studies as either micro-dosing, hill-placement, "per hill," or point-application of fertilizer or manure. These practice categories were then applied in assessing studies for combinations of practices and grouping overall outcomes of practices. In the case of practice outcomes, counts of treatment responses may be duplicated across categories to reflect treatments that included a combination of practice categories.

3 Research trends for soil management in Sahelian agricultural systems

3.1 Characteristics of research conducted

The majority of studies in this review (72%; 78 studies) occurred in Niger, with Burkina Faso (19%; 21 studies) and Mali (12%; 13 studies) also commonly represented. Studies from Senegal (5%; 5 studies) and Mauritania (1 study; 1%) were few. A few studies took place in multiple countries, so percentages do not add up to 100%. Studies included research covering the last four decades and ranging in various study designs (Fig. 3). The majority of research is from research station trials, particularly ICRISAT's Sahelian Center in Niger where several long-term trials have been established since the early 1980s (Abdou et al. 2012). The earliest research reported began in 1981 and the latest reported research was collected in 2017.

Across all study types, the average duration of studies was 4 years, with 45% of studies reporting research collected across two years or less. The studies covering the longest duration were typically trials conducted on research stations, with studies involving modelling also spanning longer time frames. On average, trials conducted on-farm were shorter in duration than on research stations, with studies reporting just on farm trials having an average duration of 2.6 years vs 4.3 years for studies reporting just station trials.

Overall, studies were dominated by station trials and on-farm trials, although on-farm trials were less than half of all trial studies (23 studies reporting just on-farm trials vs. 59 studies with just station trials). Only 10 studies combined on-station and on-farm trials. Modelling studies were few, with just 4 studies based on modelling data alone and 6 including modelling with either on-farm trials, research trials, or surveys. Studies employing surveys were only included in this review if crop measurements or soil testing were included in the study to relate use of specific practices to on-farm performance. As such, 6 studies used just surveys in their study design. In general, studies using any combination of station trials, on-farm trials, modelling, or surveys represented 16% of all studies (17 out of 109).

3.2 Soil management practices studied

A range of practices were recorded that have been tested in relation to improving soil fertility and rehabilitation of

Table 2 Measurements reported for each practice included in studies organized by practice groups. Numbers in parentheses refer to the number of studies that included each measurement in their study. Number of measurements and practices varied by study, with most studies reporting multiple measurements and practices; therefore, total numbers reported in this table are greater than the number of studies.

Groups	Soil fertility measurements	Erosion mitigation	Water regulation	Socio-economic
Crop diversity (CD)	Soil carbon (4), soil nitrogen (4), SOM (3), Soil pH (2), soil phosphorus (1), soil potassium (1), parasitic weed prevalence (1)	None	Water use efficiency (1), soil moisture (1), soil water evaporation (1)	Cost/benefit ratio (1), return to labor (1), return to capital (1), gross margin (1), profitability (1), net income (1), global income (1)
Non-crop diversity (NCD)	Soil pH (2), soil carbon (2), soil nitrogen (1), soil phosphorus (1), parasitic weed prevalence (1)	Soil loss by wind (2), soil erosion (1), wind speed (1), soil stability index (1)	Water runoff (1), soil moisture (2), potential evaporation (1), subsoil water content (1)	Cost/benefit ratio (2), return to labor (1), return to capital (1), total costs (1)
Inorganic amend-ments (IA)	Soil pH (4), soil phosphorus (3), soil carbon (2), nutrient balances (2), soil nitrogen (2), cation exchange capacity (1), SOM (1), soil fertility (1), presence of parasitic species (1), metal toxicity (1), nutrient use efficiency (1)	None	Water use efficiency (3), soil moisture (2), potential evaporation (1), soil hydraulic conductivity (1)	Profitability (6), marginal rate of return (2), net return (2), risk analysis (2), cost/benefit ratio (1), revenue (1)
Organic amend-ments (OA)	Soil carbon (15), soil pH (11), soil nitrogen (8), soil phosphorus (8), nutrient decomposition (4), nutrient balances (4), metal toxicity (3), cation exchange capacity (2), soil potassium (2), SOM (2), soil micronutrients (1), soil macronutrients (1)	Soil erosion/loss (5), quantity of windblown soil (1), soil deposition (1)	Soil moisture (5), water runoff (2), water use efficiency (2), soil hydraulic conductivity (1)	Net returns (1), net income (1)
Soil and water conserva-tion (SWC)	Soil nitrogen (9), soil phosphorus (4), soil carbon (4), soil pH (3), nutrient decomposition (2), cation exchange capacity (1), nutrient balances (1), soil potassium (1), SOM (1), soil sodicity (1)	Soil erosion (6), soil nutrient loss (1), wind speed (1), soil loss by wind (1)	Soil moisture (7), water runoff (4), water use efficiency (3), available water holding capacity (2), potential evaporation (1), soil hydraulic conductivity (1)	Cost/benefit ratio (2), revenue (2), total cost (1), profitability (1), return to labor (1), return to capital (1)
Targeted nutrient placement (TNP)	Soil carbon (3), soil nitrogen (3), soil pH (2), nutrient decomposition (2), cation exchange capacity (1), soil fertility (1), rooting depth (1), soil stability index (1)	None	Water use efficiency (3), soil moisture (2)	Profitability (4), cost/benefit ratio (2), revenue (1), marginal value–cost ratio (1)

