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Opportunities and Constraints for Using Farmer Managed Natural Regeneration for Land Restoration in Sub-Saharan Africa

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Farmer Managed Natural Regeneration (FMNR) comprises a set of practices used by farmers to encourage the growth of native trees on agricultural land. FMNR is reported to deliver a number of positive impacts, including increasing agricultural productivity through soil fertility improvement and feed for livestock, incomes, and other environmental benefits. It is widely promoted in Africa as a cost-effective way of restoring degraded land, that overcomes the challenge of low survival rates associated with tree planting in arid and semi-arid areas. Despite being widely promoted, the evidence for these bold claims about FMNR has not been systematically analyzed. This paper reviews the scientific evidence related to the contexts in which FMNR is practiced across sub-Saharan Africa, how this influences the composition of regenerating vegetation, and the resulting environmental and socio-economic benefits derived from it. This reveals that quantitative evidence on FMNR outcomes is sparse and mainly related to experience in the Maradi and Zinder regions of Niger. There is little mechanistic understanding relating how context conditions the diversity and abundance of regenerating trees and how this in turn is related to ecosystem function and livelihood benefits. This makes it difficult to determine where and for whom FMNR is an appropriate restoration technique and where it might be necessary to combine it with enrichment planting. Given the need for viable restoration practices for agricultural land across Africa, well beyond the climatic and edaphic contexts covered by existing FMNR studies, we recommend research combining functional ecology and socio-economic assessments, embedded as co-learning components within scaling up initiatives. This would fill key knowledge gaps, enabling the development of context-sensitive advice on where and how to promote FMNR, as well as the calculation of the return on investment of doing so.

Keywords: agroforestry, restoration, ecosystem, livelihoods, FMNR, tenure

INTRODUCTION

It is estimated that up to 65% of productive land in Africa is degraded, exacerbating poverty, food and nutrition insecurity, loss of biodiversity, conflicts and insecurity (UNCCD, 2013; ELD-UNEP, 2015). Land restoration has the potential to increase food and nutritional security, sequester carbon, recharge groundwater and reverse biodiversity loss (UNCCD, 2013; Nkonya et al., 2016). The United Nations General Assembly declared 2021–2030 the decade of ecosystem restoration (UN, 2019). African governments, under the AFR100 initiative, voluntarily committed to restore at least 100 million ha by 2030 as their contribution to the Bonn challenge (which targets restoration of 100 M ha by 2020 and 350 M ha by 2030); the 2010 Aichi Convention on Biological Diversity (which targets restoration of at least 15% of degraded ecosystems globally) and the Paris accords (CBD, 2010; UNFCCC, 2015). Questions have been raised about how realistic these restoration targets are, considering that annual deforestation continues to exceed restoration in Africa (Fagan et al., 2020; FAO, 2020). Over the last decade, Africa has contributed the highest rate of net forest loss globally (FAO, 2020). This underpins why large scale restoration methods and practices are being advocated for and deployed. The potential of large scale tree planting to achieve restoration has been critically examined (Holl and Brancalion, 2020) and often considered costly and labor intensive, with low survival rates common where environmental constraints such as moisture and temperature are coupled with uncontrolled livestock grazing that damage young, unprotected seedlings. Restoration techniques based on natural regeneration are less costly than tree planting making them a viable alternative for restoring degraded lands although success is likely to depend on the extent of soil degradation and the presence of forest vegetation in the vicinity (Chazdon and Guariguata, 2016; Catterall, 2020).

In sub-Saharan Africa, smallholder agriculture is a key driver of deforestation (FAO, 2020). Farmers continue to expand agricultural land and are increasingly cropping marginal areas to increase their production. They are also abandoning traditional practices (particularly fallowing and exclosure) that formerly allowed farmland to rejuvenate (Crossland et al., 2018). Recent estimates indicate 132 M ha of degraded cropland in Africa (Cai et al., 2011). There is evidence that natural regeneration on agricultural and pastoral land has great potential to restore biomass (Poorter et al., 2016), soil organic carbon (Bayala et al., 2019), biodiversity (Rozendaal et al., 2019) as well as other essential ecosystem functions (Lohbeck et al., 2015). However, most knowledge about natural regeneration comes from successional studies where agricultural lands are abandoned, or regeneration is happening in natural forests or expanding forest buffer zones (Chazdon and Guariguata, 2016; Chazdon et al., 2020). Regeneration on agricultural land that is still being farmed requires farmers to actively manage the regeneration process, a practice known as Farmer Managed Natural Regeneration (FMNR).

FMNR (or *Régénération naturelle assistée*—RNA- in French) has been variously defined as farmers protecting and managing regrowth of trees in their fields (Larwanou et al., 2006; Haglund et al., 2011) or used more specifically to refer to management practices involved in pruning the shoots growing from tree stumps (Francis et al., 2015). Since FMNR is a practice that integrates trees on agricultural land it is a form of agroforestry (Sinclair, 1999). For the purposes of this review FMNR is defined as an agroforestry practice that involves the deliberate protection and management of naturally regenerating woody vegetation by farmers on agricultural land. Agricultural land may be used for growing crops or livestock grazing or both, as often occurs in agropastoral landscapes where livestock roam across crop fields in the off-season. Management principally includes selecting, protecting and pruning regenerating plants arising from re-sprouting rootstock or from seeds. It does not include exclosures, where agriculture is excluded from an area of land to allow regeneration (Mekuria et al., 2017). As a practice, although it has often been conflated with community-managed natural regeneration, assisted natural regeneration and enrichment planting (Reij and Garrity, 2016), it can be usefully distinguished from them, albeit that combinations of these different practices are often integrated alongside one-another across landscapes (**Table 1**). Individual farmers' adapt FMNR to their own needs (Rinaudo, 2012) so that the autonomy of the farmer has been indentified as both a condition for success and an important outcome from adoption (Francis et al., 2015), resulting in highly variable manifestations of the practice.

FMNR has been widely cited as a key practice within "evergreen agriculture" defined as the integration of trees into annual food crop systems (Garrity et al., 2010, p. 198), which is a form of agroforestry. It has also often been considered synonymous with the Sahelian agroforestry parklands that comprise traditionally established farming systems with scattered mature trees selected by farmers over tens to hundreds, and sometimes thousands of years (Boffa, 1999).

