Received: 11 August 2020 | Accepted: 1 February 2021

DOI: 10.1002/agj2.20634

Agronomy Journal

SPECIAL SECTION: NEAR–TERM PROBLEMS IN MEETING WORLD FOOD DEMANDS AT REGIONAL LEVELS

Perennial grass ley rotations with annual crops in tropical Africa: A review

C. S. Wortmann[1] | **A. Bilgo**[2] | **C. K. Kaizzi**[3] | **F. Liben**[4] | **M. Garba**[5] | **N. Maman**[6] | **I. Serme**[7] | **Z. P. Stewart**[8,9]

[1] Dep. of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68503-0915, USA

[2] Institut de Environnement et de Recherches Agricoles (INERA), Ouagadougou, Burkina Faso

[3] National Agricultural Research Lab (NARL)-Kawanda, Kampala P.O. Box 7065, Uganda

[4] Ethiopian Institute of Agricultural Research, Addis Ababa P.O. Box 2003, Ethiopia

[5] International Institute of Tropical Agriculture (IITA), Niamey BP 12404, Niger

[6] Institut National de Recherche Agronomique du Niger, Maradi, Maradi BP 240, Niger

[7] Institut de l'Environnement et de Recherches Agricoles (INERA), Ouagadougou O4 BP 8645, Burkina Faso

[8] U.S. Agency for International Development, Bureau for Resilience and Food Security, Center for Agriculture-Led Growth, 1300 Pennsylvania Ave NW, Washington, DC 20004, USA

[9] Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification, Kansas State Univ., Manhattan, KS 66506-4004, USA

Correspondence
C. S. Wortmann, Dep. of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE, 68503-0915, USA.
Email: cwortmann2@unl.edu

Associate Editor: Thandiwe Nleya

Funding information
United States Agency for International Development, Grant/Award Number: AID-OOA-L-14-00006

Abstract

Rotation of grass ley with periods of annual crop production can be a means to increased farming system productivity, sustainability, and profitability. This research review offers interpretations of rotation research results for future African agriculture. Some rotation studies were with naturally generated and severely over-grazed fallows consisting primarily of annual plant species but other studies were with planted and well-managed perennial grass ley. Generally, the rotations increased annual crop yields with soil improvement. System benefits were similar or greater for ley compared with fallow with generally higher fodder yields with ley. Surface crusting of sandy soil in the Sahel is a major concern that may be worsened by fallow due to the deposition of clay and silt particles. Ley and fallow were terminated in all studies with inversion plow tillage with more tillage for subsequent crops while the rotation benefits may be greater with less tillage. Most studies did not have fertilizer use but annual crop yield response to fertilizer was greatly increased following ley in one study and with no system by fertilizer interaction effect in three studies. The profitability of ley rotations will vary with fodder demand which is rapidly increasing, especially near urban areas. Strip cropping, for example, alternate ley with annual crop strips of 5–20 m width and rotation cycles of 6–10 yr, may often be optimal

Abbreviations: SOC, soil organic carbon.

for erosion control and sediment trapping, protection from uncontrolled grazing, and nearby supply of vegetative planting material for ley re-establishment. Rotation management can be improved through experiential learning and experimentation.

1 | INTRODUCTION

1.1 | Ley/fallow rotation globally

The rotation of managed perennial grass or grass–legume mixtures (ley) with annual crops has been practiced and studied as a means to improve soil and farming system productivity, profitability, and sustainability. Recent research reviews have been written for temperate North America (Allen et al., 2007; Franzluebbers, 2007; Russelle et al., 2007; Sulc & Tracy, 2007), Australia (Hochman et al., 2013), subtropical South America (Carvalho et al., 2010; Franzluebbers et al., 2014), and Europe. Studies of rotations with leguminous woody and herbaceous fallows, and annual cover or fodder crops have been reviewed for tropical Africa (Eilitta et al., 2014). Information on ley or herbaceous fallow rotations with annual crops in the tropics has not been well reviewed and such rotations have been less studied in recent decades compared with studies in temperate and subtropical areas. This review focused on fallow and ley rotations for arable lands in Africa within 15° latitude of the equator with areas of inference for research sites indicated (Figure 1).

Numerous ecological and crop production benefits of ley rotations have been identified. Soil organic matter is likely to increase during the ley stage due to reduced erosion and increased root biomass production with benefits to soil chemical, physical, and biological properties with implications for cropping system productivity and resilience to climate extremes (Dupont et al., 2014; Franzluebbers, 2012; Franzluebbers et al., 2014; Monti & Zatta, 2009; Persson et al., 2008). Trapping of sediment from water and wind erosion can increase soil organic carbon (SOC) and clay content of the surface soil (Bielders et al., 2002). Old perennial roots remained 5 yr after the conversion of perennial grassland to annual wheat (*Triticum aestivum* L.) production (DuPont et al., 2014). In Uruguay, following 50 yr of rotating 3 yr of perennial grass ley with 3 yr of annual crops, with fertilizer applied, there were increases of 40% for annual crop yield, 20% for SOC, and 34% for exchangeable K with little effect on soil pH (Grahmann et al., 2020).

The effect of ley rotations on SOC has been simulated with the Cycles agroecosystem model (Kemanian et al., 2020; Pravia et al., 2019). The capacity for SOC accumulation during the ley stage may be affected by ley duration and the difference between the initial and saturation level for SOC. Hassink and Whitmore (1997) found the SOC saturation level to be related to soil clay content (%clay) and proposed the equation SOC saturation level = 0.021 + 0.038 × %clay. They found that clay type and percentage silt effects on the SOC saturation level to be small and inconsistent. The fractional stabilization of new organic material into stored SOC, or the humification rate, approaches zero as soil mineral surfaces become saturated with SOC and the SOC saturation level is approached (Kemanian et al., 2011; White et al., 2014). Ley rotations may have greater value on land where SOC is well below the SOC saturation level, such as due to past erosion, and where the profitability of annual crop production is low (Wortmann et al., 2019). Model simulation of ley rotation effects on SOC was improved by adding a subroutine to account for the effect of SOC saturation (Pravia et al., 2019).

Major farming system changes are driven by sufficient profit potential with acceptable risk and manageable financial investment (Wortmann et al., 2020). The profit potential may be partly due to improved net returns on investment in annual crop production or improved fodder production. In much of tropical Africa, fodder demand has rapidly increased and market prices for high-quality fodder can be near those for grain in crop–livestock farming systems (Samireddypalle et al., 2017). The crop diversification with the addition of forage production can contribute to reduced financial risk associated with climate variation and price fluctuations. Soil improvement often allows for greater and more profitable response to fertilizer use (Garba et al., 2018; Nalivata et al., 2017; Stewart et al, 2020).

1.2 | Ley/fallow rotation research in the tropics

Land productivity and gains in yield for tropical Africa have been disappointing. The mean maize (*Zea mays* L.) yield is about 2 Mg ha^{-1} compared and about one-third of the global average (FAOSTAT, 2020). Mean maize grain yield increases due to fertilizer application under good management appear to average about 1.1 Mg ha^{-1} for N, 0.4 for Mg ha^{-1} P, and 0.2 Mg ha^{-1} for K (Liben et al., 2020; Kaizzi et al., 2012; Serme et al., 2020; Wortmann et al., 2018) but these gains indicate low productivity potential. Similar results, although likely with less yield increase due to fertilizer, could be generated for other crops. Ley rotations may be a means to significantly improve land productivity and response to fertilizer use. Much ley rotation research has been done globally in recent decades but most research results for tropical Africa are decades old. Still, those results have value if interpreted for future agriculture.

Rainfall amount and distribution are likely to affect the effectiveness and management of ley rotations. At the equator, rainfall distribution is bi-modal due to the inter-tropical convergence zone allowing for two cropping seasons per year and nearly continuous growth of ley where rainfall is adequate (NOAA, 2020). As the distance from the equator increases, the rainfall distribution gradually changes from bi-modal to mono-modal so that >70% of annual rainfall may occur in 8 wk, such as in parts of the Sahel, and ley needs to survive and recover from long dry seasons. The research information is therefore presented beginning near the equator and progressing to 15° latitude. Soil texture and clay content may be important to the potential of ley rotations as clay content is important to water holding capacity, soil aggregation, and capacity to accumulate SOC. However, variation in SOC seldom accounted for within-field variation in yield such as at Samaru Nigeria (Heathcote, 1969), at Saria Burkina Faso (Ouattara, 1994), at Bondoukuy Burkina Faso (Bilgo et al., 2007; Ouattara, 2009), and Serere Uganda (McWalter & Wimble, 1976).

Interpretation of information on ley rotations for future agriculture is challenged as many of the studies were conducted decades ago (Tables 1–3). Some were conducted as fallow rather than ley rotations. The fallow vegetation was typically naturally generated, often dominated by herbaceous annuals with a low density of perennial shrubs, and severely over-grazed for low aboveground and belowground plant growth. In contrast, ley may be established from sown seed or vegetatively and well managed for highly productive grazed or harvested fodder production. Both are expected to contribute to the restoration of land productivity while providing livestock feed but much more growth and soil improvement is expected with ley than with fallow. Another factor that reduces current relevance is that all studies involved much tillage for termination of the ley/fallow and to prepare land and control weeds for the annual crops while current management may occur with no or minimal tillage to prolong the benefits of ley to soil productivity. Studies in temperate and subtropical areas have found prolonged benefits of ley with no-till compared with tillage (Carvalho et al., 2010; DuPont et al., 2014; Ernst & Siri-Prieto, 2009; Garcia-Prechac et al., 2004). Many of the studies in Africa were conducted with no fertilizer use while an expected benefit of ley rotations may be a greater and more efficient response of the annual crops to applied nutrients. The results need to be interpreted in consideration of these weaknesses and that the potential benefits of ley rotations are likely underestimated.

Demand for fodder will be key to the feasibility of ley rotations. Sagir and Santoro (2018) estimated that 11.3% of the population in Sub-Saharan Africa resided in urban areas in 2010 with a 2050 projection of 20.2% while the total population continues to grow. Population and economic growth in urban areas are expected to drive demand for livestock products whether produced in urban, peri-urban, or rural areas. The resulting increased demand for fodder increases opportunities for profitable ley rotations in areas that can supply the fodder competitively.

This paper reviews research results of ley or fallow rotations with annual crops in tropical Africa (Figure 1). Many of the studies were conducted decades ago and results are interpreted for current production systems. Recommendations and information needs are discussed.