degraded agricultural land in the Sahel. Frequently, studied topics were application of inorganic fertilizers, manure, and crop residue use; these practices were consistently investigated over recent decades (Fig. 4). TNP (manure and fertilizer) became a common research topic in the early 2000s. There was an increase in research studies on planting pits, also referenced as zai or tassa pits, around the same time. This practice often involved applying manure or fertilizer to constructed pits (e.g., a targeted nutrient practice addressing both soil fertility and land conservation). While pits were historically used by farmers to plant on hardened, degraded land, they have since been promoted as a way to markedly increase yields in the Sahel. However, since this peak in studies from early 2000s, few studies since have tested this practice (Fig. 4).

There were relatively few long-term studies of several conservation practices, including: agroforestry, tree belts, grass strips, stone bunds, half-moon, and planting pits (Fig. 4). In West Africa, an agroforestry practice of broad interest is farmer managed natural regeneration (FMNR). While definitions for this practice vary, it involves farmers supporting or allowing regeneration of native trees and shrubs in cultivated field (Pye-Smith 2013). This practice has been cited in the literature since the 1980s and it is credited with the re-greening of the Sahel (Ouedraogo et al. 2014). Our review found only a few studies, and these were recent (since 2010), revealing a lack of evidence on the impact of FMNR. An FMNR review specifically noted that while this practice has been taken up and promoted by NGOs, research trials are limited (Francis et al. 2015).

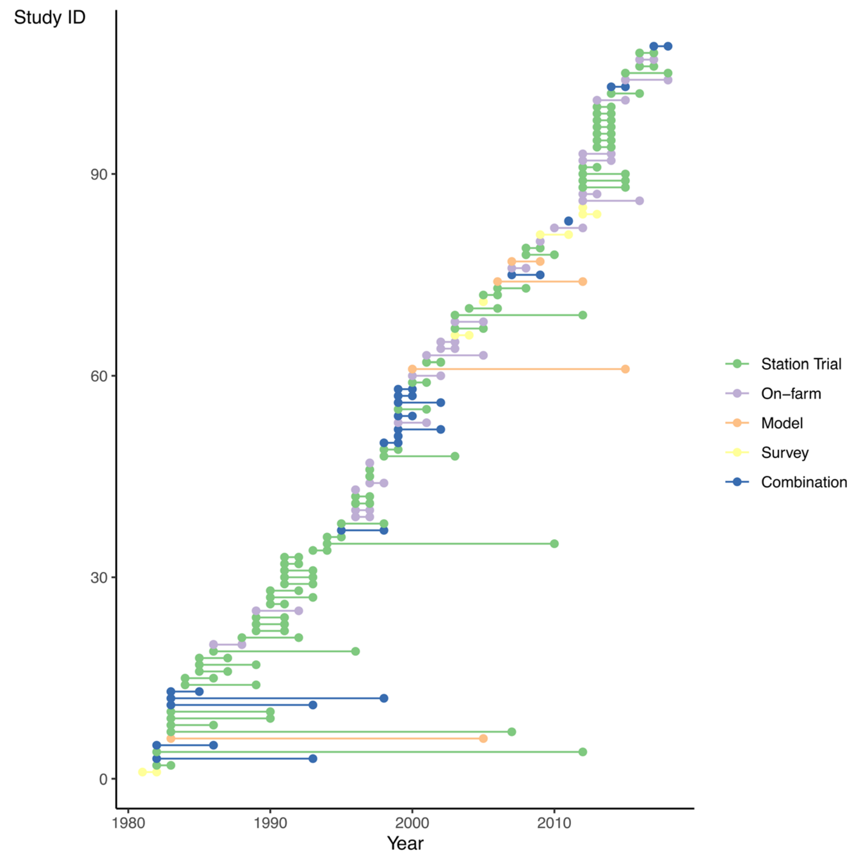

Fig. 3 Years of data collection (study duration) for studies included in review by study type. Study ID refers to a unique ID used to identify each study; therefore, each line represents a study included in this review presented in chronological order from the first year of each study's data collection. Studies were characterized by their main data collection method, such as through a research station trial (station trial), on-farm trial (on-farm), computer modelling (model), survey collection (survey), or a combination of any of these methods (combination).