The Sahel constitutes a transition zone between the Sahara Desert in the north and the Sudanian Savanna to the south (Gonzalez et al., 2012). The region is characterized by a semi-arid climate, high levels of poverty, recurrent droughts, food insecurity and armed conflicts between different groups (Sinare and Gordon, 2015). The management of woody vegetation on homesteads and in the surrounding agricultural landscape has been a livelihood strategy for thousands of years in the region (Larwanou and Saadou, 2011). Since the 1970s FMNR has been widely promoted by non-profit organizations in Sahelian countries on the basis that trees on farms play an increasingly important role in supporting different aspects of farmers' well-being, including income (Binam et al., 2015), carbon sequestration and climate resilience (Bayala et al., 2014, 2019; Mbow et al., 2014), food, fodder and agricultural productivity (Bayala et al., 2012, 2015), human nutrition (Arnold et al., 2011), preventing soil erosion, fixing nitrogen, and providing a wide range of other ecosystem services (Belsky et al., 1989; Boffa, 1999; Dawson et al., 2013). FMNR has led to restoration of approximately 5–6 M ha, particularly in Maradi and Zinder regions in Niger, while donor resources expended on extensive tree planting activities have typically resulted in low tree survival rates of only around 20% (Tougiani et al., 2009). This has led to FMNR being scaled up in the Sahel to other regions of

TABLE 1 | Definitions of related terms associated with establishment of woody vegetation as a restoration strategy as used in the present review.

Term (abbreviation)	Definition	Management	Notes
Farmer managed natural regeneration (FMNR)*	An agroforestry practice that involves the deliberate protection and management of regenerating woody vegetation by farmers on agricultural land. It is mainly practiced on individual farmer's fields.	Principally includes selecting, pruning, thinning, coppicing and protecting the regenerating trees arising from re-sprouting rootstock or from seeds.	Often combined with EP. Agricultural land may be used for cropping, livestock grazing or both at different times of the year.
Assisted natural regeneration (ANR)*	Deliberate human protection and preservation of naturally regenerating woody vegetation on forest land or abandoned agricultural land or exclosures.	Tree seedlings are principally protected from undergrowth and fire (extremely flammable plants) and management of livestock. It does not involve intensive management of trees.	Sometimes combined with EP.
Enrichment planting (EP)	Deliberate planting of trees in areas were natural regeneration is also occurring or in forests, including secondary and selectively logged forest. This can be through seedlings that are first grown in tree nurseries, saplings or direct sowing of seeds in the field or forest.	Planting of seeds or seedlings and their subsequent protection and management.	Often combined with FMNR or ANR.

**In French, the term Régénération Naturelle Assistée (RNA) is used to refer to both FMNR (on farms) as well as ANR (on abandoned agricultural lands, communal grazing lands and forests).*

Niger, Burkina Faso, and other countries (Reij et al., 2005; Carey, 2020) including spontaneous adoption when farmers witnessed the visible agricultural and economic benefits on neighboring farms (Weston et al., 2015). A synthesis of evidence about FMNR focused on benefits derived from the practice (Francis et al., 2015) called for development of a co-ordinated research strategy to build an evidence base for FMNR.

FMNR is now widely promoted beyond the Sahel to other parts of Africa, heralded as a panacea for restoring degraded lands on the basis that it is inexpensive, replicable, achieves rapid results in terms of vegetation cover while avoiding the risk of low survival rates common in tree planting; and builds on skills that farmers already possess (Reij et al., 2009; Reij and Garrity, 2016; Carey, 2020). Yet, despite these claims and stated benefits, widespread adoption beyond project localities is yet to be evidenced. Projects promoting FMNR are often characterized by intense long-term external intervention funded by donors, involving training farmers and incentive structures such as cash-for-food programs or improved marketing of tree products (Rinaudo, 2007; Larwanou and Saadou, 2011). This makes the hypothesis that FMNR is actually simple to replicate, well-known by farmers and easy to scale up without external intervention questionable. In this review, we examine the scientific evidence on the context, composition and consequences of FMNR, discuss its potential as a strategy for land restoration in Africa, and identify knowledge gaps.

ANALYTICAL FRAMEWORK

A three-stage *a priori* analytical framework was developed to structure the review based on the literature cited in the introduction (**Figure 1**). By applying this framework, we reviewed the scientific literature on FMNR structured around three aspects: (1) **context**, i.e., the social, economic and ecological conditions under which FMNR is practiced; 2) **composition**, i.e., the characterization of what woody vegetation arises from FMNR in terms of density, species diversity and functional properties; and (3) **consequences,** i.e., the benefits that are derived from FMNR. We use the term composition broadly, to refer to what the FMNR is composed of in terms of woody species diversity, density and the functional properties that together influence the consequences of the FMNR in terms of livelihood and environmental benefits, rather than a narrower concept of botanical composition referring only to which species are present or their relative abundance (Billheimer et al., 2001). Composition of FMNR is affected by the environment and what farmers select from what naturally regenerates in their fields, both of which are affected by governance issues that influence fire occurrence, livestock grazing pressure and the surrounding tree cover (Lohbeck et al., 2020). Such structured assessment of the literature is urgently needed to identify what evidence exists and where there are gaps required to develop evidence-based recommendations for (i) where FMNR is a suitable practice for land restoration, (ii) how the practice of FMNR may change the composition of the fields, and (iii) for what specific restoration targets FMNR may be a suitable strategy. This will also contribute to further improving and refining the practice of FMNR, enhance our understanding of its limitations and identification of knowledge gaps in the evidence base to target further research.

Illustrations of FMNR are shown in **Figure 2**.

ASSEMBLING AND CHARACTERIZING THE EVIDENCE BASE

Evidence about FMNR was collected from published journal articles starting from year 2005 to March 2020. We carried out a literature search using the terms "Farmer Managed Natural Regeneration" in English and "régénération naturelle assistée" in French in abstract, title, and keywords in web of knowledge and in Google scholar. This generated a total of 30 relevant articles after those on assisted natural regeneration had been excluded, 24 in English and 6 in French, that represent the core evidence base. We classified these papers based on whether they involved

