Biodiversity can support a greener revolution in Africa

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The Asian green revolution trebled grain yields through agrochemical intensification of monocultures. Associated environmental costs have subsequently emerged. A rapidly changing world necessitates sustainability principles be developed to reinvent these technologies and test them at scale. The need is particularly urgent in Africa, where ecosystems are degrading and crop yields have stagnated. An unprecedented opportunity to reverse this trend is unfolding in Malawi, where a 90% subsidy has ensured access to fertilization and improved maize seed, with substantive gains in productivity for millions of farmers. To test if economic and ecological sustainability could be improved, we preformed manipulative experimentation with crop diversity in a countrywide trial (*n* = 991) and at adaptive, local scales through a decade of participatory research (*n* = 146). Spatial and temporal treatments compared monoculture maize with legume-diversified maize that included annual and semiperennial (SP) growth habits in temporal and spatial combinations, including rotation, SP rotation, intercrop, and SP intercrop systems. Modest fertilizer intensification doubled grain yield compared with monoculture maize. Biodiversity improved ecosystem function further: SP rotation systems at half-fertilizer rates produced equivalent quantities of grain, on a more stable basis (yield variability reduced from 22% to 13%) compared with monoculture. Across sites, profitability and farmer preference matched: SP rotations provided twofold superior returns, whereas diversification of maize with annual legumes provided more modest returns. In this study, we provide evidence that in Africa, crop diversification can be effective at a countrywide scale, and that shrubby, grain legumes can enhance environmental and food security.

ecosystem services | nitrogen | rural development | sustainable agriculture

Intensification of agriculture has been cited as the only feasible pathway to food security for the world's poor (1), and fertilizer is relied upon around the globe (2). This poses a grand challenge for African smallholders at the end of a long and costly supply chain. Fossil-fuel derived inputs such as fertilizer are widely effective at improving productivity, but in Africa have often proven marginally profitable (3). Management approaches that harness biological processes to improve nutrient efficiency are urgently needed (4). Experimentation indicates that alternative systems can be economically feasible and support sustainable use of resources (5, 6); what remains is to assess scalability in a developing country context.

Africa faces declining agricultural capacity just as anthropogenic-driven reductions in rainfall are enhancing risk (7). A hopeful exception is underway in Malawi where the first African green revolution has been hailed (8). To address chronic food insecurity in this impoverished population of 13 million, the government has subsidized N-fertilizer and improved maize seed (90% of cost), and enhanced access by over a million farmers annually since 2006. Consequent increases in production have been heralded as a triumph for input intensification of rain-fed cereals (Fig. S1). This has come at a substantial cost, as the program has consistently exceeded its approved budgetary allocation (13–17% of the national budget), resulting in reductions in expenditure in other key areas (9). Neighboring countries are starting fertilizer subsidy programs in emulation, although questions about sustainability of such initiatives have arisen.

An early version of the fertilizer and maize seed subsidy, the Malawi Starter Pack, was undertaken a decade ago (10) (Fig. S1). At that time we hypothesized crop diversity to be a missing element in the maize seed/fertilizer approach and consequently we initiated a countrywide trial with thousands of farmers in close collaboration with the Malawi government to test the ecosystem (dis)services associated with monoculture versus diversified maize farming; this was led by the Maize Productivity Task Force (MPTF) (11). A complementary program of participatory research was conducted at sites in Northern (Ekwendeni) and Southern (Songani) Malawi for insights into farmer assessment of technology performance, and to support adaptation and adoption (12, 13). Ecosystem service (ES) generation provides a useful, integrated framework for evaluating performance (14). In our study the ES monitored were chosen for relevance to smallholder farmer livelihoods, e.g., provisioning services of grain and protein yield, profitability, and supporting services of plant cover, soil organic carbon (C), and fertilizer efficiency.

Many ES are under threat in sub-Saharan Africa as use of natural fallows and shifting cultivation has declined precipitously. There is a strong trajectory toward simplification in favor of cereals, and increased area planted to maize (10). This is not surprising, as the poor have an immediate and urgent need for calorie-rich food, and cereal harvest generates a high-calorie return per calorie of hand labor invested. There are clearly biological and social-economic drivers that promote sole-cropping of cereals; however, there is emerging evidence that unintended and severe consequences of this agro-simplification include reduced capacity for light capture and nutrient cycling and instability of production (15, 16).