3.3 Frequency and combinations of practice categories studied

Practices associated with OA and IA were commonly studied (Fig. 5). OA were often studied in isolation, and the second greatest number of studies combined OA and IA practices. Categories outside of OA and IA occurred in a wide range of combinations, including the SWC category: e.g., TNP, IA and OA, and NCD, and less commonly, with CD practices (Fig. 5). This reflects an interesting trend in the literature of promoting the addition of OA or IA practices, with limited research focused on integrating other conservation practices within OA or IA. The assumption behind this is that soil chemical conditions are the main soil limiting factors in these systems and can be addressed by practices such as manure or chemical fertilizer addition alone, instead of integrating multiple practices holistically through improving soil chemical, physical, and biological properties together.

Altogether, the limited integration observed here may reflect a disconnect of research from current farmer practice. Farmers in the region commonly apply a combination of practices, such as manure application with intercropping (CD), for multiple returns from investments (Bielders et al. 2001). This disconnect puts at risk the relevance of applied agricultural sciences, that technologies may not be replicable under farmer conditions. Farmers are not being fully supported if they are left to test innovations on their own. As such, more research studies are needed that combine different sets of practices to better address farmer challenges and identify solutions that cover a wide range of environmental contexts.

3.4 Soil management outcomes

3.4.1 Research metrics

Assessment of outcomes of practice demonstrated a range of reported metrics (Fig. 6). Crop yield and biomass were the most common metrics measured. Beyond crop production, metrics commonly reported included those addressing soil fertility, erosion mitigation, water regulation, or socio-economic conditions (Fig. 6). Notably missing from most research reports were erosion mitigation metrics, with none reported for any CD, IA, or TNP categories.

OA and IA categories in particular had the most practice outcomes recorded, with metrics in these studies mostly focused on crop yield, biomass, and soil fertility measurements. However, more soil fertility measurements were reported for OA practices than IA practices. Soil fertility measurements represent a variety of variables, most commonly related to soil pH and soil carbon, phosphorus, and nitrogen measurements (Table 2). Erosion mitigation variables, while few, were dominated by soil erosion measurements, with some

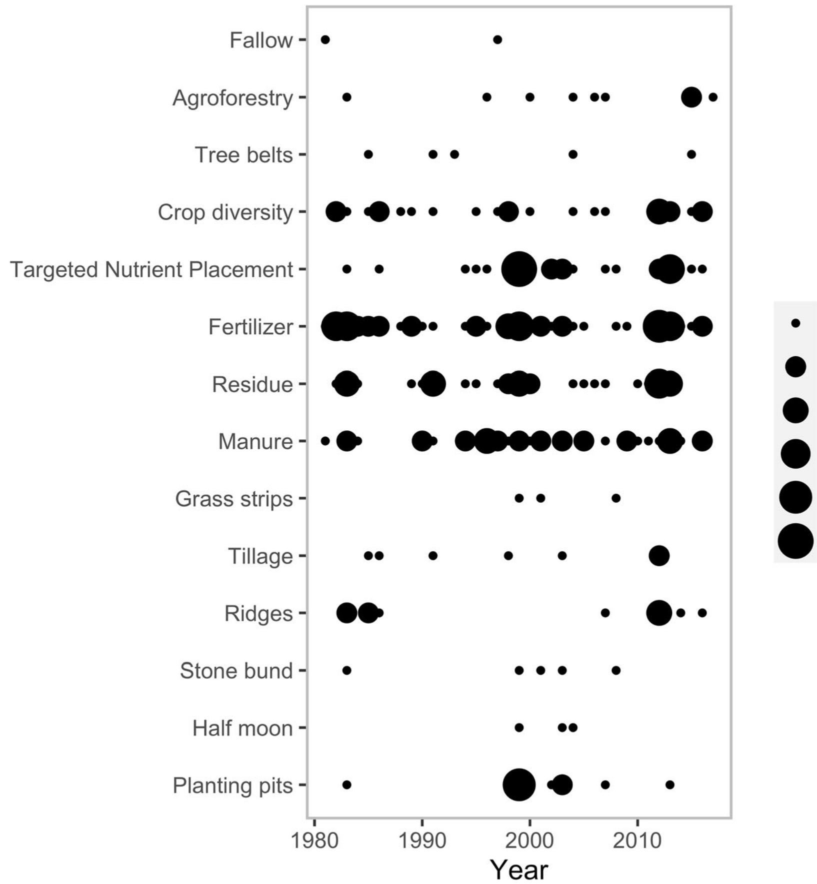

Fig. 4 Practices studied by year research started. Circle size corresponds with number of studies researching practices in the same years (1–6 studies).

differentiation between soil loss caused by wind vs. water. Water regulation metrics refer to measurements related to soil moisture, water use efficiency, and water runoff, which were measured primarily in studies of SWC practices. Socio-economic metrics were included in studies across all practice categories, although less commonly than the previously mentioned bio-physical measurements. Socio-economic assessment of practices overwhelmingly focused on monetary costs and benefits.

