Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa

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Potential interactions between food production and climate mitigation are explored for two situations in sub-Saharan Africa, where deforestation and land degradation overlap with hunger and poverty. Three agriculture intensification scenarios for supplying nitrogen to increase crop production (mineral *fertilizer*, herbaceous legume cover crops—*green manures*—and agroforestry—legume *improved tree fallows*) are compared to baseline food production, land requirements to meet basic caloric requirements, and greenhouse gas emissions. At low population densities and high land availability, food security and climate mitigation goals are met with all intensification scenarios, resulting in surplus crop area for reforestation. In contrast, for high population density and small farm sizes, attaining food security and reducing greenhouse gas emissions require mineral fertilizers to make land available for reforestation; green manure or improved tree fallows do not provide sufficient increases in yields to permit reforestation. Tree fallows sequester significant carbon on cropland, but green manures result in net carbon dioxide equivalent emissions because of nitrogen additions. Although these results are encouraging, agricultural intensification in sub-Saharan Africa with mineral fertilizers, green manures, or improved tree fallows will remain low without policies that address access, costs, and lack of incentives. Carbon financing for small-holder agriculture could increase the likelihood of success of Reducing Emissions from Deforestation and Forest Degradation in Developing Countries programs and climate change mitigation but also promote food security in the region.

carbon sequestration | land-use/cover change | nitrous oxide emissions

Clearing forests and woodlands for agriculture is the primary proximate cause of tropical deforestation (1). The agricultural systems that are established following deforestation vary across regions, from large-scale pastures in the Amazon to commercial tree plantations in Southeast Asia and subsistence agriculture in much of sub-Saharan Africa (SSA). Many of these deforestation fronts are also hot spots of poverty and hunger (2). The overall success of Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) as a climate mitigation strategy for carbon (C) sequestration is linked to agriculture practices. To meet the dual objectives of food security and mitigating climate change, REDD policies must be considered along with policies that explicitly address the livelihoods of impoverished people who depend on these areas for food production and income generation (2).

Nowhere is this nexus of land clearing and degradation with hunger and poverty more pronounced than in SSA, where 65% of the population is rural (3), agriculture comprises 61% of rural livelihoods (4), cereal yields are low and stagnant (5), and 41% of the population lives on less than $1 per day (3). Curbing deforestation and land degradation in SSA requires substantial increases in crop productivity on already cleared lands. Increasing productivity depends on reversing soil nutrient depletion on small-holder farms where decades of nutrient removal through crop harvest and erosion have not been balanced by replenishment (6). Nutrient depletion can be reversed through application of fertilizers from mineral sources, animal manures, and crop residues or through biological nitrogen (N) fixation by green manure cover crops or agroforestry practices such as legume tree fallows.

The net impacts of agricultural intensification on land-use/cover change and the associated greenhouse gas (GHG) emissions for such situations have not been quantified. Prior estimates of GHG emissions from tropical agriculture focus on pastures in the Amazon (7), paddy rice in Asia (8), sugar cane (9), and intensively managed annual crops with high inputs of mineral fertilizers (10). Estimates of net emissions from subsistence agriculture, cropping systems using biological N fixation through legume cover crops and trees, are rare (11–14).

The impact of agricultural intensification on net GHG emissions is complex and requires full life cycle analysis (15, 16). Greater inputs of N increase direct emissions of nitrous oxide (N_2O) from soils while at the same time improving yields and potentially reducing the need to clear forest to meet food requirements. Full accounting of N use needs to include preapplication emissions from manufacturing, packaging, storage, and transport of fertilizer, which can account for half of reported direct N_2O emissions (16). Furthermore, indirect emissions from N that moves from the site of application through volatilization of N as NH_3 and oxides of N (NO_x) or leaching and runoff of NO_3^--N and NH_4^+-N must also be considered (17, 18). These indirect emissions have not been estimated for many systems in SSA. Whereas the fate of biologically fixed N can be similar to that of inorganic fertilizers, agroforestry practices can also increase the total C sequestered in the system (19) and decrease net emissions. Thus the assessment of management practices requires comprehensive accounting that incorporates yields, changes in land-use/cover, N sources, GHG emissions, and C sequestration at a landscape scale over multiple years.