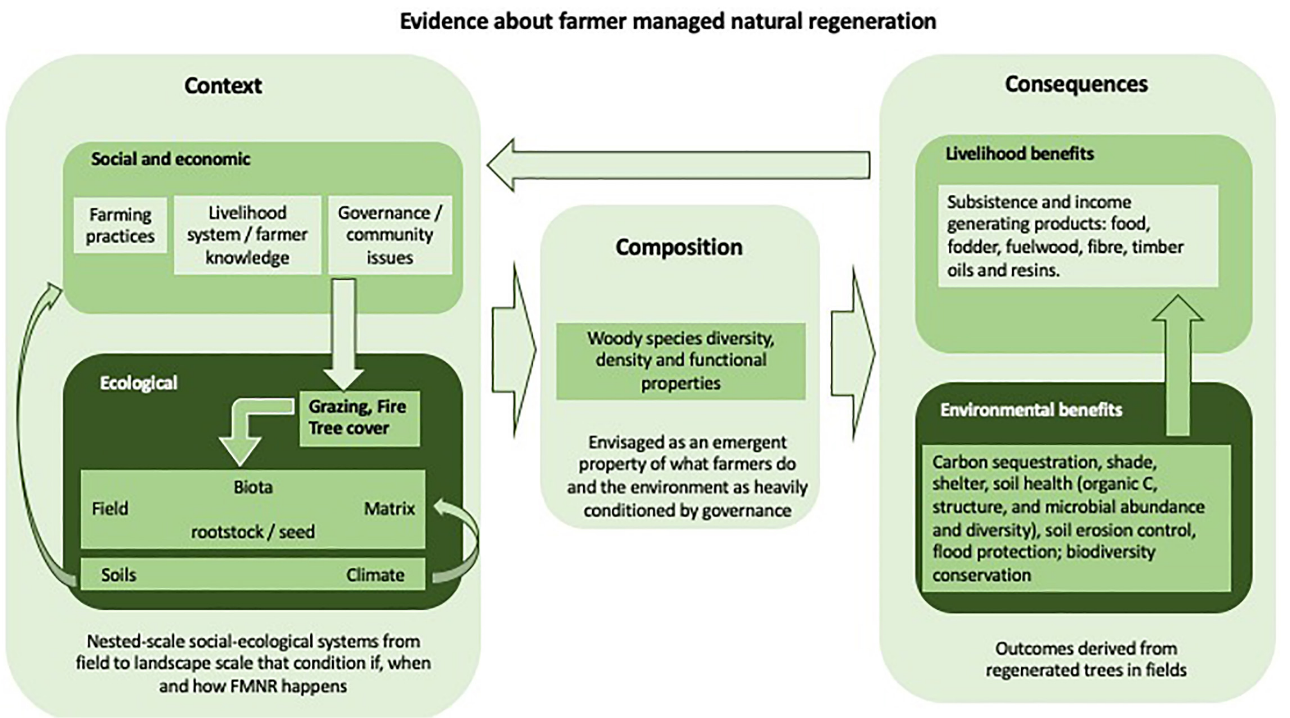

FIGURE 1 | Analytical framework for the assessment of evidence on FMNR.

original data, represented perspectives based on case studies or ideas, or were a literature review (**Table 2**). For papers based on original data, we identified the sites and countries where data were collected.

The majority of articles (22) were based on original data with a steady accumulation since 2005 and a marked acceleration since 2015 (**Figure 3**). A highly cited paper combining elements of data, perspective and review in a systems analysis (Sendzimir et al., 2011), complements five perspective papers that were published since 2009 and two reviews on specific aspects of climate-smartness and carbon stocks that appeared in 2018 and 2019, respectively.

The original data papers cover 12 countries ranging from West to East Africa but with a marked concentration in Niger and to a lesser extent Senegal, Mali and Burkina Faso (**Figure 4**). These four countries are also the only ones covered by perspective papers with four out of the five, including Niger.

THE CONTEXTS IN WHICH FMNR IS PRACTICED

Ecological Conditions

FMNR is largely being practiced in arid and semi-arid areas, also referred to as dry and sub-humid areas in sub-Saharan Africa. Rainfall is unevenly distributed and ranges between 100 and 950 mm per year (Haglund et al., 2011; Sendzimir et al., 2011; Gonzalez et al., 2012; Binam et al., 2015). This includes areas in the Sudano-Sahelian belt including countries such as Mali, Niger, Northern Nigeria, Burkina Faso, Northern Ghana, Senegal and Chad and also arid and semi-arid areas of countries in East and Southern Africa such as Kenya, Ethiopia, Tanzania, Zambia, Malawi, Sudan, and Somalia (Garrity et al., 2010; Ndegwa et al., 2017). In these regions, low moisture, high temperature, prolonged dry periods, and recurrent droughts are key factors limiting tree survival with tree planting campaigns typically having survival rates of 20% or less (Rinaudo, 2007; Tougiani et al., 2009). In contrast, in more favorable climates that allow intensive cultivation, and where tree survival is not so restricted, there is little evidence of widespread adoption of FMNR and tree planting is often favored over managing natural regeneration if farmers have sufficient assets to invest in trees (Iiyama et al., 2017).

The main soil types at the sites referred to in the literature reviewed include: arenosols (Sendzimir et al., 2011; Diallo et al., 2019) that are sandy textured soils with excessive permeability, poor structural stability and low soil fertility, prone to nutrient leaching; and ferruginous oxisols/lithosols (Yelemou et al., 2007; Badji et al., 2015; Camara et al., 2017) that are old soils characterized by alternating moist and dry soil conditions combined with nutrient leaching. Oxisols are formed through weathering, humification and pedoturbation by animals while lithosols are thin soils consisting mainly of partially weathered rocks. Sida et al. (2018) also characterize the soils under FMNR in central rift valley of Ethiopia as andosols, which are highly porous dark-colored soils of volcanic origin. This indicates that FMNR is mainly practiced in areas with low soil fertility which are sandy textured with a partially formed surface horizon,

FIGURE 2 | Pictures from the field illustrating the practice of Farmer Managed Natural Regeneration. **(A)** Shows young regeneration of Ziziphus Mauritania integrated with crops in Niger to boost soil fertility and improve crop production (photo by Patrice Savadogo). **(B)** Livestock grazing on an FMNR plot with acacia spp. in Kenya (photo by May Muthuri). **(C)** Female farmers thinning and pruning *Combretum* spp. to enhance growth of fewer but stronger stems in Ghana (photo by May Muthuri).

high permeability and low top-soil organic carbon and other nutrient contents (Larwanou et al., 2010; Haglund et al., 2011; Sendzimir et al., 2011; Moustapha et al., 2014). Agricultural use of these soils requires careful management (FAO, 2001). The soils are inherently low in fertility, very sensitive to animal pedoturbation and vulnerable to erosion, nutrient leaching and hence land degradation mainly because of their low structural stability aggravated by continuous cultivation with low organic matter inputs (Bayala et al., 2019).

Social and Economic Conditions

FMNR is predominantly practiced in agropastoral areas characterized by the cohabitation of two agrarian cultures: crop-farmers and pastoralists. Farming systems are largely subsistence oriented, predominantly based on millet and sorghum and a range of secondary crops including dual-purpose legumes such as cowpea and ground nut; or cash crops such as sesame, cotton and sorrel (Yelemou et al., 2007; Yayé and Berti, 2008; Larwanou et al., 2010; Binam et al., 2015). As trees are integrated with seasonal and annual crops, FMNR requires not only understanding of the ecological and economic function of trees in integrated land use systems, but also factors that potentially inhibit or encourage its adoption by farmers. Binam et al. (2017) note there is an optimal number of trees that can be effectively integrated with crops to optimize economic benefits before tree-crop competition results in negative impacts. Adoption of FMNR is driven by decision-making and choice of farmers, where farmers select which trees to remove and which ones to retain to suit their needs, often based on pre-existing traditional knowledge about tree management in areas where FMNR is well known and culturally accepted (Rinaudo, 2012; Francis et al., 2015).