3.4.2 Direction of outcomes

Across all categories, responses were largely positive. Publication bias may have influenced this, as studies showing positive effects are likely to be reported in the literature. However, attempts were made during the review process to reduce the extent of this bias through the inclusion of grey literature which matched the same inclusion criteria as published studies (Haddaway et al. 2015). This highlights the value derived from access to unpublished data and annual reports documenting performance. This is particularly so for long-term trials, which are often sporadically reported on in the published literature yet offer unique insights into slow processes such as soil carbon accrual. However, such reports and data are often missing from public databases and appear to be largely internal to the organizations running the trials (Abdou et al. 2012). Progress could be made if more efforts were undertaken along the lines of recent CGIAR investments in open access data platforms, to document the agricultural research of its member organizations (Arnaud et al. 2020).

Outcomes associated with IA were primarily focused on crop yield and biomass, with the majority of responses being either positive or neutral. The substantial presence of neutral responses (36% of yield and 33% of biomass measurements) indicate the considerable uncertainty associated with crop growth gains from chemical fertilizer use in the Sahel. This region in particular is susceptible to long drought periods and the prevalence of coarse textured soils, conditions which are associated with low or nil response of crops to chemical fertilizers (Bationo et al. 2007). Overall, there is modest adoption of chemical fertilizers in the Sahel (Klutse et al. 2018). The lack of consistent returns to fertilizer reported in most long-term studies deserves broader attention, as it explains minimal farmer investment in IA and points to the need for studies that go beyond testing fertilizers to examine underlying processes and interactions with genetics and environment. Furthermore, we observed limited or no response of soil fertility properties to IA practices. Taken together, this highlights the uncertainty of gains with IA, both short-term (crop growth) and long-term (soil fertility).

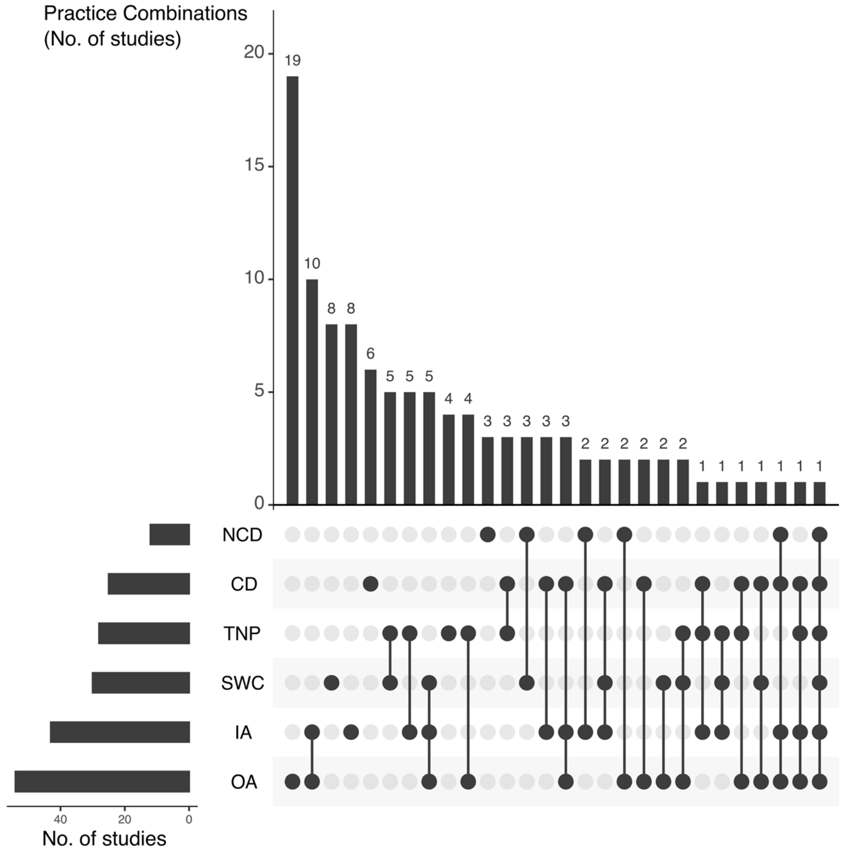

Fig. 5 Figure demonstrating the number of practice categories included in studies and the various combinations of practices studied. The left bar graph demonstrates the number of studies that included each practice category (label on the right y-axis). The center matrix represents the various combinations of categories included in studies. Combinations of practices are indicated by a black dot in the matrix cell of the corresponding practices. Black circles connected with solid lines identify the practice categories included in a given combination. The top bar graph then indicates the frequency of practice combinations observed across all studies, ordered from the highest to lowest number of studies. Practice categories represented include non-crop diversity (NCD), crop diversity (CD), targeted nutrient placement (TNP), soil and water conservation (SWC), inorganic amendments (IA), and organic amendments (OA).