Core Ideas

- Soil productivity is low and often declining in parts of tropical Africa.
- The demand for animal products and high quality fodder has increased with urban growth.
- Ley rotation with annual crop production can improve soil productivity while producing fodder.
- Past research has been reviewed and interpreted for smallholder farming system improvement.

2 | RESEARCH RESULTS

2.1 | Latitude 0–5°

Stephens (1967) reported the results of an elephant grass/napier grass (*Pennisetum purpureum* Schumach.) ley rotation study conducted from 1957 to 1964 at Kawanda Uganda at 0.4 °N with bimodal rainfall on clay loam soil (Table 1). The elephant grass was propagated by planting stem segments. It was cut bi-annually with the biomass either burned in the field or removed. The ley was terminated by tillage. No fertilizer was applied to ley or annual crops. The mean gains in annual crop yield, compared with continuous annual cropping, for the nine crops following ley were 135% for the cut and burned ley and 38% for the harvested ley. The ley benefit to annual crop yield persisted for the cut and burn ley treatment but declined over time with the harvest of ley with a mean yield increase for crops 1–6 of 56% but with no yield gain for crops 7–9. The ley benefit to yield was greatest for maize, intermediate for cotton (*Gossypium hirsutum* L.) and least for bean (*Phaseolus vulgaris* L.). The effect of the cut and burn ley was similar to the effect of applying 12.4 Mg ha^{-1} yr^{-1} of kraal manure. Following harvest of the fifth annual crop, soil improvements due to ley rotation for the cut and burned ley and the harvested ley, respectively,

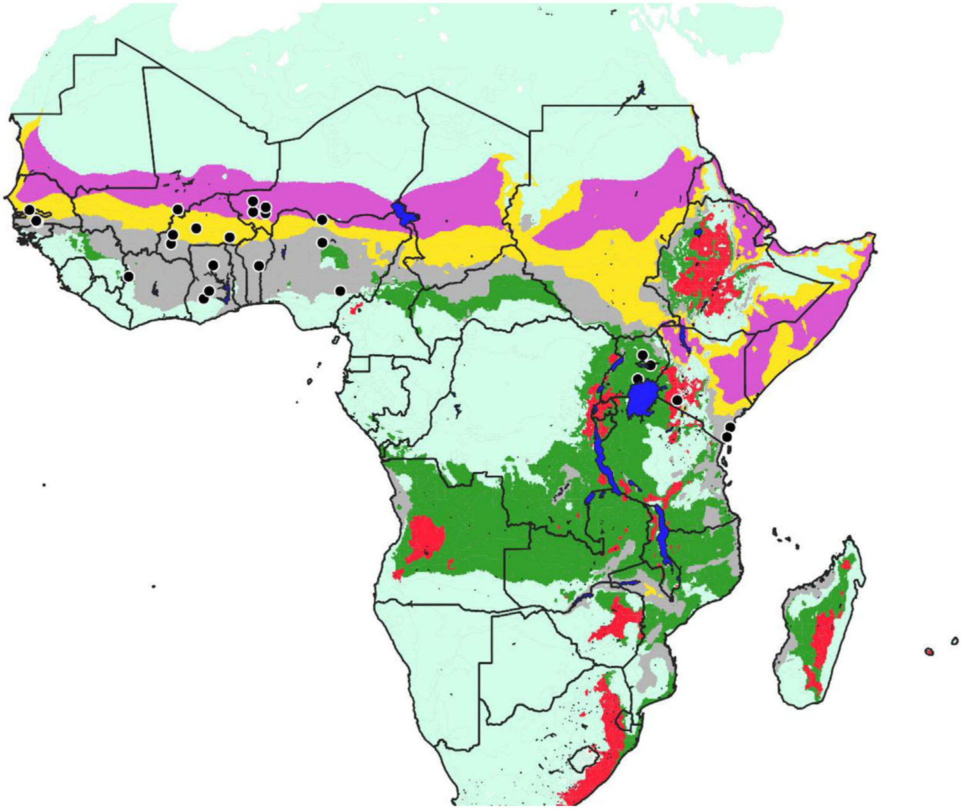

FIGURE 1 Study sites (black dots) for fallow or ley rotation with annual crop research conducted in Sub-Saharan Africa overlain on the GYGA (2020) technology extrapolation domains determined from climate variables. The colors indicate areas of semi-arid low-potential such as the Sahel (purple), semi-arid areas of greater potential such as the Sudanian savanna (yellow), low-elevation subhumid tropical savanna (gray), intermediate elevation subhumid (green) and humid (orange) tropical savanna, subhumid or wetter highlands (red), and no ecological match to the research sites (light green)

included 31 and 16% higher water infiltration rates, and 22 and 16% higher water percolation rates. Ley resulted in increased soil pH, SOC, available P, and exchangeable Ca and Mg. The yields with ley burning vs. harvest, and with annual manure application, imply that yields were affected by nutrient availability and that fertilizer application to annual crops following the harvested ley would have reduced the yield gap with the cut and burn treatment.

In another study at Kawanda Uganda, 3 yr of perennial grass, 3 yr of annual cover crops, and 3 yr of cultivated annual crops were compared for effects on wet soil aggregate stability (Pereira et al., 1954) (Table 1). Compared with the continuous annual crops, the percent of soil in water-stable aggregates >0.5 mm following 3 yr of grass was 52% more at planting of the first crop and 18% more after harvest of the second crop. The 3 yr of annual cover crops improved soil aggregation for the crop 1 but the cover crop effect was gone by the harvest of the second crop.

In a third study of elephant grass ley rotation at Kawanda Uganda, the average grain yield increase over six annual crops following ley with no N applied was 72% with either no harvest or hay harvest of but 94% with grazing of the ley (Foster, 1971). Grain yield response to fertilizer was 22% for grazed and 15% for hayed ley. The annual crop yield benefit decreased over time. Ley resulted in increased available soil N, but P and K availability were reduced by hay harvest of ley. The mean hay yield was about 10 Mg ha^{-1} yr^{-1}.

At Ngetta and Serere Uganda, rotations of ley to annual crops of 3:2, 3:3, and 2:3 yr appeared optimal as ley longer than 3 yr did not add much to annual crop productivity and ley productivity tended to decline after 3 yr (Kerkham, 1947a; Table 1). Natural regeneration of ley with perennial *Cyndon* sp. was as effective as sown ley. Annual crop yield was 6.5% more following 3 yr of grazed than with non-grazed ley (Kerkham, 1947b). The leguminous cover crops were not more beneficial than fallow or perennial grass ley. Annual crop yields were increased with increased manure rate and with increased time in rest. Application of 12.5 Mg ha^{-1} of manure once in 5 yr was sufficient to maintain productivity. The increased yields with more rest years did not compensate for the lack of production during the rest years. Ley yields were not reported. Soil chemical properties were not much affected by treatments except for increased P availability with increased manure rate. Annual crop yields and soil properties

TABLE 1 Studies of the effects of fallow or ley rotations on land productivity and soil properties between 0 and 5° latitude in tropical Africa

Site[a]	Ley/fallow[b]	Annual crop yield[c] & soil properties[d]	Source
Kawanda,UG, 0.4 °N, 1,190 m, 1,260 mm, 8.5 mo, CL	E1. 3 yr of *P.p, P.n*, & *C.g* vs. continuous cultivation E2. *P.p*; 3-yr duration; 2 cutting yr^{-1} with burning or removal. E3. 3 yr of *P.p;*	E1. Yield results were not reported. Percentage of soil in water-stable aggregates >0.5 mm following 3-yr ley was 52% more at planting of first crop and 18% more after second crop. E2. Over nine crops, yield was 135% more with ley burning and 38% more (56% for crops 1–6 and 0% for crops 7–9) with ley harvest. Ley increased pH 4%, SOC 12%, pore space 4%, percolation 12%, & infiltration 22%. E3. *P.p* hay yield was ∼10 Mg ha^{-1} yr^{-1}. Over six crops, the average grain yield increase was 72% with no N applied and with either no or hay harvest of *P.p* but 94% with grazing. The yield benefit decreased over time. Grain yield response to fertilizer was 22% for grazed *P.p* and 15% for hayed *P.p*.	E1. Pereira et al., 1954; E2. Stephens, 1967 E3. Foster, 1971
Serere, UG, 1.5 °N, 1,130 m, 1,360 mm, 6 mo, SaL; 28-yr experiment	1:4, 2:3, and 3:2 yr rest: crop; *C.p* or *C.g* vs. green manure or fallow.	Yield increases with more rest years but these did not compensate for no annual crop yield during rest periods. Similar yields for ley, fallow, and green manure rests. Higher crop yields with grazing during rest periods; see results below from Ngetta. Little rest effect on soil chemical properties	Kerkham, 1947a, 1947b; Jameson & Kerkham, 1960; McWalter & Wimble, 1976
Ngetta, UG, 2.3 °N, 1,110 m, 1,310 mm, 7.5 mo, SaL	3-yr *C.g* ley and natural *C.p* with no, light or heavy grazing	Annual crop yield was 6.5% more with grazed than with non-grazed ley and 5% more with *C.g* sown than with natural *C.p*.	Kerkham, 1947a, 1947b
Kibarani, KE, 3.4 °S, 50 m, 1,050 mm, 5.5 mo	*C. d*, ungrazed, 3 yr duration	Increased yield of three sorghum crops by 60% while the mean increase was 38% following 3 yr of pigeon pea and weedy fallow.	Clark, 1962
Matuga, KE, 4.2 °S, 130 m, 1,020 mm, 4 mo	*C. d*, grazed, 3-yr duration	Increase yield of three following sorghum crops by 61 and 8% with 0 and 25 Mg ha^{-1} manure applied for crop 1, respectively. The 3-yr ley effect was similar to cassava or pigeon pea followed by weedy fallow.	Clark, 1962

Note. C, clay; L, loam; Sa, sand; E1, Exp. 1; E2, Exp. 2; and E3, Exp. 3; *C.p, Cynodon plectostachyum*; *C.g, Chloris gayana; C.d, Cynodon dactyon; P.n, Paspalum notatum; P.p, Pennisetum purpureum;* SOC, soil organic carbon.

[a]Location, latitude (°), elevation (m), rainfall, months to accounting for 70% of rainfall.

[b]Fallow was naturally generated while ley was sown or vegetatively propagated. No fertilizer or manure was applied and termination was by tillage.

[c]No fertilizer or manure was applied. Land preparation was always with plowing or ridging.

[d]Infiltration, rate of water infiltration.

were not affected by interactions of rest vegetation type, the rest/crop year and manure application rate.