We propose legume diversification as the foundation for enhanced N fixation and C sequestration in agriculture, yet reliance on these species has been associated with yield reductions in long-term experimentation (5), a major drawback for poor farmers. There is an urgent need to test if legumes with specific traits can support sustainable, productive cropping and if this holds at regional scales. Malawi provides a unique opportunity to examine a green revolution in progress, and test the scalability of sustainability principles.

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Greening the Green Revolution

There has been 100 y of research on biologically based agriculture in southern Africa (17). Rotation of maize with annual grain legumes, such as soybean (*Glycine max*) or peanut (*Arachis hypogaea*), has been shown to increase maize yields by 10–78%, although on-farm gains have tended to be modest or nil (18, 19). A maize rotation with peanut (or soybean at about 30% of the sites, depending on agroecosystem suitability) was tested here.

To build soil productivity may require diversification with shrubby and viney leguminous crops that are vigorous producers of N-enriched vegetation and live longer than the ~4 mo typical of annuals (Fig. 1). We call these types of grain legumes semi-perennials (SP), and we tested combinations that were preferred by farmers in earlier studies (19). The SP pigeonpea (*Cajanus cajan*) is already grown as a shrubby intercrop with cereals in some parts of the world. Farmers appreciate its complementary growth habit of slow initial growth, and ability to maintain growth and produce grain late in the season, after a cereal crop is harvested. Pigeonpea has high N-fixing capacity, and has been shown to mineralize sparingly-soluble P on degraded sites (20). Pigeonpea was tested here both as a maize intercrop and as a SP rotation (pigeonpea intercrop with peanut in year 1, rotated with maize in year 2; Fig. S2). Mucuna (*Mucuna pruriens*) is another long-duration legume, one with a viney growth habit that can produce copious amounts of biomass and moderate to high amounts of grain* (11); it was tested here as the SP rotation system in the MPTF.

Agroforestry systems further "perennialize" cereal farming (21). Agroforestry species produce large amounts of leafy residues and fuel wood, but no grain. Labor requirements are often onerous, both to establish seedlings for transplanting and to minimize competition through frequent pruning of intercropped trees or shrubs (22). The maize-*Tephrosia vogelii* intercrop is an exceptional form of agroforestry because it has relatively modest labor requirements (13). Tephrosia can be planted as a relay intercrop under a maize canopy, where it grows into the dry season after maize harvest and produces large amounts of N-rich residues, but no edible grain (Fig. 1). Tephrosia was tested as a SP intercrop system at both participatory sites, but interest was limited at Ekwendeni (12), and results reported here are from Songani, which had many more sites.

Through manipulative experimentation conducted countywide and at participatory research sites, we examined intensification alternatives to enhance ES from green revolution technologies. Our hypotheses were first that cropping system diversification would improve ecosystem function robustly across the Malawi landscape. Second, temporal diversification through sequencing SP legumes before maize would be the most effective means to enhance system productivity, stability, and soil resources.

Results

Crop Yield. Moderate fertilizer application (35 kg N ha^{-1}) approximately doubled grain production in monoculture maize to 2.17 Mg ha^{-1} from an unfertilized yield level of 1.05 Mg ha^{-1} in a countrywide experiment (MPTF). Similarly, at participatory research sites, unfertilized maize was 0.89 (Songani) and 0.97 Mg ha^{-1} (Ekwendeni), which increased with fertilizer to 2.02 and 1.61, respectively. Compared with monoculture maize, a fertilized† peanut-maize rotation produced 25% less grain around the country (MPTF) and equivalent amounts of grain in farmer participatory research at Ekwendeni (Fig. 2). Due to presence of a protein-rich legume grain, protein yield was enhanced in the peanut-diversified maize system by 12% (MPTF) and 23% (Ekwendeni) compared with monoculture maize. In addition to diversification with annual legumes, we tested the effect of enhanced perenniality with a SP rotation of shrubby pigeonpea (with an understory intercrop of peanut or soybean) in Ekwendeni and Songani or viney mucuna in MPTF. A consistent response across experimentation was that SP rotation and monoculture maize produced similar amounts of grain on a 2-y basis (Table S1). As the legume grain produced in the SP rotation was enriched in protein compared with maize grain, the nutritional benefits were outstanding: protein yield was 70% (MPTF) or 43–55% (Songani and Ekwendeni) higher in SP rotation compared with monoculture maize (Fig. 2).