In contrast to IA, crop growth and yield responses to OA were substantially positive, with only about one-quarter being neutral. These consistently positive benefits to both crop production and soil fertility highlight the effectiveness of applying OA within Sahel agricultural systems. Despite the positive responses noted in our review, there are challenges to their use associated with limited availability, competing uses (specifically for crop residue), transportation and labor costs, and debates regarding whether sufficient quantities of amendments can be produced to sufficiently meet nutrient requirements of crop production (Feil et al. 1995; Baidu-Forson 1995; Powell et al. 1996). These limitations largely address scalability issues, topics which are rarely addressed in research trials. This review highlights the need for more on-farm studies and explicit investigation of scaling; these are clear research gaps related to OA.

Outcomes from TNP practices, which included site-specific application of fertilizers or manure directly to crops, also showed overwhelming positive responses for yield and biomass. Soil fertility responses were approximately equally divided between positive, neutral, and negative. This uncertain soil fertility response to TNP practices could reflect the modest amounts applied, and spatial heterogeneity of soils (Giller et al. 2011). The TNP category of practices addresses the limited resources available to farmers by targeting moderate doses of fertility. Despite this farmer-oriented goal, surprisingly few farmer preference assessments were reported on in this or any of the practices. For a few studies, socio-economic outcomes were assessed; with these being largely limited to assessments of profitability (Table 2). No assessments of labor were recorded within studies testing TNP. This is an important oversight given the potential for this practice to alter labor requirements needed due to the precision of input application (Lamers et al. 2015).

Outcomes associated with CD were primarily positive for crop biomass and yield, along with about one-third to one-quarter that were negative or neutral. Negative outcomes for yield were rarely reported in this review, so the ~10% reported for CD technology is of concern (Fig. 6). Yield reduction could be due to incompatibility of crop species or planting arrangements used in mixed cropping systems. Competition for resources can reduce yields of individual intercropped species, although the overall yield of a diversified planting is often higher than a sole crop (Himmelstein et al. 2017). It is also possible that experimentation with novel crop varieties that were not adapted to a study area contributed to reports of low yields.

Previous reviews have highlighted the role of CD in resilience of agricultural systems (Lin 2011). This supports the need to expand research on incorporating CD within IA, OA, and SWC practices, as CD was rarely combined with other practices in this review. This is particularly relevant given local farmer