In this paper, we take a step to identify the major potential synergies and trade-offs between food production and global warming potential (GWP), by exploring four contrasting scenarios for increasing food production for two sites in SSA. The two sites, Sauri, Kenya and Mbola, Tanzania, are part of the Millennium Villages Project (MVP), where food insecurity, poverty, and land degradation are high (20). The sites represent distinct but representative agroecosystems of SSA, with maize as the staple

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crop. The sites differ in rainfall, population density, degree of deforestation, and percent of landscape used for annual crops (Table 1 and Table S1). A principal goal of the MVP is to increase crop productivity and food security through a set of interventions recommended by the United Nations Millennium Project Hunger Task Force (2). Interventions include the initial provision of subsidized mineral fertilizers and improved crop germplasm. Fertilizer is applied at recommended rates of 70–90 kg of N per hectare ($\mathrm{kg\,N\,ha^{-1}}$); these are considered cost effective and below the maximum response rates. After a few cropping seasons, legume cover crops and agroforestry practices are promoted as a source of N to partially replace and complement the costly mineral fertilizers and as a source of C to rehabilitate soil organic matter.

Contrasting scenarios for increasing crop production were chosen to explore the range in sources of N, the land area needed to meet food requirements, and the net GHG emissions associated with the different N sources and C fluxes associated with any land-use change. The scenarios are (*i*) *extensification*—by clearing additional land, (*ii*) *fertilizer*—intensification by use of mineral fertilizers as a source of N, (*iii*) *green manure*—intensification with legume cover crops as a source of N, and (*iv*) *improved tree fallow*—intensification with agroforestry by using improved legume tree fallows as a source of N. A simple accounting model estimates and compares each scenario to a baseline for crop productivity and land required to meet the current population's basic caloric requirements. The model determines if increased deforestation is needed to meet caloric requirements or whether intensification would reduce pressure on forest lands thereby making agricultural land available for reforestation activities. Additionally, a partial GWP is generated from the N_2O emissions from different N management strategies and the carbon dioxide (CO_2) emissions or sequestration from land-use/cover change. This analysis is not intended to be an exhaustive investigation of best management practices for crop production; it aims to highlight the potential synergies or trade-offs that might arise between REDD policies and efforts in attempts to dramatically increase food production in SSA. The results from this static accounting approach could be used to target research in SSA on full accounting of agricultural intensification on GHG emissions and to parameterize crop and ecosystem process models that capture the dynamics and interactions of soil and crop management practices, climate variability, and population projections on crop production scenarios and GHG emissions.

Results

Baseline. The conversion of the Miombo woodlands around Mbola, Tanzania to agricultural production is recent and ongoing; 37% of the landscape remains in *dense woody cover* and much of the landscape is designated as *other* (24%), some of which may be suitable for afforestation/reforestation activities. In contrast, the subhumid tropical forests near Sauri in western Kenya were deforested almost 100 years ago. The 8% of this landscape classified as *dense woody cover* consists of small woodlots on farms and hedgerows, 10% of the area was classified as *other*. The population density of Mbola is 17 times lower than Sauri; the average farm size is 3.7 ha, 25% of which is in maize production compared to Sauri, which has a 0.6 ha average farm size, with 67% in maize. *Cropland* accounts for less than half (40%) of the Mbola landscape in contrast to Sauri, where small farms under maize dominate the landscape (82%).

Maize Yields, Basic Caloric Needs, and Land Area Requirements. The baseline case of low crop yields in Mbola produced sufficient maize to meet the basic caloric needs. Because of the low population densities and relative abundance of land, there are larger areas planted to maize (Table 1). Baseline maize yields in Sauri were slightly higher than Mbola, but with high population density and small land holdings, the total maize production was insufficient to meet caloric requirements.

In Mbola, no additional cropland was needed to meet the basic food needs; in fact, 1.7 $\mathrm{km^2}$ of cropland was available for reforestation (Table 2). Of the three intensification scenarios, yields were highest with *fertilizer*, followed by *green manures* and *improved tree fallows*. Even though crop yields with tree fallows were slightly higher than those with cover crops, the time-averaged yields, or annual yields averaged over the course of the crop rotation, were lower for tree fallows because of the period in which the land is out of crop production. These three scenarios all result in more cropland available for reforestation, with the largest land area reforested (5.5 $\mathrm{km^2}$) in the *fertilizer* scenario.

In contrast, for Sauri, an additional 38 $\mathrm{km^2}$ of land was required to meet basic food needs (*extensification*), with the land coming from other cropland and the conversion of land in woody vegetation (deforestation). As with Mbola, all three intensification scenarios produced sufficient maize, though the land-use/cover changes were quite different; only *fertilizer* freed cropland for reforestation, whereas the two scenarios that rely on N fixation required conversion of other cropland to maize. In contrast to Mbola, *improved tree fallow* resulted in higher yields, even time-averaged yields, compared to *green manure* because land is out of maize production and under tree fallows only one out of four years, compared to two out of five years in Mbola.