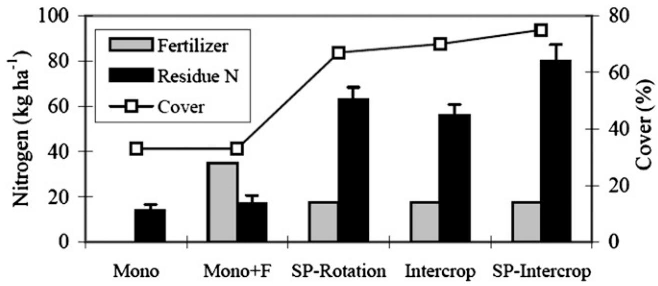

Fig. 1. Characteristics of monoculture maize and legume-diversified maize systems, based on experimentation carried out on-farm in Songani, Malawi (n = 50). Maize grown in continuous monoculture without (mono) or with fertilizer (mono + F). Maize fertilized and rotated with a pigeonpea-groundnut intercrop (SP rotation), intercropped with pigeonpea (intercrop), or intercropped with a agroforestry species tephrosia (SP intercrop). Mean residue nitrogen content (±SE), fertilizer N applied on an annual basis over 2 y, and cover (proportion of year with living plants present) are presented.

In addition to testing temporal diversification (rotations), we investigated spatial diversification (intercrops). A pigeonpea-maize intercrop produced ~15% less (MPTF and Songani) or the same amount of grain (Ekwendeni) as monoculture maize (1.67–1.87 Mg ha^{-1}). Protein yield was similar between the systems, ~5% less (MPTF and Songani) or 15% more (Ekwendeni). The agroforestry system of tephrosia-maize SP intercrop produced the same quantity of maize grain as monoculture maize (Fig. 2*B*).

Smallholder farmers are risk adverse and facing increasing climate uncertainty, so we examined spatial stability of grain yield. Spatial variability was consistently high in unfertilized maize, with CVs of 17% (midaltitude MPTF), 23% (low-altitude MPTF), 19% (Songani), and 30% (Ekwendeni), respectively (Fig. S3). Across sites, fertilized maize showed less variable grain yield than unfertilized maize. Superior stability in yield was observed in the SP rotation (CVs of 9–16%). Overall, lower elevation was associated with higher variability as might be expected given the generally dry conditions at low altitudes in Malawi (Fig. S3).

Adoption Potential. Complex socioeconomic issues such as labor and land availability are important drivers of farmer adoption, but require discussion that is beyond the scope and space limitations of this article. We documented profitability as one critical factor in farmer uptake. This was assessed by calculating the value cost ratio (VCR) for each system, compared with the baseline system of unfertilized monoculture maize. This is a useful means to systematically compare disparate farming systems (23). The VCR was favorable (>3) for all systems at a maize grain/fertilizer price ratio of 2:1, which was the prevalent ratio when the research was conducted. Since 2008, however, fertilizer prices have increased globally. A twofold-higher fertilizer price scenario was examined to test profitability of the technologies at altered maize:fertilizer price ratios. For monoculture maize,

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*Mucuna grain is eaten in some regions of Malawi, but it requires extensive processing to detoxify.

†Fertilizer use on a 2-y basis was halved, as only the maize production year was fertilized.