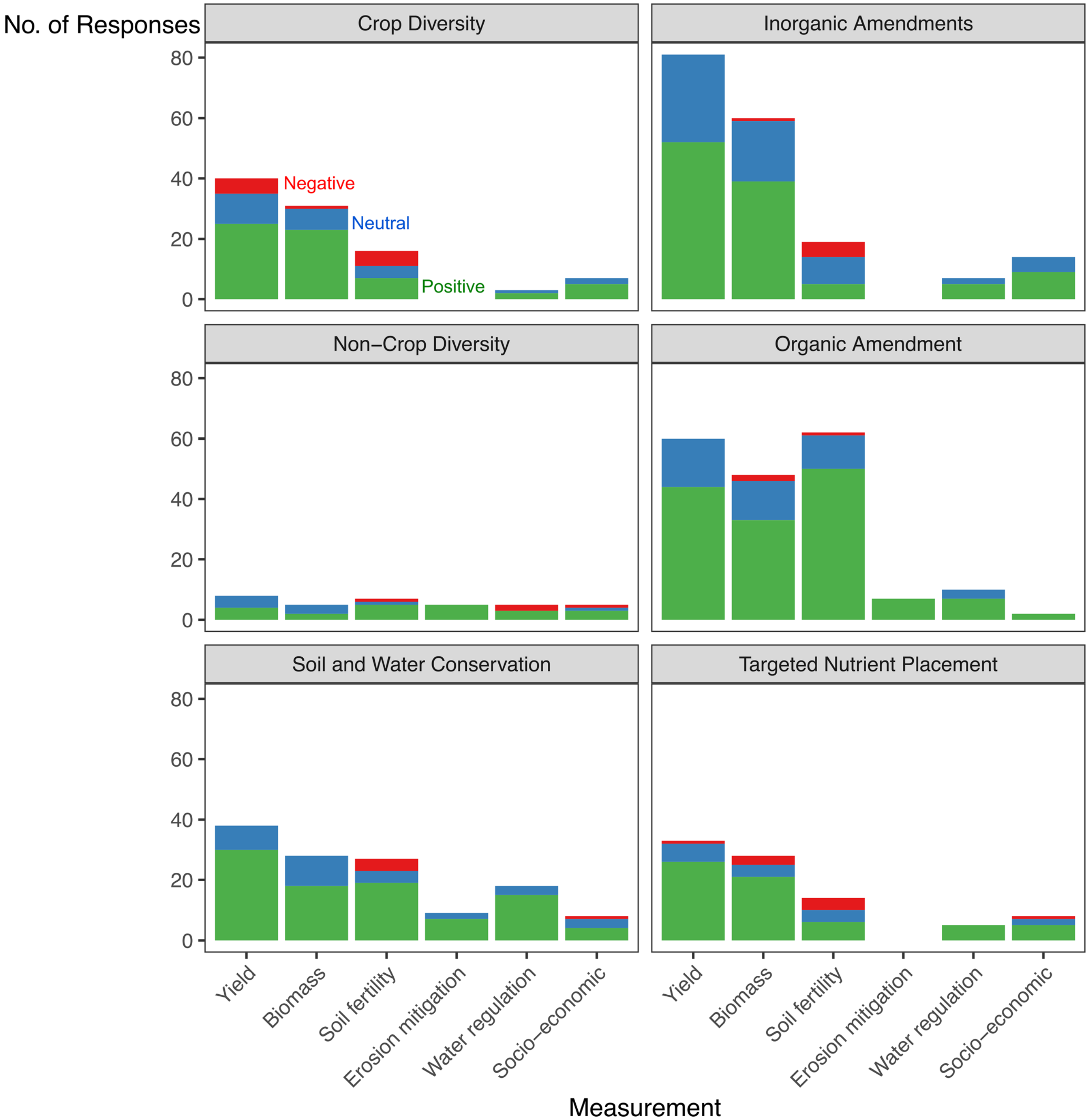

Fig. 6 Practice outcomes (positive, neutral, or negative) by categories across crop productivity, soil fertility, erosion mitigation, water regulation, and socio-economic metrics as reported in studies.

practice in the Sahel, where CD is common and often integrated with other practices (Ntare 1990). Lack of incorporation of CD in other practices additionally presents potential challenges in future adoption of promising technologies if they are not compatible with current farmer cropping systems that rely on diversified crop production. As such, research trials closer aligned to current farmer cropping systems and use of representative controls are needed to develop more comprehensive approaches to sustainable agricultural systems.

Overall, there were surprisingly few agroforestry and other NCD technologies (< 20 studies) reported in the literature we identified in this systematic review (Fig. 5). Recent meta-analyses have highlighted that there are a wide range of high performing diversity options for agriculture in the tropics, with agroforestry in particular producing positive outcomes (Beillouin et al. 2019). In the Sahel, FMNR, a form of low-input agroforestry that is in wide use, is one of the most common NCD practices (Sanou et al. 2019). Yet, we found a

Table 3 Site-specific findings noted in studies by practice groups.

Groups	Site-specific findings	References
Crop diversity (CD)	Order of crops in rotation	Falconnier et al. (2017)
	Crop rotations performed differently in different soil types - best in "black soils" compared to "gravelly soil" or "sandy soil"	Falconnier et al. (2017)
	Rotations performed best in years with > 500 mm rainfall	Subbarao et al. (2000); Abdou et al. (2012)
	Relay cropping systems performed best in seasons with early onset of rains	Sivakumar (1993)
Non-crop diversity (NCD)	None	
Inorganic amendments (IA)	Soil acidity affected effectiveness of P fertilizer in particular - most effective in alkaline soils	van Asten et al. (2005)
	Fertilizer least effective in low (600 mm) sites	Bationo et al. (1997)
	Fertilizer only found to be effective in years with sufficient rainfall (>600 mm)	Abdou et al. (2016)
Organic amendments (OA)	Organic amendments able to effectively raise yields and improve soil quality in acidic soils	van Asten et al. (2005); Rebafka et al. (1993)
	Topography/microtropography affected how much manure was needed to be applied to be effective	Brouwer & Powell (1998)
	Organic amendment application most convenient for fields closer to homestead	Prudencio (1993)
	Presence of mesofauna (termites) increased decomposition rates of organic amendments	Esse et al. (2001)
	Luvisols more responsive than Lixisols to compost application	Ouattara et al. (2007)
	Response to compost only seen in higher rainfall year (> 600 mm)	Abdou et al. (2016)
Soil and water conservation (SWC)	Ridging most beneficial in years with rainfall <500 mm	Subbarao et al. (2000)
	Zai not suitable on sandy or clay soils, best in areas with 300–800 mm rainfall and on flat, barren, hardened soils	Barry et al. (2008)
	Lixisols (higher sand content) more responsive to tillage than Luvisols	Ouattara et al. (2007)
	Stone lines and grass bunds only effective in increasing yields in low rainfall years	Traoré et al. (2020)
Targeted nutrient placement (TNP)	Targeted application of nutrients may be more appropriate in areas with land scarcity vs labor scarcity	Lamers et al. (2015)

limited number of studies reporting on NCD. This makes the direction of outcomes difficult to ascertain and reinforces the need for research on NCD, to assess both negative and positive effects.