Governance aspects have been important for the adoption of FMNR and the regreening of the Sahel more broadly and heavily influence agroecological management practices that require collective action such as control of grazing animals and fire management as well as the extent and configuration of landscape scale tree cover (Sendzimir et al., 2011). While there is evidence about governance impact on tree cover and grazing, there was no evidence relating to fire. Land and tree tenure are contentious issues in the Sahel where national policies and laws often do not allow farmers to own or use trees on their farms without authorization by state agencies (Binam et al., 2017). In arid and semi-arid areas, pastoralists often engage in seasonal migration which previously allowed FMNR to be sustained for centuries (Binam et al., 2017) but is now complicated by recent changes in governance that include land subdivision, and individual as opposed to collective land tenure, leading to collapse of traditional pastoral systems, conflicts and land degradation (Sendzimir et al., 2011).

Managing conflicts amongst crop farmers and livestock keepers is crucial for FMNR as young trees are easily destroyed by livestock. For example, crop farmers and herders in Niger cooperate and agree on grazing corridors and local institutions that enhance social cohesion through collective management of integrated landscapes (Sendzimir et al., 2011). Inclusive participatory processes that involve different user groups in formulating local by-laws and sanctions are needed to manage relations between farmers and pastoralists (Weston et al., 2015). Mapping of land uses can assist planning of rotational grazing that allows enough time for pasture and trees to regenerate (Weston et al., 2015; Reij and Garrity, 2016). Multiple actors, institutions and processes are needed at a local level to create feedback loops that reinforce each other for

TABLE 2 | Articles about Farmer Managed Natural Regeneration (FMNR) retrieved from the literature search and used as the core evidence base for this review.

#	Citation	Type	Topic	Method	Further details	Countries
1	Herrmann et al., 2005	Original data	Temporal and spatial patterns of vegetation	Remote sensing	Satellite imagery for NDVI and rainfall.	Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, Eritrea, Ethiopia
2	Yelemou et al., 2007	Original data	Farmers' perceptions and adoption	Semi-structured interviews, field observations	Semi-structured interviews of 91 household heads (86 men and 5 women) were conducted to gain understanding on adoption of specific tree species coupled with ethnobotanical assessment of commonly promoted species in FMNR	Burkina Faso
3	Kindt et al., 2008	Original data	Tree species diversity and size	Inventory	Tree diversity data from 300 quadrants, randomly sampled from main land uses.	Burkina Faso, Mali, Niger, Senegal
4	Yayé and Berti, 2008	Original data	Creation of a rural wood market	Inventory	Trees on farm inventory coupled with economic valuation of fuelwood potential	Niger
5	Tougiani et al., 2009	Perspective	Effects on community livelihoods			Niger
6	Garrity et al., 2010	Perspective	Evergreen agriculture			Burkina Faso, Niger
7	Larwanou et al., 2010	Original data	Silvicultural practices in agroforestry parklands	Survey, inventory	Surveys with farmers coupled with sylvicultural data collection and species uses	Niger
8	Haglund et al., 2011	Original data	Drivers of adoption	Household survey	410 structured household surveys across 41 villages. Stratified random sampling for village selection.	Niger
9	Larwanou and Saadou, 2011	Original data	Environmental rehabilitation	Inventory	Vegetation inventories using radial transects from 4 control and 11 intervention villages.	Niger
10	Sendzimir et al., 2011	Other	Systems analysis	Field experience and perspective	Some original data from field experience but largely perspective and review within a systems analysis.	Niger
11	Hansen et al., 2012	Original data	Local use and management of trees	Survey, interview, inventory	Interviews, participatory discussions and 40 questionnaire surveys. Woody vegetation survey of 32 plots.	Ghana
12	Baggnian et al., 2013	Original data	Impact on ecosystem resilience	Focus group discussions, inventory	Focus groups and tree measurements along transects.	Niger
13	Moustapha et al., 2014	Original data	Infiltration	Interview, soil sample, inventory, infiltration	Participatory farmer meetings and soil mapping, field visit, vegetation inventory, infiltration tests and composite soil analysis.	Niger
14	Badji et al., 2015	Original data	Assessing contribution to regreening	Participatory village resource mapping, inventory	Participatory farmer meetings and on farm trees inventory	Senegal

(Continued)

TABLE 2 | Continued

#	Citation	Type	Topic	Method	Further details	Countries
15	Binam et al., 2015	Original data	Effects on income and livelihoods	Household survey	1080 household surveys collecting socio-economic, farm plot FMNR data and markets.	Mali, Niger, Burkina Faso, Senegal
16	Weston et al., 2015	Original data	Livelihood outcomes	Focus group discussions, interview, household survey	12 focus group discussions, key informant interviews and 400 household surveys.	Ghana
17	Reij and Garrity, 2016	Perspective	Scaling up			Niger, Mali, Senegal
18	Binam et al., 2017	Original data	Effect of formal and informal institutions	Household survey, focus group discussions	1080 household surveys and focus group discussion.	Burkina Faso, Mali, Niger, Senegal
19	Camara et al., 2017	Original data	Impact on millet yield	Experimental plot for yield assessment; survey	Assessment of spatial variability of millet yield associated with tree stem density and farmers' Perception analysis	Senegal
20	Chirwa et al., 2017	Perspective	Relation between forests and people			not specified
21	Iiyama et al., 2017	Original data	Understanding patterns of tree adoption	Household survey	Socio-economic survey of 687 households.	Ethiopia
22	Ndegwa et al., 2017	Original data	Socio-economic factors influencing tree management	Household survey	189 structured household surveys.	Kenya
23	Partey et al., 2018	Review	Climate-smart agriculture promotion			Ghana, Mali, Niger, Senegal, Burkina Faso
24	Sida et al., 2018	Original data	Recruitment limitation of *Faidherbia albida*	Experimental, permanent plots	Experimental plots, and 100 permanent plots.	Ethiopia
25	Ado et al., 2019	Original data	Farmers' perceptions of climate risks and adaptation	Interview, field observations, household survey	Group interviews, field visits and 160 household head semi-structured surveys.	Niger
26	Bayala et al., 2019	Original data	Soil organic carbon	Inventory, soil sample	Soil and vegetative samples under 8 randomly selected trees in concentric zones and a control plot 40 m from the tree crown.	Burkina Faso, Mali, Niger, Senegal
27	Diallo et al., 2019	Original data	Effects of trees on soil nutrients	Soil sample	Soil samples taken from 12 randomly selected trees of four species and two treeless controls at least 15 m away from crown.	Niger
28	Ouédraogo et al., 2019	Original data	Adoption of climate smart agricultural technologies	Household survey	300 household head structured interviews.	Mali
29	Van Haren et al., 2019	Review	Land cover, land productivity and carbon stocks			Not specified
30	Carey, 2020	Perspective	Natural regeneration			Niger