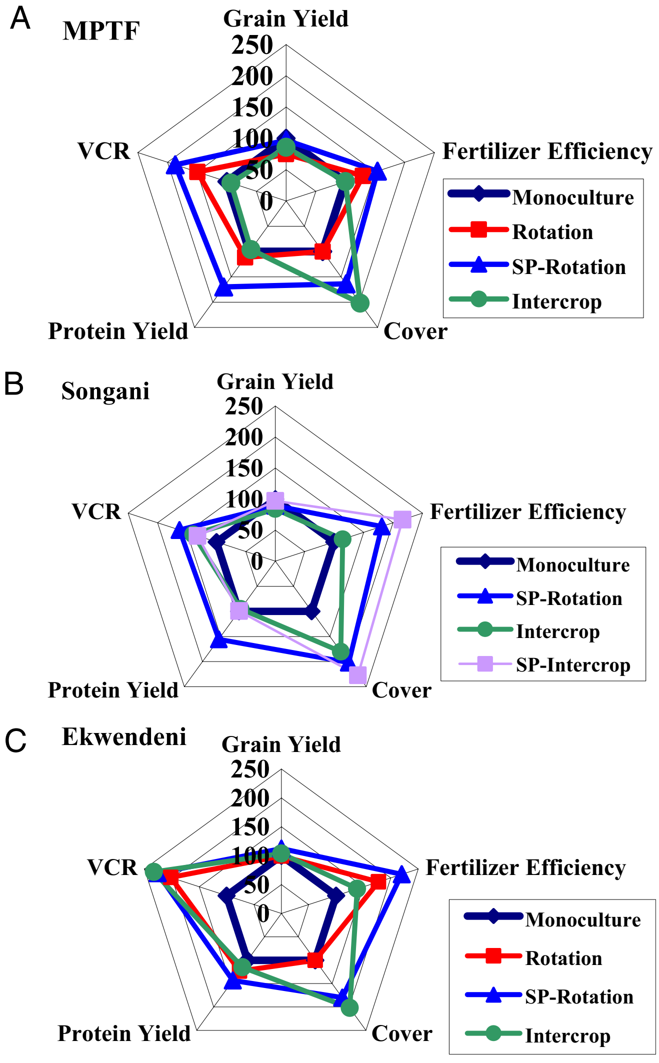

Fig. 2. Ecosystem services presented using a radial graph with values relative to baseline monoculture maize. (*A*) Ecosystem services from MPTF (n = 991). Absolute values for 100% baseline: annual yield combining maize and legume grain (2,174 kg ha^{-1}), fertilizer efficiency (24.5 grain kg^{-1} N kg^{-1}), annual cover duration (4 mo) and profitability, VCR (5.00). (*B*) Ecosystem services from Songani (n = 56). Absolute values for 100% baseline: annual yield combining maize and legume grain (2,015 kg ha^{-1}), fertilizer efficiency (23.7 grain kg^{-1} N kg^{-1}), annual protein yield (201 kg ha^{-1}), annual cover duration (4 mo), and profitability VCR (4.67). (*C*) Ecosystem services from Ekwendeni (n = 60). Absolute values for 100% baseline: annual yield combining maize and legume grain (1,611 kg ha^{-1}), fertilizer efficiency (31.3 grain kg^{-1} N kg^{-1}), annual cover duration (4 mo), and profitability VCR (3.22).

higher fertilizer prices reduced the VCR ≤2.5 (Table S1). In contrast, the VCR of the rotation, SP rotation, and SP intercrop systems remained >4.0, indicating a profitable scenario. Farmer preference provided further insights into adoption potential of technologies. Farmer surveys indicated consistent technology rankings across experiments, despite the diversity of years, locations, and participants involved. About half of participating farmers rated the SP rotation system as first (41–56%), one-third chose the peanut-maize rotation (28–34%), 10–19% chose the intercrop, and 6–8% chose monoculture, fertilized maize (Fig. 3). When technologies were assessed in terms of specific benefits and costs, nutritional benefits of legume diversification were particularly valued by female farmers and labor constraints were frequently noted by poorer households (11, 12).

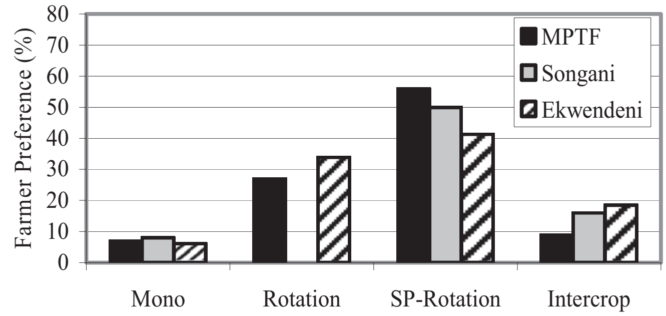

Fig. 3. Farmer preference for technologies, reporting first choice from ranking exercises conducted in surveys with the countywide trial in 1999 (MPTF, n = 991), at Songani in 1999 (n = 56), and at Ekwendeni in 2008 (n = 90). Systems compared were all fertilized: monoculture maize, rotation (peanut/maize), SP rotation (semiperennial and annual legume intercrop/maize), and intercrop (pigeonpea and maize).