Outcomes were mostly positive for SWC, across a wide range of indicators and study sites. One limitation observed was that SWC practices were most often evaluated with mono-cropped systems (Fig. 5), and this was especially true for planting pits. The promotion of planting pits and related SWC technologies has been widespread for many years now (Barry et al. 2008; Zougmoré et al. 2014). This is of concern, given the overall limited number of studies assessing this technology and the over-reliance on mono-cropped systems in the research. Farmers in contrast have been adapting the planting pit technology across West Africa, and a recent study from Northern Ghana showed many farmer adjustments to the technology from its original use in Burkina Faso to fit Ghanaian farmers' site-specific conditions (Nyantakyi-Frimpong 2020). Such adjustments and observations of farmer innovations are rarely incorporated into research trials, but their inclusion would benefit assessments of this technology and the development of agricultural systems (Reij and Waters-Bayer 2001).

3.5 Site-specific findings of performance

This review revealed that few studies considered site-specificity in their results. Of those that did, conditions most commonly involved consideration of climate (particularly seasonal rainfall) and soil properties (Table 3). This focus on environmental conditions highlights the limitations of research trials in accounting for other factors such as social or economic conditions. Literature on adoption and use of conservation practices suggests the importance of taking into consideration a range of socio-economic conditions (Loeffen et al. 2008). This could be addressed with greater use of mixed methods studies, such as ones that combine agronomic trials with farm surveys (Olsen 2019). Of particular note is that no site-specific findings were found for NCD practices such as agroforestry or fallow. This is especially limiting, considering the many studies focused on adoption of these practices and which could benefit from improved alignment of practices with appropriate farmer contexts (Pye-Smith 2013; Bayala et al. 2015; Sanou et al. 2019).

While few studies reported on site–specific findings of practices, those that did elucidated conditions where practices were well suited. Rainfall was especially seen as a barrier to performance for practices across CD, IA, OA, and SWC categories. Both chemical fertilizers and compost were found to be most effective in locations with >600 mm rainfall and crop rotations were noted to perform best where rainfall was greater than 500 mm. Both ridging and planting pits performed well in low rainfall areas (<500 mm), but above certain amounts were less advantageous over control treatments. Planting pits were found to possibly perform best when rainfall was between 300 and 800 mm, below which rainfall was insufficient for cereal crop production and above which water logging became a hindrance to production.

Greater use of multi-location trials within studies would provide more robust site-specific conditions. At the same time, observations of seasonal rainfall in this review highlight the highly variable rainfall conditions observed in the Sahel. Rainfall influences the performance of many of the practices studied, highlighting the risk and variability associated with implementing improved soil management practices in this region (Dayamba et al. 2018).

Soil properties such as texture and soil acidity further affected the performance of several practices. Chemical fertilizers were less effective in acidic soils. OA on the other hand were effective in increasing yields and overall performance of acidic soils. SWC practices were also affected by soil texture. Certain tillage practices for example had larger treatment effects in sandier soils (Ouattara et al. 2007). Planting pits were found to perform best in hardened soils, but only if soils were not high in sand or clay (Barry et al. 2008).

This information on-site specificity is key to scaling out technologies, particularly in a changing climate (Owen 2020). Yet promotion of technologies often overlooks specificity and the need for local adaptation. A review on agronomic practices with potential for sustainable intensification of agriculture in sub-Saharan Africa identified planting pits as one promising practice, however the review focused on the labor limitations of this practice more than the environmental conditions under which it may be most effective (Kuyah et al. 2021). As such, there is a need to document both the socio-economic and environmental conditions under which practices perform best so that efforts to disseminate these practices may be targeted towards appropriate locations and communities.

4 Lessons for research-extension-farmer knowledge exchange

Extension systems that are effective at reaching farmers increasingly depend upon knowledge exchange between research, extension, and farmers (Fu and Akter 2016; Dayamba et al. 2018). The studies found in our review highlight limitations in knowledge creation through a lack of integration of practices, and few on-farm, multi-locational or long-term studies (Snapp et al. 2019). The result of this includes low adoption rates of technologies and development of management practices that may not perform to the same level as found on research stations. Despite past emphasis for on-farm research, the majority of knowledge generated through research in this region is from research station trials. This is surprising, given the extensive literature on the need for participatory and farmer-relevant research (Sumberg and Okali 1988; Defoer et al. 1998; Stoop et al. 2000). This makes research outcomes potentially irrelevant to expected performance under smallholder farmer conditions (IAASTD 2009).

Research has a unique role within the research-extension-farmer knowledge system in that researchers are well positioned to study slow and erratic processes. This includes dynamics such as soil organic matter alteration or response to variable weather that influences the long-term viability of cropping systems (Cusser et al. 2020). A large number of study sites may be required, which are representative of local agricultural areas, along with long-term monitoring. While our review found some long-term studies (n=15 studies longer than 5 years; Fig. 3), these were mostly located on research stations. Local agricultural soils of very low fertility may not be present on research stations, and response to fertilizer and organic amendment practices may not be representative (Haussmann et al. 2012).