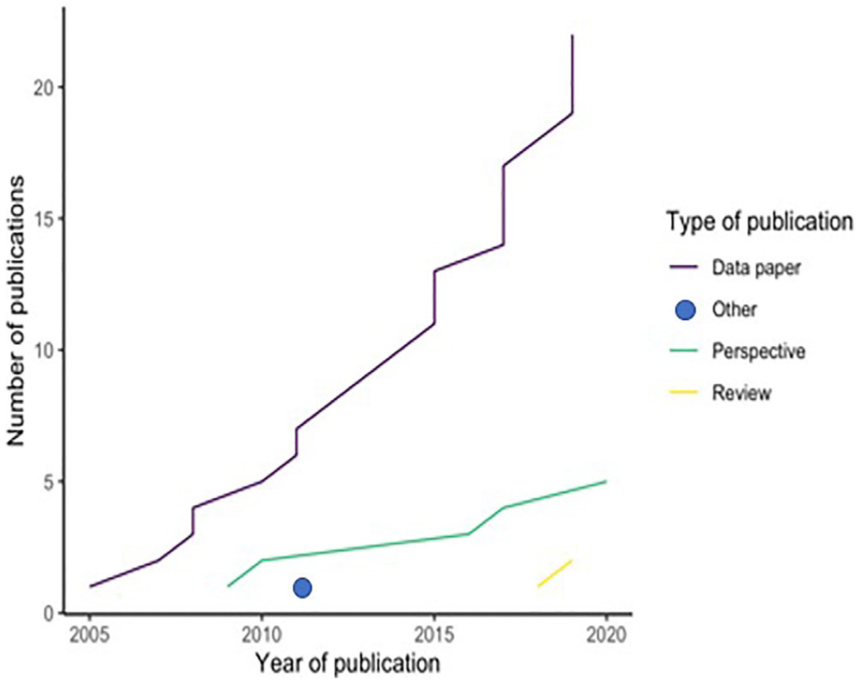

FIGURE 3 | Accumulated number of publications on Farmer Managed Natural Regeneration (FMNR) classified by type (Table 1) forming the core evidence base for this review (n = 30).

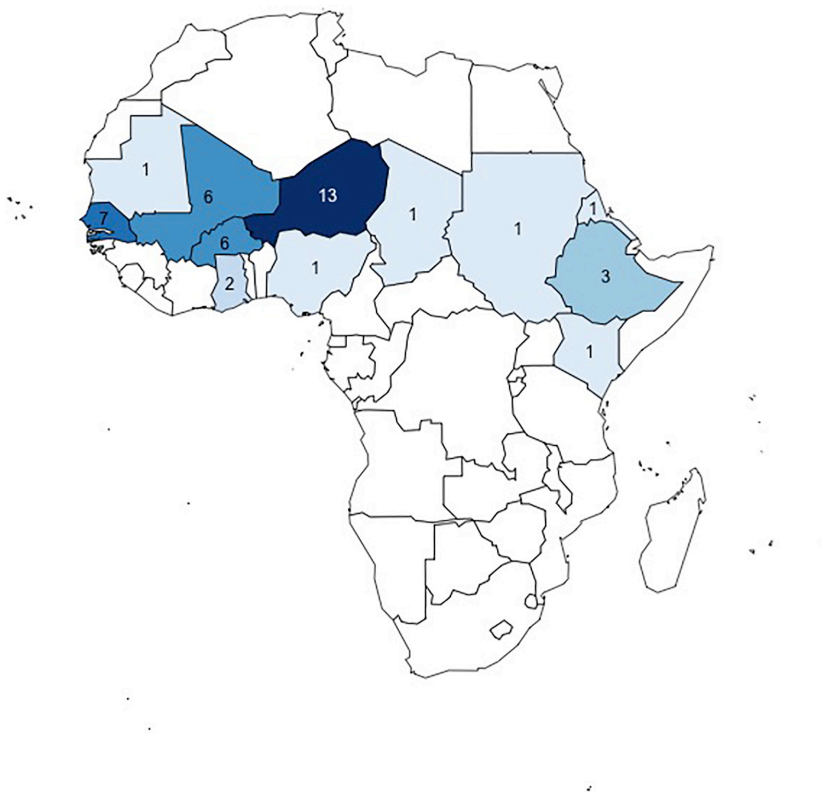

FIGURE 4 | Map showing the number of original data articles (indicated by color and number) for different African countries.

successful restoration using FMNR (Sendzimir et al., 2011). Both formal and informal institutions affect FMNR practices. Binam et al. (2017, p. 1) indicate "*in areas with well-structured formal and informal institutions, communities seem to have adopted a better collaboration attitude with the local government by developing plans for a good management and protection of natural resources including FMNR practices*."

Under current restrictive policy environments, rights to local resources may require negotiation with state agencies, and this requires collective action through farmers cooperatives, user groups or FMNR committees (Reij et al., 2009; Brown et al., 2011; Baggnian et al., 2013). Regions where FMNR is practiced have often seen shifts in formal and informal policies that have affected peoples rights and access to local resources (Binam et al., 2017). For example, in Niger, reduced oversight and interference by forestry officials and changes in land and tree tenure policy gave farmers a sense of ownership of trees and, therefore, encouraged FMNR (Larwanou et al., 2006; Reij et al., 2009; Rinaudo, 2012; Reij and Garrity, 2016) while in Ethiopia, official government recognition of user rights of communities as a group rather than as individuals, and the formulation of by-laws which defined management practices (when, how and by whom), led to regeneration of trees on farms and communal areas (Brown et al., 2011). There is also a strong effect of external agencies on the adoption and scaling of FMNR, where NGOs focusing on reversing deforestation have played a key role in catalyzing FMNR through providing training and incentives to farmers including through cash-for-work programs or in-kind contributions of farm inputs such as improved seeds and fertilizers in both Sahelian countries and parts of Ethiopia (Larwanou and Saadou, 2011; Rinaudo, 2012).

COMPOSITION OF REGENERATED VEGETATION

It is not clear in most of the articles reviewed, whether trees were established primarily through natural regeneration, or through a combination of planting (which could include use of seedlings or direct sowing of seeds) and natural regeneration (Binam et al., 2015; Ndegwa et al., 2017). As such, there is little evidence about the specific effects that FMNR may have on the abundance and diversity of trees. Of the 30 papers reviewed, eight studies reported densities of natural regeneration. These ranged widely from 19 to 360 trees ha^{-1} (Larwanou and Saadou, 2011; Badji et al., 2015; Reij and Garrity, 2016). The quantitative information of naturally regenerated tree densities from Niger were more consistent—between 100 and 151 trees ha^{-1} were reported (Yayé and Berti, 2008; Baggnian et al., 2013). Reij and Garrity (2016) estimated there are over 100 *Faidherbia albida* trees ha^{-1} in cropland in Zinder. Tree densities on FMNR fields in Niger were higher by 12–16 trees ha^{-1} compared to areas where FMNR was not practiced (Haglund et al., 2011). Programs actively promoting FMNR at scale in Niger have recommended a target of 40 mature trees ha^{-1} (Tougiani et al., 2009; Rinaudo, 2012).