Jameson and Kerkham (1960) and McWalter and Wimble (1976) reported results of 28 yr of research at Serere Uganda which compared 5-yr rotations with sown grass ley that was grazed or harvested as hay with rotations with natural fallow and with a leguminous green manure crop that was incorporated by plowing at the end of the following dry season (Table 1). The rest/crop duration ratios were 1:4, 2:3 and 3:2 yr. There were three levels of manure application. The rest vegetation was terminated by plowing and land preparation for the annual crops involved tillage. No fertilizer was applied. The vegetation and management during the rest period did not affect annual crop yield implying that ley could be harvested for hay or by grazing with no decrease in benefits.

Stephens (1970) summarized the results of other ley rotation research in Uganda. Including legumes in ley did not improve yields of ley or of the following annual crops at Serere Uganda. Ley of 2 yr was as effective as ley of 3 or 5 yr for improving annual crop yield if no manure or fertilizer was applied. The annual crop yield with 2-yr ley was similar to yield with continuous annual cropping with 25 Mg ha^{-1} manure applied once every 3 yr. Annual crop yields were higher with grazed compared with ungrazed ley.

At two locations in coastal Kenya, 3 yr of bermudagrass [*C. dactylon* (L.) Pers.] ley compared with continuous annual crop production resulted in a 60% mean grain yield increase during the following 3 yr of sorghum [*Sorghum bicolor* (L.) Moench] production if no manure was applied (Clark, 1962) (Table 1). The mean yield increase due to ley was just 8% with 25 Mg ha^{-1} manure applied for the first crop. Grazing did not reduce the effectiveness of ley. However, 3 yr of ley was only marginally more beneficial to sorghum yield than 3 yr of either pigeon pea (*Cajanus cajan* L. Millsp.) or cassava (*Manihot esculenta* Crantz) followed by weedy fallow.

2.2 | Latitude 5–12°

Valentin et al. (2004) reported fallow and ley effects on the physical properties of a clay loam soil in northwestern Ivory Coast (Table 2). Farmers often initiated fallow, which was not grazed or hayed, because of difficulty in perennial weed management. Soil aggregate stability peaked with about 10 yr of fallow or with 4 yr of managed perennial grass ley such as with elephant grass, *Panicum maximum* Jacq., or *Andropogon gayanus* Kunth (Andropogon). Soil aggregate stability declined by 40% during 10 yr of annual cropping. Termites and earthworms (*Lumbricus terrestris*) had a great effect on surface soil properties during the first 10 yr of fallow with a reduced rate of effect during subsequent fallow years. Erosion crusts were reduced from about 30% of the surface soil at the start of fallow to about 10% after 10 yr of fallow for red soil, and from 70% of the soil surface at the start of fallow with a linear decrease to about 10% during 40 yr of fallow for yellow soil. The water infiltration rate was increased from 60 mm h^{-1} at the start of fallow to about 90 mm h^{-1} after 10 yr of fallow. Measured runoff was reduced by about 80% with 10 yr of fallow.

Stephens (1960) reported on perennial grass ley rotation experiments at Kwadaso, Ejura, and Nyankpala in Ghana (Table 2). Mean ley yields ranged from 9 to 32 Mg ha^{-1} yr^{-1}. In all trials, the ley was terminated with tillage and land was tilled and ridged for annual crops. No effects of ley on water infiltration were detected at all locations.

The Kwadaso site near Kumasi was in the moist semi-deciduous forest zone with sandy loam soil and 1,450 mm mean annual rainfall. The land was in secondary forest before experimentation and the soil pH was 6.4 and the SOC was 14.5 g kg^{-1}. The elephant grass ley was cut and burned annually. The average grass yield was 32 Mg ha^{-1} yr^{-1}. No fertilizer was applied to the ley. The annual crop yields following 2 yr of ley compared with continuous annual crops were 65, 88, and 34% more respectively for maize (*Zea mays* L.) in Years 1 and 2 and groundnut (*Arachis hypogaea* L.) in Year 1. Potassium availability was increased with ley but there was little other ley effect and no rotation x fertilizer interaction effect on soil properties.

The Ejura Ghana site was 100 km North of Kumasi with sandy soil and 1,470 mm rainfall. The trial site was in grass–bush fallow for 7 yr before the trial. The soil pH was 5.9 and SOC was 3.6 g kg^{-1}. The ley was of sown Andropogon and *Pennisetum polystachyon* (L.) Schult. with the invasion of *P. pedicellatum* Trin. No fertilizer was applied to the ley. The mean grass yield was 9.4 Mg ha^{-1} yr^{-1}. Annual crop yield with ley compared with continuous cropping was −14, 16, and 18% more respectively for the maize in Years 1 and 2 and groundnut in Year 1. On average, maize response to fertilizer N following ley was greater than three times that with continuous annual cropping. The maize of Year 2 after ley had more response to fertilizer P compared with continuous annual cropping. The SOC and available P and K were increased with ley.

The Nyankpala Ghana site was 20 km west of Tamale in the Guinea savanna at 9.4 °N with 1,090 mm yr^{-1} mean rainfall. The soil was sandy and shallow with pH = 6.4 and SOC = 5.0 g kg^{-1}. The sown ley was of Andropogon and *P. polystachyon* (L.) Schult. but *P. pedicellatum* Trin. invaded. No fertilizer was applied to the ley. Mean grass yield was 15.8 Mg ha^{-1} yr^{-1}. Annual crop yield after ley compared with continuous cropping was not increased. Fertilizer N and P did not result in increased yields. Ley increased SOC.

At Samaru-Zaria Nigeria, Andropogon ley treatments of varying duration were included in a long-term trial with sandy loam soil at 11.2 °N with a mean of 1,110 mm yr^{-1} rainfall (Table 2). Wilkinson (1975) reported greatly increased water infiltration at the end of fallow with 67, 66, 80, and 88% of the infiltration with a 6-yr ley, respectively, for the 2-, 3-, 4-, and 5-yr ley. The gain in infiltration during ley was attributed primarily due to earthworm casts and less to termite holes. However, the improvement in the infiltration rate was very fragile with 50% of the gain lost with the first land preparation which consisted of two tillage operations for ridged cotton (*Gossypium hirsutum* L.) production and no effect detected after harvest of the first annual crop. The earthworm casts and termite channels remained intact in the subsoil that was not disturbed by tillage. The increase in SOC was 57% more with 6 yr compared with 3-yr ley and declined from 4.5 to 3.3 g kg^{-1} during the annual crop phase (Jones, 1971). The SOC was 36% more with the application of fertilizer N to ley compared to no N application. The ley rotation effect on annual crop yields was not reported.

At Farako-Ba and Koure in Burkina Faso at 11–12 °N, fallow resulted in 66 and 75% more sorghum grain yield compared with sorghum following sorghum but fallow did not increase yield compared with having groundnut (*Arachis hypogaea* L.) or cowpea (*Vigna unguiculata* L. Walp) as the crop preceding sorghum (Bado et al., 2006) (Table 2). Fertilizer including N, P, K, and S was applied to the annual crops. Fallow resulted in increased SOC and exchangeable Ca. Fallow increased soil pH and decreased Al saturation at Farako-Ba but these properties were not affected at Koure. The fallow was not described.

At Bondoukuy Burkina Faso at 11.5 ˚N with a mean of 800–900 mm yr^{-1} rainfall, 5–7 yr of fallow and Andropogon ley resulted in an increase of SOC, N, microbial biomass, basal respiration, and β-glucosidase activity of 64, 35, 76, 141, and 86%, respectively (Bilgo et al., 2007; Table 2). There was no difference between the fallow and Andropogon. The rotation effect on annual crop yields was not reported. In a related study at this location, fallow resulted in 20–50% more maize

TABLE 2 Studies of the effects of fallow or ley rotations on land productivity and soil properties between 5 and 12° latitude in tropical Africa

Site[a]	Ley/fallow[b]	Annual crop yield[c] & soil properties[d]	Source
Kumasi, GH, 6.7 °N, 260 m, 1450 mm, 6 mo, SaL	*P.p*, 2 yr duration, 32 Mg ha^{-1} yr^{-1} yield	76% more maize yield in Years 1 & 2, 34% more groundnut yield in Year 1; little fertilizer effect; no fertilizer × rotation interaction. Increased N, P, & K availability but no other soil effects	Stephens, 1960
Yandev, NG, 7.3 °N, 218 m, 850 mm, 4.5 mo, SaL	*A.g*, 3 yr duration, no harvest data	Yield increases were more with *A.g* ley than with shrub fallow	Bowden, 1963
Ejura, GH, 7.4 °N, 260 m, 1,470 mm, 6 mo, Sa	*A.g* & *P.po*, 9.4 Mg ha^{-1} yr^{-1} yield	Maize yield unaffected; 18% more groundnut yield; 300% more maize yield response to fertilizer-N; increased response to fertilizer P. Soil OC, P, & K increased, infiltration rate unaffected.	Stephens, 1960
Touba, CI, 8.5 °N, 510 m, 1,360 mm, 4.5 mo, CL	10-yr fallow; 4-yr ley	Much reduced crusting, 50% more water infiltration, 80% reduction in runoff	Valentin et al., 2004
Nyankpala, GH, 9.4 °N, 170 m, 1,090 mm, 5 mo, Sa	*A.g* & *P.po*, 15.8 Mg ha^{-1} yr^{-1} yield	No yield increase. Increased SOC but no effect on N & P availability or infiltration rate	Stephens, 1960
Samaru, NG, 11.2 °N, 690 m, 1,110 mm, 4.5 mo, SaL	*A.g*, 2–6 yr duration	Gains in infiltration and SOC were lost in one season of cotton production.	Jones, 1971 ; Wilkinson, 1975
Farako-Ba, BF, 11.4 °N, 410 m, 610 mm; 3.5 mo, SaL	Fallow	66% more sorghum yield. Fallow and rotation with groundnut had similar sorghum yield. Fertilizer was applied. Increased pH, SOC, and Ca but reduced Al saturation.	Bado et al., 2006
Kouare, BF, 11.6 °N, 850 m, 580 mm, 3.5 mon	Fallow	75% more sorghum yield. Fallow and rotation with cowpea had similar sorghum yield. Fertilizer was applied. Increased SOC and Ca but pH and Al saturation were unaffected.	Bado et al. 2006
Bondoukuy, BF, 11.8 °N, 290 m, 900 mm, 3.5 mo, SaL	E1. *A.g* ley & fallow, 5-7 yr duration. E2. 5-, 10- & 20-yr fallow	E1. 64% more SOC, 35% more N, 76% more microbial biomass, 141% more soil respiration, and 86% more β-glucosidase activity in fallow and ley than in cultivated areas. E2. 20–50% maize yield increase. Increased pH, SOC and soil monosaccharides.	E1. Bilgo et al., 2007; E2. Ouattara, 2009

Note. C, clay; L, loam; Sa, sand; *P.p, Pennisetum purpureum*; P.po, *Pennisetum polystachyon; A.g, Andropogon gayanus*; SOC, soil organic carbon; E1, Exp. 1; E2, Exp. 2.