Soil Resources. The presence of SP legumes increased the extent of living cover from 4 mo to >7 mo, and the inputs from N-enriched residues (15 kg N ha^{-1} monoculture maize to ∼60 kg N ha^{-1} SP legumes; Fig. 1). The SP intercrop system provided the longest duration of leafy cover, 10 mo of the year. Soil C was expected to accrue in the presence of long-lived legumes; however, we did not observe this (Table S1). It requires years to detect changes in soil properties, and background soil C variability is high in smallholder fields (24). A trend toward higher soil C with legume diversification was seen in Songani, as monoculture maize soil C was 1.46 ± 0.11 and SP intercrop soil C was 1.57 ± 0.12 (P value = 0.10). At the Ekwendeni site no difference was observed in soil organic C in legume-diversified vs. monoculture maize fields (1.3 ± 0.4%) (25).

Fertilizer efficiency was defined here as the incremental maize grain response to N fertilizer (2, 3), calculated after subtraction of unfertilized maize yield from maize response to 35 kg N fertilizer ha^{-1} applied in year 2 of the cropping system. This provided a metric for the semiclosed nature of the cropping system. In monoculture maize, fertilizer efficiency was 24.5 grain kg N kg^{-1} (MPTF), 23.7 grain kg N kg^{-1} (Songani), and 31.3 grain kg N kg^{-1} (Ekwendeni). Diversification of maize through a SP rotation substantively improved fertilizer efficiency by 53% (MPTF), 81% (Songani), and 120% (Ekwendeni), respectively (Fig. 2). The SP intercrop system investigated in Songani increased fertilizer efficiency by 116%. Further, by design, on a whole-system basis, fertilizer efficiency was increased, as fertilizer was only applied in one year of two in legume-diversified systems compared with every year in monoculture maize (Fig. 1).

Discussion

Cereal systems dominate African rain-fed cropping (7). The experimentation reported on here provides evidence at scale of benefits from biodiversification. Not all types of diversification were equivalent: temporal systems (rotations) were more effective than spatial systems (intercrops), and long-lived legumes were uniquely suited to producing nutrient-enriched grain, while simultaneously being acceptable to farmers, and supporting efficient, sustainable use of fertilizer.

We found provisioning services were minimal in unfertilized maize, across all sites (∼1 Mg grain ha^{-1}). Improved maize genetics were expected to enhance grain yield, but there was no evidence for this in the absence of fertilizer: hybrid maize produced 1.19 Mg grain ha^{-1} ± 0.19 and local maize 1.37 Mg grain ha^{-1} ± 0.24 (MPTF). The low productivity observed reflects soil degradation and in particular the highly N-deficient status of these soils (24). The nitrophilic nature of the maize crop was illustrated by a consistent response to N fertilizer, which almost doubled yields to 1.61–2.15 Mg ha^{-1}. This response is consistent with the literature (3, 23), and the rationale for Malawi government subsidizes (Fig. S1).

Sustainability. Profitable production in the face of rising input costs is crucial for long-term sustainability of an intensification pathway. If fertilizer prices were to double relative to grain market prices, which has occurred in recent years, then the fertilized, diversified systems tested here remained economically attractive with VCRs >3.6, whereas fertilized monoculture declined to <2.5 (Table S1). The maize-pigeonpea intercrop system in the MPTF was the one exception: there was no increase in VCR compared with VCR of sole maize. Higher VCRs were associated with intercrops at the participatory research sites, which may have been related to long-term educational efforts. The SP rotation system was an outstanding performer countrywide, with VCRs of 7.3–9.4 at historical prices and 4.8–5.1 at higher fertilizer prices. Although a VCR >2.0 is generally considered economically attractive to farmers, a VCR may need to be >4 to support technology adoption by risk-adverse, cash-poor farmers in a highly variable environment (23).

Diversification with legumes is widely promoted in Africa for sustainable productivity of agroecosystems (22). Yet degraded soils and limited access to improved seeds and superior rhizobia have often led to poor performance of annual legumes (19). It was a surprising and welcome result that shrubby SP legumes performed reliably across diverse soil types and precipitation patterns. The mixed systems tested that included pigeonpea, mucuna, and tephrosia appeared to be suited to soil rehabilitation, and did not impose undue competition with the staple cereal. Mechanisms were not studied here, but may have included niche partitioning, facilitation, and compensatory growth (15, 16).