Eleven out of the 30 papers reported the species that regenerate and are managed under FMNR. A total of 49 species from 15 families were reported with 21 in the Leguminosae and eight in Combretaceae (see **Supplementary Appendix 1**). Species were identified through tree inventories (Yayé and Berti, 2008; Larwanou et al., 2010; Bayala et al., 2019) while other studies used farmer recall or expert knowledge and were inexhaustive in their listing. For that reason, the number of species reported is likely to be an underestimation of the total that actually regenerate through FMNR in the regions covered. Kindt et al. (2008) reported 105 species regenerated naturally across systematically inventoried plots in Burkina Faso, Mali, Niger and Senegal. These species were not included in our tabulation because the inventories included plots in forest reserves and fallows or abandoned lands and it is not possible to distinguish which species occurred in actively managed farmers' fields. Nevertheless, the 105 species reported show that parkland landscapes in the Sahelian countries where FMNR is practiced are species-rich and that 95% of species encountered are able to regenerate naturally. This is what farmers can select from when they practice FMNR.

The majority of species mentioned in the reviewed articles (46 out of 49 or 93%) were native while the remainder were exotic to the African continent. The fact that exotics also regenerate through FMNR contradicts assertions that farmers use FMNR to regenerate indigenous tree species only, while exotics are established through tree planting (Ndegwa et al., 2017). Kindt et al. (2008) also found that of the small proportion of exotics found across farming landscapes 90% were also able to regenerate naturally. This demonstrates how exotic species can become naturalized in certain contexts and are then actively managed by farmers under FMNR. Ten out of the 30 articles mentioned the source of regeneration, all of which mention rootstock as important while five of these same articles also mention seed stock and the other 20 articles do not specify the source.

CONSEQUENCES OF FMNR

The consequences in terms of livelihood and environmental benefits that arise from FMNR are determined by the composition of what regenerates (**Figure 1**). The articles in the core evidence base focus on benefits, consistent with FMNR being a deliberate practice that farmers engage in on the expectation that benefits will accrue. Evidence is, therefore, available about benefits but there may also be other largely undocumented consequences and publication bias, since positive outcomes may be more likely to be reported than cases where FMNR does not work out (Coe et al., 2014).

Environmental Benefits

Increasing tree density, associated with FMNR, is reported to enhance various soil properties (Garrity et al., 2010; Sendzimir et al., 2011; Diallo et al., 2019). Tree species that commonly occur under FMNR, such as *Faidherbia albida* and *Piliostigma reticulatum,* are reported from comparing soil under and away from tree crowns within FMNR fields, to have a strong positive effect on different soil nutrients in studies conducted in Niger (Diallo et al., 2019) and Burkina Faso (Yelemou et al., 2007).

Faidherbia albida is promoted by FMNR proponents for its N_2-fixing ability, and for its unique characteristic of reverse phenology. This refers to *F. albida* shedding its leaves at the start of the wet cropping season (unlike most other deciduous species), thereby releasing nutrients to crops when they most need it, and being leafless over the cropping season thereby reducing competition for light and water (Garrity et al., 2010). FMNR has lead to 25–46% increases in soil organic carbon (SOC) especially in sandy soils in parkland systems across the Sahel (Bayala et al., 2007, 2019), with SOC being an important indicator of soil health. Bayala et al. (2019) reported an increase in total SOC in the top 0–10 cm soil, with SOC being more under trees than away from the tree and larger effects in sandy soils. Trees have also been reported to have a positive effect on infiltration due to the formation of root channels as well as macro and micro pores (Moustapha et al., 2014). Increase in SOC is caused by accumulated biomass from leaf litter and root turnover and the cooler and moister microclimate under shade, that reduces CO_2 efflux, so that the difference between under and away from trees is associated with the balance between inputs of organic matter and outputs as soil respiration (Bayala et al., 2019).

Some authors suggest FMNR as a mitigation strategy for climate-change by sequestering large amounts of carbon in tree biomass and the soil (Binam et al., 2015; Weston et al., 2015; Reij and Garrity, 2016), but none of the studies reviewed here quantified the actual amounts of carbon sequestered as a result of the practice. Partey et al. (2018) suggest for the Sahel that sequestration rates could be expected to be analogous to those for parkland systems as reported in Luedeling and Neufeldt (2012). Sahelian parklands are reported from a range of measurements to have a mean stock of 33.4 Mg C ha^{-1} with a range of 5.7–70.8 and a mean annual sequestration rate of 0.5 Mg C ha^{-1} yr^{-1} with a range of 0.2–0.8 (Mbow et al., 2014; Sinclair et al., 2019). Ado et al. (2019) found 85% of sampled households in Maradi region of Niger reported that they used FMNR as a climate change adaptation strategy, because their perception was that it prevents soil erosion and reduces the risks associated with increased wind speed and temperatures.

A range of other environmental benefits that were reported included reduced wind speed, higher soil moisture, shade, microclimate creation and micro-scale water effects which can buffer crops from heat stress (Garrity et al., 2010; Sendzimir et al., 2011; Reij and Garrity, 2016; Camara et al., 2017). The attributes of trees under FMNR that provide these benefits are rarely quantified, which may be because of the challenges of making the measurements and of making systematic comparisons with non-FMNR sites leading authors to often infer benefits under FMNR from literature addressing agroforestry more broadly.

Livelihood Benefits

FMNR promotes woody vegetation in crop fields. A hypothesized positive effect of FMNR on food security is explained through FMNR enhancing farm productivity, nutrition and farm income. A link between FMNR and increased crop yields was reported in a number of publications from the Sahel (Binam et al., 2017; Camara et al., 2017; Ouédraogo et al., 2019), but was only quantified in the case of millet in Senegal where a 41% improvement was recorded in two year study (Camara et al., 2017). In Mali, improved crop productivity was the reason farmers gave for practicing FMNR (Ouédraogo et al., 2019). Across four Sahelian countries, Binam et al. (2017) found a positive impact of FMNR on crop yields when the tree density was between 15 and 40 trees ha^{-1}. Beyond this density, a decrease in crop yields was observed. Overall there were variances in the reported relationships between FMNR and crop productivity. Reij and Garrity (2016) proposed that mature fertilizer trees contributed to 15–30% of cereal yields across three Sahelian countries while Haglund et al. (2011) found no significant relationship between FMNR and grain yield of cereal crops in Niger although FMNR was associated with higher overall value of crop production, attributed to higher intercrop yields of crops such as cowpea and groundnut.