Carbon Sequestration. In Mbola, basic caloric needs could be met while increasing C stocks across the landscape by 2–6%, through reforestation with woodlots. Reforestation in the *fertilizer* scenario sequestered three times the C as that with *extensification* and almost twice that of *green manure*. By combining the C sequestered through agroforestry and reforestation, the *improved*

Table 1. Total population estimates, yields, and basic caloric needs projected for four management scenarios relative to baseline data for landscapes (100 $\mathrm{km^2}$) of two Millennium Village sites

Site	Management scenarios	Baseline population (people 100 $\mathrm{km^{-2}}$)	Annual maize grain yield ($\mathrm{Mg\,ha^{-1}}$)	Time-averaged maize grain yield ($\mathrm{Mg\,ha^{-1}\,yr^{-1}}$)	Per capita grain yield ($\mathrm{Mg\,person^{-1}\,landscape^{-1}}$)	Required change in maize production area to meet basic caloric needs* (%)
Mbola, Tanzania	Extensification	3,970	1.53	1.53	0.29	−23
	Fertilizer	"	4.43	4.43	0.83	−74
	Green manure	"	1.94	1.94	0.36	−40
	Improved tree fallow	"	2.75	1.65	0.31	−29
Sauri, Kenya	Extensification	68,319	1.70	1.70	0.13	75
	Fertilizer	"	5.40	5.40	0.40	−45
	Green manure	"	2.16	2.16	0.16	37
	Improved tree fallow	"	3.06	2.30	0.17	29

*Basic caloric requirement is 0.219 Mg of maize per person per year.

Table 2. Land-use/cover change and associated projected carbon stocks across the landscape (100 km^2) to achieve basic caloric needs for four management scenarios at two Millennium Village sites

Site	Management scenario	Land-use/cover (km^2)				Total above ground biomass carbon (10^3 Mg C landscape^{-1})			
		Cropland		Reforested cropland	Dense woody cover	Maize to agroforestry	Maize to reforestation	Dense woody cover	Total
		Maize production area	Other crops						
Mbola, Tanzania	Baseline	7.4	32.2	0	36.8	0	0.0	51.5	51.5
	Extensification	5.7	32.2	1.7	36.8	0	0.9	51.5	52.4
	Fertilizer	2.0	32.2	5.5	36.8	0	2.9	51.5	54.4
	Green manure	4.5	32.2	3.0	36.8	0	1.6	51.5	53.1
	Improved tree fallow	5.3	32.2	2.2	36.8	1.0	1.1	51.5	53.6
Sauri, Kenya	Baseline	50.4	31.1	0	8.4	0	0.0	8.8	8.8
	Extensification	88.0	0.0	0	1.9	0	0.0	2.0	2.0
	Fertilizer	27.7	31.1	22.7	8.4	0	9.3	8.8	18.1
	Green manure	69.3	12.2	0	8.4	0	0.0	8.8	8.8
	Improved tree fallow	65.2	16.3	0	8.4	19.8	0.0	8.8	28.6

tree fallow sequestered almost three-quarters that of the *fertilizer*. About half of the C sequestration from the *improved tree fallow* was from the time-averaged woody biomass of the fallow itself, and the other half was from reforestation.

In Sauri, deforestation resulting from *extensification* caused a loss of 78% of an already minor stock of C stored in above ground biomass (AGB) across the landscape. Alternately, reforestation with woodlots made possible with *fertilizer* doubled the amount of C stocks in AGB across the landscape. Higher yields after *green manure* had little impact on C stocks in AGB. *Improved tree fallows*, however, increased the C in AGB more than three times that of baseline and was higher than that of *fertilizer* because of the large area of the landscape converted to a system with high average C stocks.

Nitrous Oxide Emissions. Per hectare N_2O-N estimates followed a similar pattern for each scenario at both sites, although they were lower in Mbola (Table S2). N_2O-N emissions from *fertilizer* were 10–20 times higher than those for *extensification* at Mbola and Sauri, respectively. *Green manure* produced the largest emissions in both sites, 30–60% higher than *fertilizer*. Although the N supplied from *improved tree fallow* was 75% more than that of *green manure*, emissions were only a third to a half that of the *green manure* because they occurred only once every 4 to 5 years, whereas those from the *green manure* were annual.