Alarm regarding the sustainability of farming in Africa has often centered on the markedly low levels (8–10 kg ha^{-1}) of fertilizer used, and lack of consistent profitability, which is in part due to technical and administrative barriers to efficient use of fertilizer (3). A major finding from this study was that fertilizer efficiency could be substantially enhanced through diversification with SP legumes: from 24 to 31 kg grain kg N^{-1} in monoculture maize to 38–67 kg grain kg N^{-1} in SP rotation. This gain in efficiency occurred across >1,000 farms, with diverse soil types (soil C by agroecozone ranged from 0.7% to 1.8%) and variable climate (annual rainfall of 660–1,060 mm). These region-wide results are consistent with findings from long-term experimentation in Malawi, where gains in maize fertilizer use efficiency were >100% with an intercropped perennial legume (21). The fertilizer efficiency metric we used provided a conservative measure, and did not indicate the cause, which we expect were related to N inputs from symbiotic fixation and soil biophysical improvements.

Ecosystem services that build soil resources are crucial to ensured or improved response to scarce inputs, and to the stability of this response in the face of inevitable shocks (2). In our study, duration of vegetative cover indicated the potential of the agroecosystem to support complex trophic soil food webs and conserve soil. Annual cropping was associated with 4-mo growth, whereas SP legume systems perennialized by providing an additional 2–6 mo of cover. Soil organic C sequestration is a slow process, so it was not surprising that improved soil C with the SP intercrop system at Songani was a trend, not definitive, and no detectable changes in soil C were found at Ekwdendeni (Table S1).

Reducing Vulnerability. There was no evidence that the staple food crop of southern Africa will be resilient in the face of climate change. The observed CV for maize was 18–30% (Fig. S3), and others have observed even higher variability (CVs of 28–88%) (21). Access to fertilizer may help reduce this exposure, as shown by the reduction in maize yield variability with fertilization (CVs of 12–26%). Variability was further reduced in the SP legume diversified systems (CVs of 9–17%). Our experimentation provides evidence of broad improvements in yield stability, associated with both intensification and diversification (Fig. S3).

Another facet of vulnerability is that of grain quality. On a system-wide basis, fertilized monoculture maize produced about 200 kg ha^{-1} of protein. Adding annual legumes to maize systems produced only slightly more protein-enriched grain (Fig. 2). Technologies with SP legumes, however, consistently produced 50–70% more protein-enriched grain, due to the presence of the SP legume. There is an overwhelming reliance on high-starch staples in Africa, and substantial deficits in terms of nutrient-enriched grains (26), suggesting the value of further research on SP legumes as a protein source.

Through participatory research we documented farmer knowledge concerning ES benefits preferentially associated with SP legumes, such as weed suppression, medicinal products, and fuel. Unique vulnerabilities were highlighted as well, such as the susceptibility to herbivore attack. For example, pigeonpea grain is highly edible with few antiquality factors, but herbivore competition was severe and contributed to the low grain yields observed (Table S1). Mucuna, however, produced high yields of grain with toxic properties that consistently repelled pests, yet extensive postharvest processing is required before it can be consumed (11). Renewed efforts by plant breeders to develop insect-deterrent properties in legumes—without relying on antinutritional biochemistry—would support greener farming.

Scaling Out. The Malawi government is exploring adding legume seed to the portfolio of subsidized inputs (8). There are, however, challenges to this strategy, as shown by our experimentation. Rotation and intercrop systems often produced moderately reduced quantities of grain compared with monoculture maize (Fig. 2), which could be unacceptable to risk-adverse farmers (even though legume grain has enriched value) (19). The notable exceptions were the long-lived legumes, which produced the same quantity of grain as monoculture maize, and fostered enhanced fertilizer efficiency in the year fertilizer was applied. This suggests that shrubby grain legumes could transform the economic viability of fertilizer subsidy policies. At the same time, questions remain regarding the extent to which this technology may be accessible to the poorest farm households, many of whom face severe resource constraints in the form of labor, land, and cash.