FMNR has been shown to provide a range of tree products that are consumed locally and sold, thereby contributing to the amount and diversification of household income and wellbeing. These include home consumption or sale of fuelwood (firewood and charcoal) and non-timber forest products (NTFPs) including wild leafy vegetables, fodder, nuts, fruits, pharmacopeia, honey, and edible seeds (Yelemou et al., 2007; Tougiani et al., 2009; Larwanou et al., 2010; Larwanou and Saadou, 2011; Hansen et al., 2012; Reij and Garrity, 2016; Ouédraogo et al., 2019). These benefits were rarely quantified but Reij and Garrity (2016) suggested an annual value of 127–154 USD per household in Niger from the firewood from FMNR, with tree-based revenue reported as a modest contribution of around 10% of the household revenue. Quoting a non-peer reviewed study by Yamba and Sambo (2012), Reij and Garrity (2016) reported that one *Adansonia digitata* (baobab) could generate an annual income of 34–75 USD. In the Sahel, commercialization of non-timber tree products from indigenous tree species under FMNR such as shea (*Vitellaria paradoxa*), baobab (*A. digitata*), *Parkia biglobosa, and Tamarindus indica* provide cash income for households (Binam et al., 2015).

Haglund et al. (2011) estimated that FMNR adoption in Maradi region of Niger increased gross annual household income by 46–56 USD (or 18–24%) per capita, mostly arising from increases in the value of crop and wood production. Binam et al. (2015) found a 72 USD per household increase in four countries in the Sahel and an increase in value of products for those practicing FMNR by 34–38%. Stands comprising over 100 trees ha^{-1} of mainly *Combretum glutinosum* and *Piliostigma reticulatum* in the early 2000's in Niger could produce fuelwood and timber valued at 1 million CFA (approximately 1,400 USD) but there was local demand for only a third of the production from local purchasers at that time (Yayé and Berti, 2008). Weston et al. (2015) calculated that an FMNR project in Talensi Ghana generated a value of 887 USD per year for each of the 180 lead farmer households, including the social, health, environmental, community cohesion and economic benefits accrued. In Kenya, regenerated species were valued for subsistence products and environmental services such as charcoal and fodder while planted trees were valued for nutrition and medicinal products, these values were not quantified (Ndegwa et al., 2017). In Burkina

Faso, *P. reticulatum* was used for improved nutrition by 97% of surveyed farmers (Yelemou et al., 2007). Binam et al. (2015) reported that FMNR leads to a significant increase of dietary diversity by about 12–14% against control households. A gradual increase in food consumption score was reported where tree density was above 20 trees ha^{-1} across four Sahelian countries (Binam et al., 2017).

A study of 400 households from Ghana in the Upper East Region found that FMNR adoption led to indirect economic benefits such as increased consumption of wild resources, health improvements and psycho-social benefits, as well as asset creation which were of higher value than income and agricultural benefits (Weston et al., 2015). Adoption of FMNR has been linked to community empowerment as committees to manage tree protection are formed across social groups and networks of communities (Reij and Garrity, 2016). Higher migration rates in households adopting FMNR were explained through income gains from FMNR being used to finance migration for employment opportunities elsewhere (Haglund et al., 2011). The opposite was reported by Sendzimir et al. (2011) who suggest that increased production was likely to result in reduced need for migration in search of work. It remains unclear under what conditions increased production or income will promote or deter migration.

DISCUSSION

The evidence underpinning promotion of FMNR as a restoration practice in Africa was reviewed in the previous sections covering the ecological and socio-economic context under which it is practiced, the composition of the resulting regenerated vegetation and the environmental and socio-economic benefits derived from it. The lack of paired data from FMNR and non-FMNR sites limits the possibility of making systematic comparisons of FMNR outcomes. Evidence of adoption of FMNR in Africa is confined to specific agroecological contexts characterized by arid to sub-humid climate, with a wide range of mean annual rainfall of between 100 and 950 mm yr^{-1} and low fertility soils vulnerable to degradation. There is an indication that soil improvement, indicated by increased SOC content is greater on sandier soils (Bayala et al., 2019). There is need for further research to establish how suitable FMNR could be outside these conditions, given the interest in promoting the practice in other regions in Africa that may benefit from FMNR but fall outside these climatic and edaphic contexts. This can be achieved through embedding planned comparisons within the scaling up initiatives of development projects to foster co-learning about how context conditions FMNR outcomes (Sinclair and Coe, 2019).

Widespread adoption of FMNR is heavily influenced by the social context, especially governance factors commonly known to play a role in adoption and scaling up of technologies. These include farmer's choices and their decisions about tree selection and management, land and tree tenure, policy and institutions such as by-laws relating to grazing and conflict management, especially between crop farmers and pastoralists (Binam et al., 2017). NGOs often create incentives and build capacity to facilitate adoption, especially for farmers with limited previous knowledge of FMNR, through training and various other forms of support (Larwanou and Saadou, 2011; Rinaudo, 2012). This is consistent with five categories of factors that have been posited as determinants of technology adoption more broadly: (i) household preferences; (ii) resource endowments; (iii) market incentives; (iv) biophysical factors; and (v) risk and uncertainty (Pattanayak et al., 2003).

Insecure land and tree tenure remain key bottlenecks for adoption of FMNR. Complexities in tree and land tenure security can be traced back to the colonial era which set forest codes and management regimes characterized by asymmetrical power vested in the hands of forest officials that persist to date in many African countries (Chomba et al., 2016; Binam et al., 2017). Relationships between security of land and tree tenure and the adoption of agroforestry technologies by smallholder farmers is well documented (Franzel et al., 2001). Tenure rights determine the types and amounts of benefits that farmers can obtain from tree resources (Zhang and Owiredu, 2007; Chomba et al., 2016). Secure forms of tenure provide stronger rights and benefits for their holders and are more likely to stimulate tree conservation than short-term or less secure forms of tenure. There is little incentive to engage in FMNR, or other long-term investments in land, if tenure is insecure. Where trees remain property of the state, there are often perverse incentives to cut them down in order to secure access to land without state interference. Incentives provided to farmers such as, extension services, information, technical assistance, and guaranteed markets for wood and non-timber forest products (NTFPs) can increase farmers' willingness to conserve trees on-farm through FMNR (Binam et al., 2017).

Literature in ecology shows that ecosystem recovery through natural regeneration is dependent on climatic conditions (Poorter et al., 2016), soils (Becknell and Powers, 2014), landscape characteristics (Arroyo-Rodríguez et al., 2017), and land management (Jakovac et al., 2015). For the success of FMNR as a practice, but also for predicting specific restoration benefits that may be achieved, characterizing which tree species will regenerate in an area, and which ones get selected by farmers is important. Currently, there is insufficient systematic characterization of the species composition of regenerating vegetation in different circumstances. Consequently, the extent to which regeneration is facilitated by farmers (Binam et al., 2015) and the trees occurring in fields are derived from planted seedlings, direct sowing of seeds or through natural regeneration remains uncertain (Ndegwa et al., 2017).