[a]Location, latitude (°N), elevation (m), rainfall, distribution of rainfall expressed as months to accounting for 70% of rainfall.

[b]Fallow was naturally generated while ley were sown or vegetatively propagated. No fertilizer or manure was applied and termination was by tillage.

[c]No fertilizer or manure was applied. Land preparation was always with plowing or ridging.

[d]Infiltration, rate of water infiltration.

yield compared with continuous annual cropping (Ouattara, 2009).

2.3 | Latitude 12–15°

2.3.1 | This zone includes the Sahel and the northern part of the Sudanian Savanna

The average rainfall is 400–500 mm yr^{-1} with a CV of 25–30% for much of the Sahel with >70% falling in July and August (Le Barbé & Lebel, 1997). It appears that the frequency of dry periods during the cropping season has increased with a negative effect on pearl millet (*P. glaucum* L.) grain yield (Wildemeersch et al., 2015), especially soil water deficits that occur within 40 d of sowing and during grain formation. Average national sorghum and pearl millet yields in Niger from 2014 to 2018 were estimated to be < 0.5 Mg ha^{-1} while the mean yield gain since 1980 was estimated to be 5 kg ha^{-1} yr^{-1} (FAOSTAT, 2020). Application of fertilizer plus 2.5 Mg ha^{-1} yr^{-1} of manure may increase pearl millet and sorghum yields by an average of 60% (Garba et al., 2018) but productivity remains low.

2.3.2 | The traditional fallow of the Sahel

Fallow durations have been reduced over time with the abandonment of shifting cultivation from up to 25 yr duration to 6–10 yr bush fallow to short fallows of 1–2 yr duration with about two-thirds of the arable land in continuous cropping. Gandah et al. (2003) found in southwestern Niger that 60–90% of pearl millet fields did not receive fallow, manure application, or fertilizer application, depending on landscape position and farmer's distance to the field.

Hiernaux et al. (2009) reported a mean fallow duration of 4.8 yr in southwestern Niger. Fallow duration increased as the farmer's distance to the field increased. The fallows were naturally generated and 130 plant species were identified. The three most common fallow species accounted for an average of 38% of the ground cover. The species accounting for most ground cover were annual grasses *Ctenium elegans* Kunth and *Schizachyrium exile* (Hochst.) Pilg., and the leguminous herb *Indigofera strobilifera* Hochst. ex Baker. Annual grasses such as *Cenchrus biflorus* Roxb. and *Aristada mutabilis* Trin. & Rupr. that can germinate and produce seed within 5–6 wk are common for fallow land in the Sahel. Natural vegetative regeneration of fallow land occurred slowly (Kessler et al., 1998) and the annual grasses *Andropogon pseudopricus* Stapf. and *P. pedicellatum* Trin. gave 25% ground cover after 4 yr. There was an absence of perennial grass species and herbaceous legumes. Fallow land is typically severely over-grazed which may contribute to the dominance of short-lived annuals and little perennial grass survival.

The mean biomass yield of fallow was just 1.3 Mg ha^{-1}, likely reflecting the role of short-lived annual species, the absence of perennial grasses, and the effect of over-grazing on productivity (Hiernaux et al., 2009). Turner et al. (2005) reported an average of 0.75 Mg ha^{-1} of palatable herbaceous biomass in October, at the end of the rains, including from fallow and rangeland. In Kolda Senegal at 13.3 °N with 1,016 mm yr^{-1} of rainfall, natural fallow fodder yield was 5.9 Mg ha^{-1} compared with ley yields of 10.9 Mg ha^{-1} yr^{-1} for Andropogon and 8.3 Mg ha^{-1} yr^{-1} for *P. maximum* Jacq. (Diatta et al., 1997).

Shrubs are an important component of the fallow such as with about one *Guiera senegalensis* J.F. Gmel shrub per 100 m^2 (Bielders et al., 2002). Woody shrubs of 0–0.5 m height can spread quickly from 0.2 to 16 plants m^{-2} in 4 yr (Kessler et al., 1998). The shrubs are often preserved through the cropping period and into the next fallow as crop growth is often best in the near vicinity of shrubs (Dossa et al., 2012, 2013) including leguminous *Philiostigma reticulatum* (DC.) Hochst. and *G. senegalensis* with its hydraulic lifting properties (Bogie et al., 2018). The shrubs are often browsed and branches are periodically harvested for wood. The shrub compared with the herbaceous component of grazed natural fallow on sandy soils in the Sahel may contribute more to system productivity. However, Bowden (1963) reported that a 3-yr Andropogon ley established from rooted-tillers was more effective in increasing annual crop yields than shrub fallow at Yandev Nigeria. Tree species such as *Faidherbia albida* (Delile) A.Chev. as a legume with reverse phenology are also important to these systems but are hard to establish with heavy grazing.

A major challenge to cropping system improvement in the Sahel through the use of fallow or ley rotations is uncontrolled grazing including severe over-grazing during the rainy season and grazing any remaining palatable plant matter remaining during the dry season including the crowns of perennial grasses (Thëbaud & Batterbury, 2001). Local governments often have the power to protect land, such as land in ley rotation, from grazing. The benefits of ley rotations will need to be great enough to overcome the traditional practice of uncontrolled grazing of uncultivated lands.

2.3.3 | Fallow and land productivity

Hiernaux et al. (2009) reported on the monitoring of 71 fields in the Fakara area of southwestern Niger for land use and productivity from 1994 to 2006 (Table 3). Annual crop yields were very low and were found to be declining by 5% yr^{-1} with continuous production. Rotation of several years of annual crops with several years of fallow declined over time

TABLE 3 Studies of the effects of fallow or ley rotations on land productivity and soil properties between 12 and 15° latitude in tropical Africa

Site[a]	Fallow[b]	Annual crop yield[c] & soil properties	
Saria, BF, 12.3 °N, 310 m, 790 mm, 3 mo, SaL	Fallow	Fallow increased sorghum yield by 20–55%. Much less runoff and water erosion with fallow than cultivated.	Valentin et al., 2004; Ouattara, 1994
Fakara, NE, 13.5 °N, 230 m, 500 mm, 2.5 mo, Sa	Fallow of 4–8 yr	33% more pearl millet yield for the three following crops. 17.5 Mg ha^{-1} of sediment loss from cultivated land & 10.5 Mg ha^{-1} gained in fallow during a windstorm. In 0-to-2-cm soil depth, fallow gained 120% clay and 64% SOC.	Bielders et al., 2002; Hiernaux et al., 2009
Lagassagou, MA, 13.8 N, 295 m, 610 mm, 2.5 mo, Sa	Fallow of 0, 2, 5, and 7 yr followed by 4 yr of annual crops.	Mean pearl millet yield over 4 yr was 25% greater after fallow of ≥2 yr and was not reduced by intercropping. Cowpea yield was not affected by fallow. Soil OC was 44% higher during 4 yr following 2 yr compared with 0 yr fallow. *Striga hermonthica* was reduced with increased length of fallow and by intercropping compared with pearl millet sole crop.s	Samaké et al., 2006
Banizoumbou, NE, 13.6 °N, 230 m, 400 mm, 2.5 mo, Sa	Field survey with fallow of >10 yr and 3–5 yr compared to no recent fallow. Interpretation of results needs to consider that land-use decisions were likely affected by land productivity. The SOC and soil content in the 2-to-20-cm depth were higher with >10 yr fallow compared with 3–5 yr fallow and continuous cropping. With manure or fertilizer applied, the highest grain yield (0.71 Mg ha^{-1}) was with no fallow and the lowest was with the 3–5 yr fallow (0.41 Mg ha^{-1}). Lower yields with fallow may have been due to an increase in soil crusting with fallow compared to a decrease with continuous cultivation.		De Rouw & Rajot, 2004; Valentin et al., 2004

Note. *P.m, Pennisetum maximum* Jacq.; *A.g, Andropogon gayanus* Kunth; C, clay; L, loam; Sa, sand; SOC, soil organic carbon.

[a]Location, latitude (°N), elevation (m), rainfall, distribution of rainfall expressed as months to accounting for 70% of rainfall.

[b]Fallow was naturally generated with a high proportion of annual grasses and perennial shrubs while ley was sown or vegetatively propagated. No fertilizer or manure was applied and termination was by tillage.

[c]No fertilizer or manure was applied. Land preparation was always with plowing or ridging.

with fallow area decreasing by about 1.5% yr^{-1}. The mean cropping period was 4.6 yr but 9.1 yr for more intensively managed fields. With no fertilizer applied, crop yield was about 33% higher for the 3 yr following fallow compared with the mean for 4–8 yr after fallow. No results were reported for fallow effects with fertilizer or manure applied or how the crop response to fertilizer was affected by fallow.

In a survey of 40 fields in Niger, De Rouw and Rajot (2004) found that with fertilizer or manure applied, grain yields were highest with fields under continuous cultivation and no recent history of fallow and lower yield following 3–5 yr compared with >10 yr fallow (Table 3). However, the study did not account for factors affecting farmers' land-use decisions.

2.3.4 | Fallow, soil improvement, and crusting

Total dustfall in the Sahel could average 0.2 mm per year but much more for lands with vegetative cover (Herrmann, 1996; Orange & Gac, 1990). Sediment gain with fallow can be great with even a single windstorm (Table 3; Hiernaux et al., 2009). Samaké et al. (2006) reported a substantial gain in SOC which persisted over 4–7 yr of annual cropping. In Senegal, Masse et al. (2004) in a comparison of naturally regenerated, planted Andropogon or planted *Acacia holosericea* A.Cunn ex G.Don fallows, SOC, and nutrient availabilities during the annual crop phase were similar. The highest pearl millet yield was with treatments with the largest amount of biomass burned at the end of the fallow.