Green revolution technologies to date have focused on monocultures. We found integrated use of inorganic fertilizer with diversity from SP legumes was an effective means to support agroecosystem services. There are clearly challenges to broad adoption of legume diversification, but we found evidence for farmer preference for SP legume rotations (Fig. 3), and spontaneous uptake in Ekwendeni (>8,000 farmers). Agroforestry systems such as the SP intercrop faced steep adoption barriers. This was shown by the <8% of farmers in Ekwendeni interested in continued testing of this system (*T. vogelii*-maize), and low ranking by farmers in Songani (12). This system produced no legume grain, with a preponderance of soil-building services. Long time horizons for ES may necessitate government subsidizes and farmer education (22). Supporting this contention is our experience in Ekwendeni, where technology adoption has been facilitated by over a decade of participatory action research on nutrition and agroecology. This suggests that phased integration of the right type of legumes and educational support can help overcome adoption constraints, including labor.

There are initial steps being taken in Malawi (8), including formation of a national legume task force, release of improved varieties, and government support for multiplying legume seeds

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for a future agricultural subsidy program. Agroforestry species are being scrutinized to identify candidates for promotion. As shown here, not all legumes have the same impact on sustainability, nor universally acceptable to farmers. Crucially, the sequential form of agroshrubbry tested here enhanced fertilizer efficiency, profitability, and stability of grain produced. This shows a way forward: rotation of shrubby grain legumes with maize to produce protein-enriched grain and increase affordability of fertilizers to poor farmers as they face increasingly erratic weather. Government expenditure on fertilizer subsidies could be steadily reduced, allowing investments in education, health, and civil society. Fertilizer savings would also conserve fossil fuels, which has long-range environmental benefits and should be an integral part of a "greener" revolution.

Materials and Methods

Countrywide Trial. In the mid-1990s, the Malawi MPTF was tasked by the Ministry of Agriculture to coordinate efforts to improve maize-based farming (10). Maize is commonly planted on >80% of fields; other crops grown include tobacco, cotton at low altitude, and minor crops such as pulses and pumpkins. Hand-hoe agriculture is the norm, and livestock density is very low (19). A series of maize-fertilizer recommendation trials were conducted countrywide by the MPTF, and in 1998 the focus shifted to crop diversification. At over a 1,000 farm sites a MPTF trial was conducted (supervised by front line extension staff) over the 1999[‡] and 2000 growing seasons, where monoculture maize was compared with legume-diversified maize.

Three monoculture treatments were included: (*i*) hybrid maize fertilized with 35 kg N ha^{-1} fertilizer, (*ii*) unfertilized local maize, and (*iii*) unfertilized hybrid maize. Diversified treatments included (*iv*) rotation of maize with a short-duration grain legume (peanut or soybean, depending on agroecological suitability), (*v*) intercrop of maize with pigeonpea, and (*vi*) a SP-rotation system, rotation of maize with *Mucuna pruriens*. In year 2, all treatments except *ii* and *iii* were planted to hybrid maize and fertilized with 35 kg N ha^{-1}. This allowed fertilizer efficiency to be calculated for each treatment: maize yield (after unfertilized hybrid maize yield was subtracted to account for soil N) per unit of N fertilizer applied (2).

The cropping systems tested were chosen based on farmer participatory adaptive experimentation to establish population densities and plant arrangements that did not compromise maize yield, and were consistent with farmer resource-levels and priorities (12, 19). Improved varieties were used for maize (MH17 at midaltitude, and MH18 at low altitude), peanut (CG7), soybean (Magoye), and pigeonpea (ICP9145). Following recommended practice, maize was planted three seeds per planting station for a population density of 37,000 ha^{-1}, in a 0.9 × 0.9-m grid of planting stations along row ridges spaced at 0.9-m intervals. Intercrop species were planted at 0.45-m intervals between maize planting stations, maintaining maize population density in an additive design.