Some general patterns that characterize regeneration through FMNR can be elicited from the review. First, that species diversity can be promoted through FMNR in stark contrast to the experience of most tree planting campaigns that rely on few species amenable to rapid multiplication in nurseries (Derero et al., 2020). Second, and linked to the first, FMNR encourages the regeneration of mainly indigenous species. In this review, only three out of 49 species reported in vegetation regenerating under FMNR were exotic, consistent with the literature on natural regeneration more generally (Kindt et al., 2008; Ndegwa et al., 2017). A positive aspect about FMNR is that the indigenous species found are likely to be in their native ecological niche. This is in contrast to plantations, where native species may exhibit different traits than when observed where they grow naturally because their interactions with other species have a critical influence. Third, tree densities differ widely under FMNR ranging from 18 trees ha^{-1} observed in some areas (Hansen et al., 2012), through 40 trees ha^{-1} promoted by projects and experts (Tougiani et al., 2009; Rinaudo, 2012) to 360 trees ha^{-1} observed in other areas (Baggnian et al., 2013). We found little justification for these numbers except where Binam et al. (2017) found that the positive impact of trees on crop yields becomes negative beyond 40 mature trees ha^{-1} for particular species. We would caution against prescriptive tree densities because optimal tree cover is highly context-dependent. Tree cover is often measured as projected crown area to take account of tree size, although sometimes, stem basal area is used as a proxy even though relationships between stem basal area and projected crown area may not hold where trees have been pruned (Shimano, 1997). Optimal tree cover is influenced by many aspects including climatic and edaphic conditions (Ilstedt et al., 2016), what crops the regenerating trees are growing with, and the characteristics of the woody vegetation promoted in terms of their canopy, size, ontogenetic stages and functional traits as well as the prevailing farm management practices such as degree of mechanization (Lohbeck et al., 2018; Sauvadet et al., 2020).

Different ecosystem functions are associated with particular tree species (Lohbeck et al., 2018). Water regulation, for example, is influenced by the balance between tree transpiration, evaporation (influenced by shading) and infiltration, crucial in arid and semi-arid areas where FMNR is predominantly practiced (Ilstedt et al., 2016). Tree species with high Leaf Area Density (LAD) tend to be competitive with crops for moisture, a phenomenon that farmers are acutely aware of Cerdan et al. (2012). Farmers often have detailed local knowledge about how a range of tree attributes influence tree-crop competition (Smith Dumont et al., 2018). Despite this, the aspects of functionality of the system being targeted for restoration through FMNR are rarely explicitly addressed through selecting species with appropriate attributes. Advocates of widescale promotion of FMNR underscore how it fosters tree diversity and abundance (Garrity et al., 2010) and hence household income (Haglund et al., 2011; Binam et al., 2015; Reij and Garrity, 2016). They rarely, however, present mechanistic detail about how tree diversity and abundance contribute to better functioning agroecosystems, and how, and by how much, this generates livelihood benefits. It is evident that a better understanding of how the composition of regenerating vegetation relate to its functioning and the provision of ecosystem services would be valuable for more targeted restoration planning. To achieve this, we can draw from the field of functional ecology that links functional characteristics of vegetation to specific local conditions and consequences for ecosystem functions, and has proven useful in the context of restoration generally (Laughlin, 2014), and agroforestry for restoration specifically, indicating contexts where enrichment planting may be required to complement FMNR to meet restoration targets (Lohbeck et al., 2018, 2020). Adopting such an approach goes beyond an emphasis on simply increasing tree densities and species richness in fields, to consider whether functional diversity increases. This is a promising avenue for further research, that also has the potential to incorporate understanding of the consequences of the composition of regenerating vegetation for system resilience (Laliberté and Legendre, 2010).

With respect to scaling FMNR, most cases in the reviewed literature involve long-term presence of donor-funded projects and interventions as opposed to a spontaneous process of adoption from farmer to farmer, and the costs of this are rarely included in discussion of FMNR as a low-cost alternative to tree planting. The often quoted figure that FMNR can be achieved at a cost of 20 USD ha^{-1} (Reij and Garrity, 2016) are based on expert estimates and personal communications rather than explicit economic analysis. Many studies completely ignore or undervalue farmer's labor and the opportunity cost of land that could have other uses. There are clear benefits for farmers in terms of access to food, fodder and fiber from FMNR, but these have rarely been fully quantified, not least because doing so for variable, species rich contexts is complex. Binam et al. (2015) found on average, households are likely to get an additional USD 72 per year from FMNR. The majority of other studies make claims based on perceptions, proxy values, unpublished data, internal project reports and views of a few farmers not systematically collected or analyzed, mainly derived from project officers or authors involved in promoting FMNR (Garrity et al., 2010; Haglund et al., 2011; Larwanou and Saadou, 2011; Weston et al., 2015; Reij and Garrity, 2016). Further research to quantify costs and benefits of FMNR in comparison with alternative restoration techniques is urgently needed to calculate the return on investment in promoting its adoption in different contexts.

In conclusion, it is clear that FMNR is promoted on the basis that it can restore land while enhancing rural livelihoods and environmental sustainability through a wide range of benefits, and that it is low cost, easy to replicate and hence can be easily scaled-up over large areas. This review cautions that FMNR has all the characteristics of what Coe et al. (2014) call "an iconic practice," that from limited experience in selected sites, is picked up and widely promoted without clear understanding of the mechanisms involved or the contexts to which scaling out may be appropriate. The evidence underpinning widescale promotion of FMNR is heavily biased toward a few studies in the Sahel, and particularly the widely cited successful case of restoration in the Maradi and Zinder regions of Niger. Overall, the scientific evidence for the general claims made about the suitability of FMNR in different contexts and the full range of benefits, including ecosystem functions, is sparse. There is, however, a widespread need for cost-effective restoration methods for agricultural land in Africa to meet multiple objectives of poverty alleviation, protecting biodiversity, climate change mitigation and adaptation; and where FMNR has been extensively practiced, indications are that land restoration and livelihood benefits accrue. This generates a strong case for systematic research to explore the variations of FMNR practice suitable for different contexts and to quantify and value the full range of costs and benefits that are likely to accrue from it. This can be achieved through embedding co-learning strategies within the scaling-up initiatives of development projects.

AUTHOR CONTRIBUTIONS

SC contributed to lead the ideas and the framing of the manuscript, research questions, literature review, and all sections of the manuscript including thorough editing, references, and finalization. FS contributed to theoretical framing and diagram, ideas in the manuscript, editing of content, and writing the discussions and conclusions. PS contributed to framing and content, wrote some of the introductions, and reviewed the French literature. MB contributed to ideas in the manuscript, reviewed the literature, and wrote the economic and livelihoods in the results section of the manuscript. ML contributed to the framing of the manuscript as well as the literature review, produced the map of countries and studies reviewed, and wrote the functional aspects of FMNR and other sections. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2020.571679/full#supplementary-material

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The handling editor is currently organizing a Research Topic with one of the authors ML, and confirms the absence of any other collaboration.