Bielders et al. (2002) reported on wind erosion and sediment trapping by fallow strips in southwestern Niger with sandy soil (Table 3). The fallow was simply described as bush fallow with dense herbaceous vegetation and about one *G. senegalensis* shrub per 100 m^2. No details of the height or density of the fallow vegetation, or if and how it was grazed, were provided. In a single windstorm, pearl millet [*Pennisetum americanum* (L.) Leeke] cropland lost 17.5 Mg ha^{-1} sediment with a linear increase in the erosion rate for up to 75 m of field width. The adjacent fallow land gained 10.5 Mg ha^{-1} with 89% of that trapped within the first 20 m and 55% within the first 10 m. In the fallow area, clay content was 120% more and SOC was 64% in the 0-to-2-cm soil depth for 10–40 m compared to 0–5 m into the downwind fallow strip. The authors suggest that grass fallow strips of 20 m width can be very effective in reducing the loss of sediment with <0.05 mm diam., including SOC and nutrients, if perpendicular to the prevailing wind during a windstorm. However, wind directions vary and strips of >20 m width may be desired.

Soil crusting of the sandy soils and its effect on water infiltration and runoff is of great concern in the Sahel with maybe 13% of rainfall lost as runoff for crop production land of 2–2.5% slope in Niger (Rockström & Valentin, 1997). The information on crusting is, however, fragmented and incomplete (Valentin et al., 2004). Graef and Stahr (2000) reported that the percentage land area with crusting averaged 19% for continuous millet, 7% for the pearl millet–cowpea intercrop, and 9% for pearl millet–fallow rotation. They found the dominant crust type to be structured as depositional laminated crusts with coarse sand on top, a vescular fine sandy layer and a seal of fine particles at the bottom (Valentin, 1994). The next most common crust type was an erosion layer with a smooth sealed surface of fine cemented particles resulting from slaking and disintegration of dry soil aggregates when suddenly wetted. Both of these crust types increased with increased soil sand content and decreased with increased SOC.

Valentin et al. (2004) reported on the examination of the sandy soil surface conditions of 34 plots in southwestern Niger. Fallowing did not consistently improve soil physical properties. Erosion crusts covered 2% of the cropland but this increased to 5% during the first 3 yr of fallowing and then to about 13% after 7 yr of fallow. The increase in crusting during fallow was attributed to increased clay and silt content in the surface soil.

Water runoff and infiltration effects of fallow for sandy soil in the Sahel were reviewed by Valentin, Rajot and Mitja (2004). Runoff was 23% of precipitation for fallow compared to 5% from a cultivated pearl millet field at Banizoumbou, Niger, and 51% for fallow compared to 33% from a pearl millet field at Oursi, Niger. The fallow effects on the maximum runoff coefficient measured for a shallow sandy loam soil at Saria, Burkina Faso, however, were 60% for a sorghum field, 30% for fallows of 1–4 yr and 5% for a fallow of >30 yr. Water erosion loss was >1,000% more for the sorghum field than for fallow. The conflicting fallow effects on runoff were attributed to the clay+silt content at the surface of sandy soil which increased during fallow due to sediment accumulation. The crusting for sandy soil was great when the clay plus silt content was around 10% but much less with <5% or >15% clay plus silt content. When the soil clay plus silt content is well above 10% as with the sandy loam at Saria, runoff is much reduced by fallow. Blue-green algae can colonize soil crusts when the soil clay plus silt content is >5% which helps to consolidate the crusts. Such algae "biocrusts" can protect small particles from loss to water and wind erosion but also reduces the water infiltration rate (Malam-Issa, 1999). Algae crusts of sandy soil were of relatively low importance for cultivated land but greater importance with fallow (Valentin, 1994).

Moderate, but not high, grazing and trampling decreased crusting of sandy soil in fallow compared to no grazing (Hiernaux et al., 1999). When compared to the non-grazed control, soil pH, organic C and N concentrations, and to a lesser extent P concentration, decreased after 4 yr of grazing. Soil P and pH further decreased after 9 yr of very high grazing pressure. If alternating ley and cropland strips are perpendicular to the slope, runoff due to reduced infiltration rate in fallow may be harvested in the crop strip to supplement the water received directly from rainfall (Valentin et al., 2004).

2.4 | Ley fodder

Some annual crop yield gain is expected with ley rotations and often following naturally generated fallow as written above. This gain, however, did not occur consistently and maybe less with higher latitudes, less rainfall, and sandy soils. The yield gain generally was not enough to compensate for the loss of annual crop production when the land is in fallow. Therefore, fodder yields and fodder values will be important to the profitability of ley rotations. The soil productivity gains may be greater with well-managed perennial grass-based ley than with natural fallows, but information for ley rotations north of 12^o latitude such as in the Sahel is relatively scarce as most studies were with fallow rotations (Table 3).

The ley rotation studies often did not report grass yields. Stephens (1960) reported yields as high as 32 Mg ha^{-1} yr^{-1} for elephant grass in humid Ghana and 16 Mg ha^{-1} yr^{-1} for Andropogon in semi-arid northern Ghana. Elephant grass yield during a 3-yr ley was about 10 Mg ha^{-1} yr^{-1} in Uganda (Table 1; Foster, 1971). In Benin on sandy soil, *P. maximum* Jacq. and Andropogon were established at 50-cm spacing by planting four to five rooted-tillers hole^{-1}, and elephant grass was established by planting stem cuttings at 1 m spacing (Adjolohoun et al., 2008). No fertilizer was applied. The 3-yr average annual yield was 7.3 Mg ha^{-1} for *P. maximum* Jacq., 5.9 Mg ha^{-1} for Andropogon, and 4.2 Mg ha^{-1} for elephant grass. Hay yields on sandy soil of Andropogon at Katsina, Nigeria, were 3 Mg ha^{-1} yr^{-1} with no fertilizer and 11.4 Mg ha^{-1} yr^{-1} with fertilizer applied (Bowden, 1963).

However, the fodder yield potential in the Sahel is expected to be relatively low and many perennial species may fail to survive the long dry season with sandy soil. Much of the fodder marketed in Niamey, other than crop residues, is from annual grass species (Gomma et al., 2017). Andropogon is a perennial grass exception that is common in the Niamey markets although it is marketed primarily as reeds for making mats. Andropogon does provide good quality fodder if cut regularly (Bowden, 1963). Important to the Sahel is that Andropogon propagated from rooted tillers planted at 0.5 by 1 m spacing resulted in the good establishment with rapidly expanding tussocks so that it soon provided good ground cover (Bowden, 1963). Andropogon survives long dry seasons, tolerates burning well, gives growth with the earliest rains, and forms a deep root system allowing much growth after cessation of the rains.

There is ample evidence of high demand for fodder in urban and peri-urban areas and along the main roads to urban areas (Gomma et al., 2017; Samireddypalle et al., 2017). Improved availability of good quality fodder is needed. About 50% of the fodder marketed in Niamey was crop residues with the remaining mostly naturally occurring vegetation that was cut, dried, and transported from non-cropland including fallow and rangeland. The stalks of pearl millet and sorghum were of relatively low nutritional and market value and crop residue of cowpea and groundnut was of relatively high value with most other fodder types of intermediate value. The market price ranged from about 20–150 CFA kg^{-1}, depending on the fodder type and time of year, with an average price of 99 CFA kg^{-1} (the mean exchange rate in 2017 was about 560 CFA US\$$^{-1}$ giving an average fodder value in urban areas of about \$177 Mg^{-1}). Increased ley area can contribute to meeting the growing demand for fodder while providing an alternative source of income for farming households and improving the sustainability of cropping systems.

In Kenya where >80%f of the milk supply is from smallholders, confined smallholder dairy production in the Kenya highlands has continued to grow at about 6% per year demonstrating high demand for milk (Odero-Waitituh, 2017). These dairy systems typically integrate ley such as of elephant grass or *Brachiaria* spp. in the cropping systems as strips through fields or in fodder lots with manure applied to the ley or other cropland.

3 | DISCUSSION

3.1 | Interpretation of the research findings for future African agriculture

The results conducted in the 0–5^o latitude zone found substantial yield increases following ley or fallow although generally not enough to fully compensate in terms of grain yield for the years with no annual crop production. However, returns to labor was increased. While ley yields were not reported, the ley was often grazed or hayed implying significant production. Results from other work indicate that grass yields may be >10 Mg ha^{-1} yr^{-1} if fertilized (Bowden, 1963; Foster, 1971; Stephens, 1960). Significant persistent soil improvements resulted from ley for clay loam soil (Foster, 1971; Stephens, 1967). Samaké et al. (2006) reported a persistent improvement in SOC due to fallow for sandy soil in the Sahel but others reported less benefit to soil properties for sandy soils in the 5–12^o and 12–15^o zones even though ley yields can be substantial with good response to fertilizer application (Adjolohoun et al., 2008; Bowden, 1963; Stephens, 1960). Observations were not made on erosion but the potential was likely reduced by good vegetative growth during ley and increased annual crop growth.

The full ecological benefit of ley rotations probably was not achieved in past research in tropical Africa. Greater and longer-lasting benefit is expected with less or no tillage which leaves plant residues on the soil surface as mulch and protection against erosion and does not bury the surface soil with improved soil aggregation (Carvalho et al., 2010; DuPont et al., 2014; Ernst & Siri-Prieto, 2009; Garcia-Prechac et al., 2004). Annual crops following ley may be more responsive to fertilizer use (Stephens, 1960) as well as giving greater returns to land and labor but there was no cropping system x fertilizer interaction in other studies (Foster, 1971; Stephens, 1960).

In Uganda, a 3:3 yr ley/annual crop rotation in strips across the field, of maybe 30-m width, was recommended (Stephens, 1970). Ley rotations were recommended for the Kenya highlands and 22% of the lands were found to be in ley in the Uasin Gishu area where 65% of arable land was planted to maize and dairy was important (Clayton, 1956). Planting perennial grasses such as elephant grass or a *Brachiaria* spp. in strips across arable land or in fodder lots, which may be rotated with annual crops, is common with smallholder dairy farmers in Kenya (Odero-Waitituh, 2017). Such strip farming may be a good option for other parts of tropical Africa. The strips can reduce water and wind erosion from cultivated lands with trapping of sediment, SOC, and nutrients (Rockström & Valentin, 1997; Valentin, Rajot & Mitja, 2004). Grass bands through annual crop fields increased rainwater capture and reduced soil erosion in Burkina Faso which reduced the negative effect of drought on crop yield and revenue (Traoré et al., 2020). The alternating strips of ley can provide easy access to rooted tillers and stem segments for vegetative propagation of new ley. Ley rotations conducted as strip cropping may be easier to protect from grazing livestock due to the tradition of respecting annual crop fields.

Grazing control will be essential to successful ley rotations. In many places, fields are opened to uncontrolled grazing at some time during the dry season. The grazing of grasslands is often uncontrolled throughout the year. Such management or lack of management is incompatible with successful ley rotation. Local governments can often impose restrictions on grazing but opposition may be strong. The value of ley rotations needs to be demonstrated to overcome such opposition.