Importantly, studies focused on SWC practices were short duration studies on average, with 80% of studies conducted over 3 years or less. This limits the amount of knowledge generated on long-term dynamics of SWC practices and could misinform farmers interested in implementing these practices. In fact, studies on adoption of SWC practices often highlight barriers related to inadequate training and poor access to education on implementation (Sidibe 2005). Modelling studies which seek to predict long term effects of agricultural management systems are increasingly being used to supplement research knowledge in many fields. Yet, our review found a small number of studies that included modelling, possibly due to the data-intensive requirements associated with some models (Lançon et al. 2007). Overall, few studies investigated how soil management practices function, or potential fit with farming systems, which is suggestive of the need for both process-based studies, and participatory research.

Another research challenge is that many of the control comparisons utilized in trials are unrealistic, relative to farming practice. While this serves the purposes of reductionist research, where a controlled environment is used to test treatment response, it does not provide a reliable indication of response on-farm, or whether improvements will be seen relative to current practice. Smallholder farming practices, especially in this region, are often variable and include adaptations to local conditions not accounted for in formal research trials (Morton 2007). This illustrates the need for on-farm research, especially where results are directly compared to adjacent farmer practice. Results from Eldon et al. (2020) indicate that combinations of practices that are locally fine-tuned and differ from specific recommendations can reliably increase yields and be farmer-attainable. Expanding on-farm trials and participatory approaches has the potential to generate relevant knowledge in support of smallholder farming (Snapp et al. 2002; Snapp et al. 2019).

This is consistent with the need for agronomic knowledge that is generated with farmers rather than the reductionist research that dominated the studies reviewed. In addition to moving research from on-station to on-farm, participatory approaches such as those described in Falconnier et al. (2017) advocate for researcher co-learning with farmers in an iterative process of design and re-design throughout the research process. In Tanzania the use of information and communications technology (ICT), specifically the smartphone application LandPKS, as part of participatory research and extension has been explored as another way to build communication and support research and extension that is relevant to farmer's context (Nord and Snapp 2020). LandPKS, which allows users free access to identify and record soil and landscape characteristics, is one example of current tools which could link site-specific characteristics with appropriate management practices. While these examples of knowledge exchange are currently an exception rather than usual practice, it highlights ways forward for normalizing knowledge exchange between researchers, extension, and farmers.

5 Lessons for sustainable soil management

The dominance of research focused on IA and OA in addressing sustainable soil management found in this review reflects greater historical trends of investments in agricultural research in sub-Saharan Africa. Research was first driven by attempts to replicate the Green Revolution approach that found success in Asia, resulting in testing large doses of chemical fertilizers, followed by recognition of the need for also considering manure and crop residues as part of integrated organic and inorganic management (Vanlauwe et al. 2017). Surprisingly, this review found little attention to understanding farmer's own practices, nor much evidence that the research has influenced farmer practices (Ibrahim et al. 2021). Research that focuses on inputs alone overlooks the complexity of farming systems, where combined approaches are common, as well as the range of bio-physical and socio-economic constraints that influence smallholder farm management. Previous reviews have found approaches that combine practices were effective, as conservation of water, nutrient inputs, and addressing physical soil constraints can be synergistic (Zougmoré et al. 2014). Our review is the first systematic assessment of all these types of practices for Sahel agricultural systems, and we found limited research combining these elements (less than 20% of studies combined three or more practice categories; Fig. 5).

Overall, research integrating not just combinations of approaches but also mixed research methods to capture the multi-dimensionality of farming conditions is needed to holistically address sustainable soil management (Nord and Snapp 2020). This has been suggested for other land regeneration initiatives in the Sahel (Goffner et al. 2019). Given the challenging context of Sahelian agricultural systems, planning for maximum relevance is important and we argue for more systematic linkages to on-farm, multi-location experimentation, and surveys (Snapp et al. 2019), along with participatory and process-based research that investigate combined practices representative of farmer innovations (Reij and Waters-Bayer 2001). Systematic assessments of research such as this review are important to understand and address shortcomings, to improve research relevance and effectiveness in addressing the challenging conditions of the Sahel.

6 Conclusion

The findings from this review highlight important trends in soil management research in Sahel agricultural systems over the last thirty years. We found that research was heavily focused on IA and OA to restore soil fertility. A moderate number of studies addressed SWC, CD, NCD, or combinations of practices. Promising findings emerged from studies that considered site-specific properties such as rainfall and soil properties, which identified conditions under which practices were most effective at improving yield or soil conditions and should be integrated into recommendations for farmer application. These findings on-site specificity and the availability of ICT tools provide a way forward to diagnose and tailor recommendations to farmers' individual conditions. This calls for improved knowledge exchange between researchers, private and public extension, and farmers whereby extension empowered by new tools and research findings may better serve farmers. Specifically, extension should be encouraged to adapt recommendations through observations and discussions with farmers resulting in demand-driven, farmer-oriented extension. We recommend expanded use of longitudinal studies that are linked to participatory on-farm studies to study sustainable soil management, and to generate viable alternatives. In this way, the research-farmer-extension network may contribute to resilient cropping systems in the Sahel.

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