Extension field staff located throughout Malawi were tasked with implementing a single replicate of the trial per farm site, where each treatment was randomly assigned a 6.5 × 9-m plot. Extension staff had previous experience in countrywide trials and were well-trained and supervised with four visits over the growing season by MPTF staff (10). We report here on 991 sites where high-quality data—assessed through site visits, evaluation of trial manual recordkeeping, and data checking—were produced in both years. Grain yields were determined for the net plot: four rows per plot hand-harvested in the field (±10 g accuracy). Subsamples were collected and brought back to the laboratory to determine yield components (grain, residue, and cob), grain moisture content, and dry-weight to fresh-weight conversions. Treatment grain yields were adjusted to a standard 12.5% to account for moisture conversion, and decreased 20% to account for small plot management effects. Protein was calculated using grain conversions, based on literature values and checked against subsamples of grain collected in Songani experimentation: maize 100 g protein kg^{-1}, peanut 210 g protein kg^{-1}, soybean 350 g protein kg^{-1}, pigeonpea 200 g protein kg^{-1}, and mucuna 310 g protein kg^{-1} (11).

A survey conducted at the end of each season documented socioeconomic characteristics of participating farmers, perceptions of benefits and associated costs, and farmer ranking of the technologies.

Participatory Research. The MPTF trials were followed up by participatory action research and detailed examination of acceptable legume systems to labor-constrained smallholders. Two locations in Malawi were the site of adaptive research, initiated in Songani, southern Malawi, in 1996 (12), and in Ekwendeni, northern Malawi, in 1999 (11). The research reported here is for years when intensive monitoring was undertaken, which has not been previously reported on: 1997–1999 in Songani and 2007–2008 in Ekwendeni. The sites were located in midaltitude agroecozones of 1,200–1,500 m above sea level with a mean annual temperature of 21–23 °C and a unimodal rainfall pattern that provided 800–1,100 mm precipitation from November through April. Soils are Ultisols or Alfisols of moderate fertility and well-drained, deep profiles. Songani represents a high-population-density area (160 k^{-2}), and Ekwendeni a moderate population density area (65 k^{-2}).

Participatory research approaches used include surveys, farmer research groups, and the "mother-baby" trial design to evaluate performance of the technologies, and foster farmer-researcher communication (12, 13). Data presented are from "baby trials" where farmers chose three or four promising technology options (one-farmer, one-replicate plots, sized 100 m^2 in Ekwendeni and 64 m^2 in Songani), n = 56 in Songani, and n = 90 in Ekwendeni. The identical recommended crop varieties were used to those described for the MPTF. Farmers were surveyed at the end of the second season to document their assessment of technologies after they had gained experience. Grain yield was monitored, and nitrogen-use efficiency and protein yield calculated as described for MPTF.

The proportion of year with living cover provided an index of soil conservation. Plant residue N measurements were conducted at Songani, where five plants per plot were randomly selected and cut at the base for destructive harvest at maximum biomass (3–4 wk before reproductive maturity). Dry weights were determined in the laboratory after drying at 65 °C. Plant tissues were ground to pass a 1-mm mesh, and total N determined on a subsample by wet acid digestion and colormetric determination. At the Songani site, soil was collected (0–20 cm) in November 1996 and in 1999, a composite sample of 10 subsamples per plot, and similarly, soils were sampled at the Ekwendeni site in 2007. Soils were air-dried, ground, sieved (2-mm sieve), and analyzed using wet acid digestion and colormetric determination of soil organic C.

Analysis. To evaluate profitability, the VCR was calculated on a 2-y basis for fertilized systems compared with a base scenario of monoculture, unfertilized maize (10) using the following equation. VCR = IRR × (product price/input price), where IRR is the input response rate; in this case, maize grain yield response to fertilizer and improved seed after yield of unfertilized maize was subtracted. The market value of grain was determined by multiplying production over 2 y by output prices, using input and output prices were from one point in time (September 2001) (11). Fertilizer price was \$0.42 kg N^{-1}, maize seed \$0.97 kg^{-1}, peanut seed \$0.98 kg^{-1}, pigeonpea seed 0.74 kg^{-1}, mucuna seed \$0.25 kg^{-1}, maize grain \$0.28 kg^{-1}, peanut grain \$0.82 kg^{-1}, pigeonpea grain \$0.35 kg^{-1}, and mucuna \$0.11 kg^{-1}. No discount rate was included for this short-term rotation. Ecosystem service results were evaluated relative to a base system of fertilized monoculture maize, and presented using radial graphs.

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[‡]The year designated is the end of the growing season, because unimodal precipitation in Malawi extends from approximately November to April of the following year.

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