3.2 | Research and extension for ley rotation improvement

Research and extension are first needed to demonstrate the value of ley rotations in areas with high demand for the fodder. Given that ley rotation experimentation can require years and much land, experiential learning may be the main approach to gaining information for fine-tuning ley rotations. This may involve establishing the rotations such as through strip cropping on farmer fields and at research centers which may not be experiments with replication and randomization but opportunities for systematically making and interpreting observations. Farmer participation in such research may be valuable, including for evaluation of socio-economics of the rotations.

The research is needed to optimize ley rotations including species and varieties for the ley phase, ley management and harvesting, duration of the ley, the transition between phases, annual crop sequence, and use of fertilizer and other inputs throughout the rotation cycle. Vegetative propagation for ley establishment, such as with rooted-tillers or stem segments, is likely to be best for many situations, especially where soil crusting and unreliable soil water availability during seedling establishment is a great concern. However, sowing seed may be most appropriate in other situations, including the possibility of establishing the grass while producing a maize crop where rainfall amount and distribution is adequate (Edwards, 1941). The duration of ley may partly be subject to the current demand for fodder compared with the annual crop produced. Optimized ley duration may be longer in the Sahel than in more humid areas anticipating slower establishment and the need to avoid much investment of labor ha^{-1} for such low productivity lands. With strip ley rotations, strips may be gradually converted to annual crop production so that an 18-m wide strip in a 3-yr rotation may have 6 m yr^{-1} converted to cropland each year while providing planting material to add 6 m to the other side of the ley strip.

Generally in past research, the crop that followed ley or fallow was a non-legume but planting of an N_2-fixing legume may be a better choice to reduce problems associated with fertilizer-N immobilization (Wortmann et al., 2019). Differing with most past fallow and ley studies in tropical Africa, fertilizer use is likely to be a component of future ley rotation research and extension promotion. While crusting is a problem associated with grazed natural fallows on sandy soils of the Sahel, it is anticipated that this problem will be reduced and soil improvement enhanced with well-managed ley such as with the tussocks of Andropogon.

Avoiding or minimizing tillage is likely to be important to ley rotation management for enhancing and preserving the soil benefits gained during the ley phase (Carvalho et al., 2010; DuPont et al., 2014; Ernst & Siri-Prieto, 2009; Garcia-Prechac et al., 2004). The low tillage management is likely to require some herbicide use to terminate ley although shallow sweep tillage may be feasible for sandy soil. Research is needed for better targeting of ley rotations in consideration of agronomic and economic factors. Ley rotations may be more valuable for lands that are marginal for annual crop production and where runoff and erosion potential are high (Wortmann et al., 2019). Soil that was much eroded is likely to have SOC well below the SOC saturation level with high potential to sequester SOC during the ley phase with likely benefits to soil physical, chemical, and biological properties. However, fodder market demand will be very important to the targeting of ley rotations.

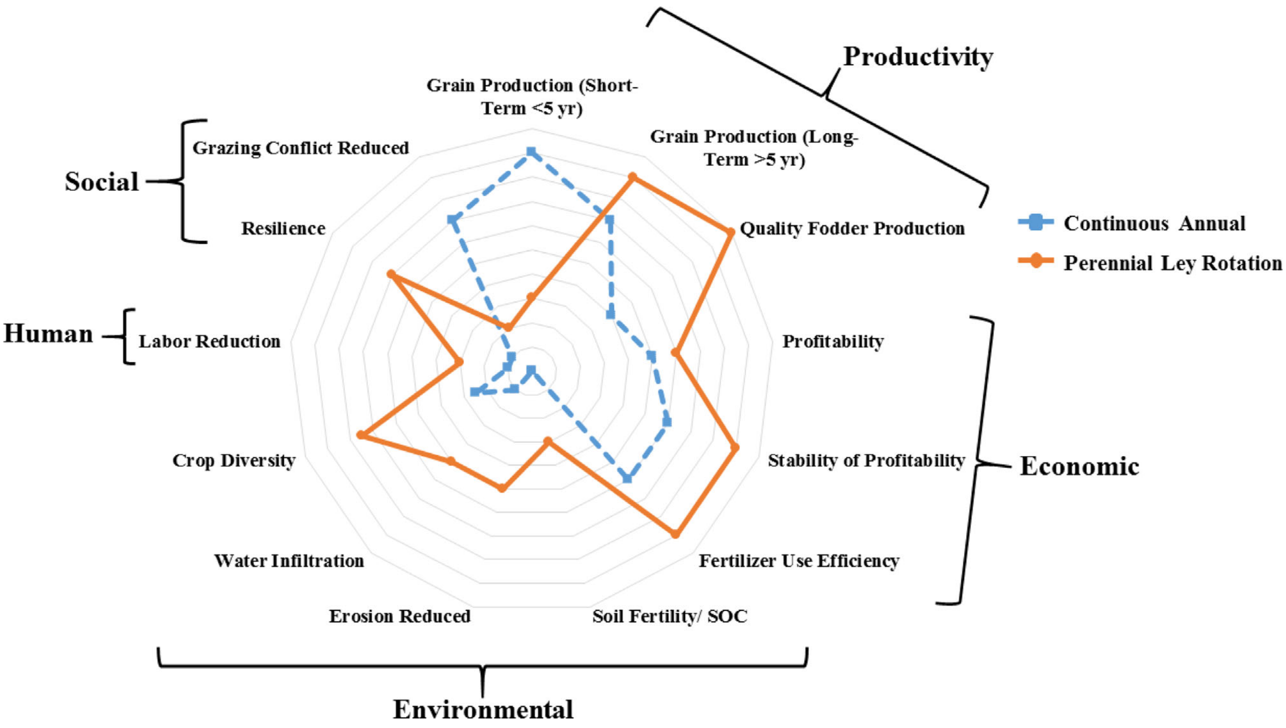

FIGURE 2 Generalized systems assessment of continuous annual cropping compared to annual cropping rotated with ley perennial grass (Stewart et al., 2018)

3.3 | Systems assessment

Using a farming systems approach, it is clear that ley perennial rotations offer numerous benefits over continuous annual cropping (Figure 2). In general, ley perennial rotations improve long-term (i.e., over 3–5 yr) annual grain yield, quality fodder yield, fertilizer use efficiency, soil fertility/SOC, erosion reduction, water infiltration, crop diversity, return to labor, resilience (i.e., ability to bounce-back from shocks such as climate extremes), and likely profitability and profit stability. These synergies can likely be further enhanced with perennial grass leys compared with traditional fallows, when fertilizer is applied to the ley crop or annual crops, and reduced or no tillage used for ley termination and annual crop production. However, there are two primary tradeoffs that need to be minimized before ley rotations would be readily adopted and begin to reverse declining productivity of African farming systems. First, short-term losses in annual grain production are hard to justify for many smallholder farmers. Substantial profit potential in fodder markets is needed to diminish this tradeoff. Second, loss of ley biomass to open grazing reduces the overall return to the farmer. Policies or agronomic practices that prevent this loss, such as local policies and with ley – annual crop strip cropping, will be needed to minimize this tradeoff. The magnitude of these tradeoffs and synergies across productivity, economic, environmental, human, and social dimensions will vary by location but in general, ley perennial rotations have many of the required traits required to sustainably intensify smallholder farming systems in many areas of tropical Africa.

4 | CONCLUSIONS

Opportunities for perennial grass ley rotated with annual crop phases as a means to improve farming systems are abundant in Africa. While land for annual crop production is often scarce, ley rotations are a means to reverse the common occurrence of soil degradation, sustainably improve soil, and increase annual crop yields and often yield response to fertilizer application. Perennial grasses develop extensive root systems that sequester C for increased SOC, cycle deep nutrients and water, and improve soil physical properties. The aboveground and belowground grass growth protects soil from wind and water erosion and traps sediment such as harmattan dust. Demand for fodder, which in many places is increasing, offers the opportunity for ley rotations to provide economic growth, diversification, and stability. Further research is needed to fine-tune the targeting and management of ley rotations for diverse cropping systems and environments, and to better understand the system edaphic, agronomic, social, and economic interactions. Barriers to adoption may be more social and political rather than bio-physical limitations. A major concern in many places is the practice of uncontrolled over-grazing of arable lands during the dry season which could be very damaging to ley but this can often be managed by local government policies. Agricultural productivity and sustainability in Africa can often be improved by the introduction of ley rotations with reduced erosion and runoff, sediment trapping, increased SOC and other soil improvement, higher crop yields and responsiveness to fertilizer, fodder supply, and enhanced economic growth, diversification, and stability. Information needed to fine-tune ley rotations may be most efficiently gained through experiential learning from the practice of ley – annual crop strip cropping with farmer participation in the research.

ACKNOWLEDGMENT

Manuscript preparation was made possible with the support of the American People provided to the Feed the Future Innovation Lab for Sustainable Intensification through the U.S. Agency for International Development (USAID). The contents are the sole responsibility of the authors and do not necessarily reflect the views of USAID or the U.S. Government. Program activities are funded by the U.S. Agency for International Development (USAID) under Cooperative Agreement no. AID-OAA-L-14-00006.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ORCID

C. S. Wortmann https://orcid.org/0000-0001-9715-8469
M. Garba https://orcid.org/0000-0002-3377-3064
Z. P. Stewart https://orcid.org/0000-0003-4058-8526

REFERENCES

Adjolohoun, S., Buldgen, A., Adandedjan, C., Dardenne, P., & Decruyenaere, V. (2008). Production and nutritive value of three grass species cultivated for ley pasture in the Borgou region of Benin. *Tropical Grasslands*, *42*, 237–244.

Allen, V. G., Baker, M. T., Segarra, E., & Brown, C. P. (2007). Integrated irrigated crop-livestock systems in dry climates. *Agronomy Journal*, *99*, 346–360. https://doi.org/10.2134/agronj2006.0148

Bado, B. V., Bationo, A., Lompo, F., Segda, Z., Cescas, M. P., & Sedogo, M. P. (2006). Long-term effects of cropping systems and fertilization on crop production, soil characteristics and nitrogen cycling in the Guinean and Sudanian savannah zones of Burkina Faso (West Africa). In F. Zapata, & L. M. Nguyen (Eds.), *Management practices for improving sustainable crop production in tropical acid soils* (pp. 47–64, The Joint FAO/IAEA Programme of Nuclear Techniques in Food and Agriculture, IAEA Proceedings Series). Vienna: International Atomic Energy Agency.

Bielders, C. L., Rajot, J. L., & Amadou, M. (2002). Transport of soil and nutrients by wind in bush fallow land and traditionally managed cultivated fields in the Sahel. *Geoderma*, *109*, 19–39. https://doi.org/10.1016/S0016-7061(02)00138-6

Bilgo, A., Masse, D., Sall, S., Serpantié, G., Chotte, J. L., & Hein, V. (2007). Chemical and microbial properties of semiarid tropical soils of short-term fallows in Burkina Faso, West Africa. *Biology and Fertility of Soils*, *43*, 313–320. https://doi.org/10.1007/s00374-006-0107-4

Bogie, N. A., Bayala, R., Diedhiou, I., Conklin, M. H., Fogel, M. L., Dick, R. P., & Ghezzehei, T. R. (2018). *Hydraulic redistribution by native sahelian shrubs: bioirrigation to resist in-season drought*. Frontiers in Environmental Science: Agroecology.

Bowden, B. N. (1963). Studies on *Andropogon gayanus* Kunth. I. The use of *Andropogon gayanus* in agriculture. *Empire Journal of Experimental Agriculture*, *31*, 267–273.

Clark, R. T. (1962). The effects of some resting treatments on a tropical soil. *Empire Journal of Experimental Agriculture*, *30*, 57–62.

Clayton, E. S. (1956). Land use and grain yields in the Kenya highlands. *East African Journal of Agriculture*, *22*(1), 32–33. https://doi.org/10.1080/03670074.1956.11665058

de Faccio Carvalho, P. C., Anghinoni, I., de Moraes, A., de Souza, E. D., Sulc, R. M., Lang, C. R., Flores, J. P. C., Terra Lopes, M. L., da Silva, J. L. S., Conte, O., de Lima Wesp, C., Levien, R., Fontaneli, R. S., & Bayer, C. (2010). Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. *Nutrient Cycling in Agroecosystems*, *88*, 259–273. https://doi.org/10.1007/s10705-010-9360-x

De Rouw, A., & Rajot, J. L. (2004). Soil organic matter, surface crusting and erosion in Sahelian farming systems based on manuring or fallowing. *Agriculture, Ecosystems & Environment*, *104*, 263–276.

Diatta, A., Bodian, A., & Babene, D. (1997). Production fourragère des graminées *Andropogon gayanus Kunth* et *Panicum maximum Jacq. CV. CI* utilisées en substitution de la jachère en Haute Casamance au Sénégal. In C. Floret & R. Pontanier (Eds.), *Jachère et maintien de la fertilité* (pp. 127–131). CORAF European Union Project 7 ACP RPR 269 Workshop Proceedings, Bamako.

Dossa, E. L., Diedhiou, I., Khouma, M., & Sene, M. D. (2012). Crop productivity and nutrient dynamics in a shrub (*Guiera senegalensis*)-based farming system of the Sahel. *Agronomy Journal*, *104*, 1255–1264. https://doi.org/10.2134/agronj2011.0399

Dossa, E. L., Diedhiou, I., Khouma, M., Sene, M., Badiane, A. N., Samba, S. A. N., Assigbetse, K. B., Sall, S., Lufla, A., Kizito, F., Dick, R. P., & Saxena, I. (2013). Crop productivity and nutrient dynamics in a shrub-based farming system of the Sahel. *Agronomy Journal*, *105*, 1237–1246. https://doi.org/10.2134/agronj2012.0432

Dupont, D. T., Beniston, J., Glover, J. D., Hodson, A., Culman, S. W., Lal, R., & Ferris, H. (2014). Root traits and soil properties in harvested perennial grassland, annual wheat,and never-tilled annual wheat. *Plant and Soil*, *381*, 405–420. https://doi.org/10.1007/s11104-014-2145-2

Edwards, D. C. (1941). The possibility of establishing grass under maize. *East Africa Agricultural Journal*, *6*, 233–235. https://doi.org/10.1080/03670074.1941.11664118

Eilitta, M., Mureithi, J., & Derpsch, R. (Ed.). (2014). *Green Manure/Cover Crop Systems of Smallholder Farmers*. Amsterdam, The Netherlands: Kluwer Academic Publishers. Amsterdam, The Netherlands.

Ernst, O., & Siri-Prieto, G. (2009). Impact of perennial pasture and tillage systems on carbon input and soil quality indicators. *Soil & Tillage Research*, *105*, 260–268.

FAOSTAT. (2020). http://www.fao.org/faostat/en/#data/QC. Accessed June 11 2020. Rome.

Foster, H. L. (1971). Crop yields after different elephant grass ley treatments at Kawanda Research Station, Uganda. *East African Agricultural and Forestry Journal*, *37*, 63–72. https://doi.org/10.1080/00128325.1971.11662505

Franzluebbers, A. J. (2007). Integrated crop-livestock systems in the southeastern USA. *Agronomy Journal*, *99*, 361–372. https://doi.org/10.2134/agronj2006.0076

Franzluebbers, A. J., Sawchik, A., & Taboada, M. A. (2014). *Agronomic and environmental impacts of pasture-crop rotations in temperate North and South America. Agriculture, Ecosystems and Environment*, *190*, 18–26.

Franzluebbers, A. J. (2012). Grass roots of soil carbon sequestration. *Carbon Management*, *3*, 9–11. https://doi.org/10.4155/cmt.11.73

Gandah, M., Brouwer, J., Hiernaux, P., & Van Duivenbooden, N. (2003). Fertility management and landscape position: Farmers' use of nutrient sources in western Niger and possible improvements. *Nutrient Cycling in Agroecosystems*, *67*, 55–66. https://doi.org/10.1023/A:1025105014135

Garba, M., Serme, I., Maman, N., Ouattara, K., Gonda, A., Wortmann, C. S., & Mason, S. C. (2018). Crop response to manure plus fertilizer in Burkina Faso and Niger. *Nutrient Cycling in Agroecosystems*, *111*, 175–188. https://doi.org/10.1007/s10705-018-9921-y

Garcia-Prechac, F., Ernst, O., Siri-Prieto, G., & Terra, J. A. (2004). Integrating no-till into crop-pasture rotations in Uruguay. *Soil & Tillage Research*, *77*, 1–13.

Gomma, A. D., Chaibou, I., Banoin, M. N., & Schlecht, E. (2017). Forages trade and nutritive value in urban centers in Niger: Maradi and Niamey cities cases. *International Journal of Innovation and Applied Studies*, *21*, 508–521.

Graef, F., & Stahr, K. (2000). Incidence of soil surface crust types in semi-arid Niger. Soil and Tillage Research, *55*, 213–218. https://doi.org/10.1016/S0167-1987(00)00117-3

Grahmann, K., Dellepiane, V. R., Terra, J. A., & Quincke, J. A. (2020). Long-term observations in contrasting crop-pasture rotations over half a century: Statistical analysis of chemical soil properties and implications for soil sampling frequency. *Agriculture, Ecosystems & Environment*, *287*. https://doi.org/10.1016/j.agee.2019.106710

GYGA. (2020). Global yield gap atlas data download. https://www.yieldgap.org/download_data. Accessed Oct 27 2020.

Hassink, J., & Whitmore, A. P. (1997). A model of the physical protection of organic matter in soils. *Soil Science Society of America Journal*, *61*, 131–139. https://doi.org/10.2136/sssaj1997.03615995006100010020x

Heathcote, R. G. (1969). Soil fertility under continuous cultivation in northern Nigeria. I. The role of organic manures. *Experimental Agriculture*, *6*, 229–237.

Herrmann, L. (1996). Dust deposition on soils in West Africa. In *Properties and areas of origin of the dust and its effect on soils and site characteristics* (Vol. 36,). (In German.) Stuttgart, Germany: Hohenheimer Bodenkundliche, University of Hohenheim.

Herrmann, L., Stahr, K., & Sivakumar, M. V. K. (1995). Dust deposition on soils of SW-Niger. *Proceedings of an International Seminar on Wind Erosion in West Africa: The Problem and its Control*. (pp. 5.7). Dec. 1994, Stuttgart-Hohenheim, Germany.

Hiernaux, P., Ayantunde, A., Kalilou, A., Mougin, E., Gérard, B., Baup, F., Grippa, M., & Djaby, B. (2009). Trends in productivity of crops, fallow and rangelands in southwest Niger: Impact of land use, management and variable rainfall. *Journal of Hydrology*, *375*, 65–77. https://doi.org/10.1016/j.jhydrol.2009.01.032

Hiernaux, P., Bielders, C. L., Valentin, C., Bationo, A., & Fernadez-Rivera, S. (1999). Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian range lands. *Journal of Arid Environments*, *41*, 231–245. https://doi.org/10.1006/jare.1998.0475

Hochman, Z., Carberry, P. S., Robertson, M. J., Gaydon, D. S., Bell, L. W., & McIntosh, P. C. (2013). Prospects for ecological intensification of Australian agriculture. *European Journal of Agronomy*, *44*, 109–123. https://doi.org/10.1016/j.eja.2011.11.003

Jameson, J. D., & Kerkham, R. K. (1960). The maintenance of soil fertility in Uganda. I. Soil fertility experiment at Serere. *Empire Journal of Experimental Agriculture*, *28*, 179–192.

Jones, M. J. (1971). The maintenance of soil organic matter under continuous cultivation at Samaru, Nigeria. *Journal of Agricultural Science Cambridge*, *77*, 473–482. https://doi.org/10.1017/S0021859600064558

Kaizzi, C. K., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza, W., Nansamba, A., Musinguzi, P., Ebanyat, P., Hyuha, T., & Wortmann, C. S. (2012). Maize response to fertilizer and nitrogen use efficiency in Uganda. *Agronomy Journal*, *104*, 73–82. https://doi.org/10.2134/agronj2011.0181

Kemanian, A. R., Julich, S., Manoranjan, V. S., & Arnold, J. R. (2011). Integrating soil carbon cycling with that of nitrogen and phosphorus in the watershed model SWAT: Theory and model testing. *Ecological Modeling*, *222*, 1913–1921. https://doi.org/10.1016/j.ecolmodel.2011.03.017

Kemanian, A. R., White, C. M., Shi, Y., & Stockle, C. O. (2020). *Cycles*. https://plantscience.psu.edu/research/labs/kemanian/models-and-tools/cycles Accessed on June 10 2020.

Kerkham, R. E. (1947a). Effect of different systems of pasture management on yield of arable crops. *East African Agricultural Journal*, *13*, 78–79.

Kerkham, R. E. (1947b). Grass fallow in Uganda. I. Grazing during the fallow period. *The East African Agricultural Journal*, *13*, 3–7. https://doi.org/10.1080/03670074.1947.11664572

Kessler, J. J., Slingerland, M. A., & Savadogo, M. (1998). Regeneration of sylvopastoral lands in the Sahel zone under village management conditions. *Land Degradation & Development*, *9*, 95–106.

Le Barbé, L., & Lebel, T. (1997). Rainfall climatology of the Hapex-Sahel region during the years 1950–1990. *Journal of Hydrology*, *188–189*, 43–73. https://doi.org/10.1016/S0022-1694(96)03154-X

Liben, F. M., Adisu, T., Atnafu, O., Bekele, I., Berhe, H., & Wortmann, C. S. (2020). Maize and sorghum nutrient response functions for Ethiopia. *Nutrient Cycling in Agroecosystems*, *117*, 401–410. https://doi.org/10.1007/s10705-020-10077-7

Malam-Issa, O. (1999). *Etude du r^ole des cro^utes microbiotiques dans les sols sableux de deux écosystèmes sahéliens (jachères et brousse tigrée) au Niger. Micromorphologie, propriétés physiques et biogéochimie* (Ph.D. thesis, University of Orléans). http://www.sudoc.abes.fr/cbs/xslt//DB=2.1/SET=2/TTL=1/SHW?FRST=2

Masse, D., Manlay, R. J., Diatta, M., & Pontanier, R. (2004). Soil properties and plant production after short-term fallows in Senegal. *Soil Use and Management*, *20*, 92–95. https://doi.org/10.1079/SUM2003226

McWalter, A. R., & Wimble, R. H. (1976). A long-term rotation and manurial trial in Uganda. *Experimental Agriculture*, *12*, 305–317.

Monti, A., & Zatta, A. (2009). Root distribution and soil moisture retrieval in perennial and annual energy crops in northern Italy. *Agriculture, Ecosystems & Environment*, *132*, 252–259.

NOAA. (2020). *Inter-tropical convergence zone*. NOAA National Weather Service. https://www.weather.gov/jetstream/itcz. Accessed Oct 26 2020.

Odero-Waitituh, J. A. (2017). Smallholder dairy production in Kenya: A review. *Livestock Research for Rural Development*, *29*, http://lrrd.cipav.org.co/lrrd29/7/atiw29139.html, Accessed May 2020.

Orange, D., & Gac, J. Y. (1990). Bilangéochimique des apports atmosphériques en domaines sahélien et soudano-guinéen d'Afrique de l'Ouest (bassins supérieurs du Sénégal et de la Gambie). *Géodynamique*, *5*, 51–65.

Ouattara, B. (1994). *Contribution à l'étude de l'évolution de propriétés physiques d'un sol ferrugineux tropical sous culture: pratiques culturales et états structuraux du sol* (Thèse UNCI, Abidjan). https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers16-05/010013757.pdf

Ouattara, B. (2009). *Analyse–Diagnostic du statut organique et de l''etat structural des sols des agrosystemes cotonniers de l''ouest du Burkina Faso (Terroir de Bondoukui)*. (Thèse UPB, Bobo Dioulasso). http://bibliovirtuelle.u-naziboni.bf/biblio/opac_css/docnume/idr/agriculture/UniversiteIDR-2009-OUA-ANA.pdf

Nalivata, P., Kibunja, C., Mutegi, J., Tetteh, F., Tarfa, B., Dicko, M. K., Ouattara, K., Cyamweshi, R. A., Nouri, M. K., Bayu, W., & Wortmann, C. S. (2017). Integrated soil fertility management in Sub-Saharan Africa. In C. S. Wortmann & K. Sones (Eds.), *Fertilizer use optimization in sub-Saharan Africa* (pp. 25–39). London, UK: CABI. https://doi.org/10.1079/9781786392046.0025

Pereira, H. C., Chenery, E. M., & Mills, W. R. (1954). The transient events of grasses on the structure of tropical soils. *Empire Journal of Experimental Agriculture*, *22*, 148–160.

Persson, T., Bergkvist, G., & Katterer, T. (2008). Long-term effects of crop rotations with and without perennial leys on soil carbon stocks and grain yields of winter wheat. *Nutrient Cycling in Agroecosytems*, *81*, 193–202. https://doi.org/10.1007/s10705-007-9144-0

Pravia, M. V., Kemanian, A. R., Terra, J. A., Shi, Y., Macedo, I., & Goslee, S. (2019). Soil carbon saturation, productivity, and carbon and nitrogen cycling in crop-pasture rotations. *Agricultural Systems*, *171*, 13–22. https://doi.org/10.1016/j.agsy.2018.11.001

Rockström, J., & Valentin, C. (1997). Hillside dynamics of on-farm generation of surface water flows: The case of rainfed cultivation of pearl millet on sandy soil in the Sahel. *Agricultural Water Management*, *33*, 183–210. https://doi.org/10.1016/S0378-3774(96)01282-6

Russelle, M. P., Entz, M. H., & Franzluebbers, A. J. (2007). Reconsidering integrated crop–livestock systems in North America. *Agronomy Journal*, *99*, 325–334. https://doi.org/10.2134/agronj2006.0139

Sagir, J., & Santoro, J. (2018). *Urbanization in Sub-Saharan Africa: Meeting challenges by bridging stakeholders*. Washington, DC: Center for Strategic and International Studies.

Samaké, O., Stomph, T. J., Kropff, M. J., & Smaling, E. M. A. (2006). Integrated pearl millet management in the Sahel: effects of legume rotation and fallow management on productivity and Striga hermonthica infestation. *Plant Soil*, *286*, 245–257. https://doi.org/10.1007/s11104-006-9041-3

Samireddypalle, A., Boukar, O., Grings, E., Fatokun, C., Prasad, K., Devulapalli, R., Okike, I., & Blömmel, M. (2017). Cowpea and groundnut haulms fodder trading and its lessons for multidimensional cowpea improvement for mixed crop livestock systems in West Africa. *Frontiers in Plant Science*, *8*, article 30. https://doi.org/10.3389/fpls.2017.00030

Serme, I., Tarfa, B., Ouattara, K., & Wortmann, C. S. (2020). Maize response to applied nutrients for the Sudan and Guinea Savannas of West Africa. *Agronomy Journal*, *112*, 2230–2239. https://doi.org/10.1002/agj2.20152

Stephens, D. (1960). Three rotation experiments with grass fallows and fertilizers. *Empire Journal of Experimental Agriculture*, *28*, 165–178.

Stephens, D. (1967). Effects of grass fallow treatments in restoring fertility of Buganda clay loam in South Uganda. *Journal of Agricultural Science Cambridge*, *68*, 391–403. https://doi.org/10.1017/S0021859600012909

Stephens, D. (1970). Soil fertility. In J. D. Jameson (Ed.), *Agriculture in Uganda* (pp. 72–89). London, UK: Oxford University Press.

Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Prasad, P. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. *Journal of Experimental Botany*, *71*, 632–641. https://doi.org/10.1093/jxb/erz446

Stewart, Z. P., Middendorf, B. J., & Prasad, P. V. V. (2018). *SIToolKit.com©. Feed the future innovation lab for collaborative research on sustainable intensification*. Manhattan: Kansas State University.

Sulc, R. M., & Tracy, B. F. (2007). Integrated crop–livestock systems in the U.S. Corn Belt. *Agronomy Journal*, *99*, 335–345. https://doi.org/10.2134/agronj2006.0086

Thëbaud, B., & Batterbury, S. (2001). Sahel pastoralists: Opportunism, struggle, con#ict and negotiation. A case study from eastern Niger. *Global Environmental Change*, *11*, 69–78.

Traoré, H., Barro, A., Yonli, D., Stewart, Z., & Prasad, V. (2020). Water conservation methods and cropping systems for increased productivity and economic resilience in Burkina Faso. *Water*, *12*, 976. https://doi.org/10.3390/w12040976

Turner, M. D., Hiernaux, P., & Schlecht, E. (2005). The distribution of grazing pressure in relation to vegetation resources in semi-arid West Africa: The role of herding. *Ecosystems*, *8*, 668–681. https://doi.org/10.1007/s10021-003-0099-y

Valentin, C. (1994). *Sealing, crusting and hardsetting soils in Sahelian agriculture*. Marseille France: Institute of Research for Development (OSTROM).

Valentin, C., Rajot, J. L., & Mitja, D. (2004). Responses of soil crusting, runoff and erosion to fallowing in the subhumid and semi-arid regions of West Africa. *Agriculture, Ecosystems and Environment*, *104*, 287–302. https://doi.org/10.1016/j.agee.2004.01.035

White, C. M., Kemanian, A. R., & Kaye, J. P. (2014). Implications of carbon saturation model structures for simulated nitrogen mineralization dynamics. *Biogeosciences*, *11*, 6725–6738. https://doi.org/10.5194/bg-11-6725-2014

Wildemeersch, J. C. J., Garba, M., Sabiou, M., Fatondji, D., & Cornelis, W. M. (2015). Agricultural drought trends and mitigation in Tillaberí, Niger. *Soil Science and Plant Nutrition*, *61*, 414–425. https://doi.org/10.1080/00380768.2014.999642

Wilkinson, G. E. (1975). Effect of grass fallow rotations on the infiltration rate of water into a savannah zone soil of northern Nigeria. *Tropical Agriculture*, *52*, 97–103.

Wortmann, C., Amede, T., Bekunda, M., Kome, C., Masikati, P., Ndungu-Magiroi, K., Snapp, S., Stewart, Z., Westgate, M. E., & Zida, Z. (2020). Lessons for achieving impact with smallholders in Africa. *Agronomy Journal*, *112*. https://doi.org/10.1002/agj2.20363

Wortmann, C. S., Anderson, B. E., & Redfearn, D. D. (2019). Perennial grass or grass-legume in rotation with annual crops *(NebGuide 2313)*. Lincoln: University of Nebraska.

Wortmann, C., Senkoro, C. Cyamweshi, A. R., Kibunja, C., Nkonde, D., Munthali, M., Nalivata, P., Nabahungu, L. N., & Kaizzi, K. (2018). Maize-nutrient response functions for eastern and southern Africa. *Agronomy Journal*, *110*, 2070–2079. https://doi.org/10.2134/agronj2018.04.0268

How to cite this article: Wortmann C, Bilgo A, Kaizzi C, et al. Perennial grass ley rotations with annual crops in tropical africa: A review. *Agronomy Journal*. 2021;1–17. https://doi.org/10.1002/agj2.20634