Partial Global Warming Potential. Combining N_2O emissions (from soil and preapplication fertilizer) and net CO_2 emissions from changes in land-use/cover results in a GWP for the sites. In Mbola, the partial GWP was positive (net mitigation) for all of the scenarios, and the partial GWP for *fertilizer* was 40–200% higher than the other scenarios (Fig. 1) with an offset of 1.0 Mg carbon dioxide equivalents (CO_2e) ha^{-1} because of reforestation. Preapplication fertilizer emissions for both sites were almost two-thirds of the calculated postapplication CO_2e emissions but negligible in contrast to the potential offsets from land surplus (1% and 3% for Mbola and Sauri, respectively). In Sauri, *extensification* resulted in a substantial GWP (negative mitigation), 2.6 Mg CO_2e ha^{-1} emissions, most of which was from deforestation. *Green manure* resulted in the next highest emissions with net losses of 1.0 Mg CO_2e ha^{-1} entirely because of N_2O emissions. In contrast, *fertilizer* and *improved tree fallow* resulted in net offsets for partial GWP emissions (5.3 and 6.8 Mg CO_2e ha^{-1}, respectively).

Discussion

The practice of applying low N inputs to staple food crops in SSA perpetuates hunger and land degradation. It also results

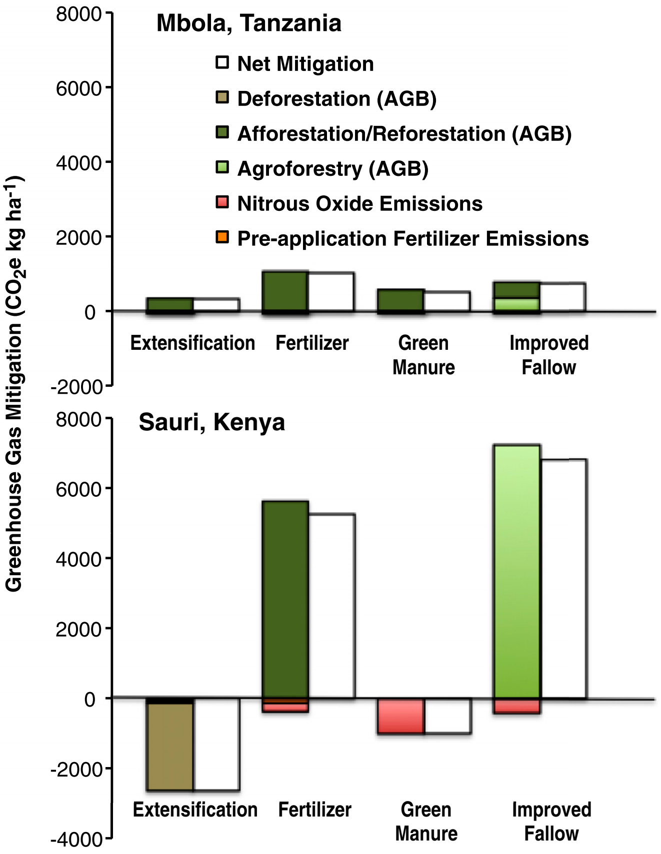

Fig. 1. Projected average per hectare partial global warming potential across the landscape (100 km^2) of two Millennium Village sites if minimum caloric needs were achieved for four management scenarios. Positive values indicate greenhouse gas mitigation, whereas negative values indicate emissions.

in agricultural extensification, continued deforestation, and land degradation, which increase GHG emissions. Agricultural intensification scenarios in two contrasting land-use/cover situations in SSA demonstrate that REDD activities, which include landscape management of agriculture and forestry, could meet food security requirements and contribute to climate change mitigation.

This simple modeling exercise illustrates how synergies or trade-offs between meeting food security and climate mitigation goals depend on several factors, including population density, soils, climate, land availability, and crop and soil management. At low population densities in the case of the Miombo woodlands in Tanzania, multiple N management strategies meet both food requirements and climate mitigation. In contrast, in situations such as western Kenya with high population density, small farm sizes, and little land in woody vegetation, attaining food security and reducing GWP is possible only through agricultural intensification with mineral fertilizers.

Intensification with legume cover crops and tree fallows, in the latter situation, could meet minimal food requirements without deforestation but requires conversion of other cropland to maize and so does not provide C sequestration from reforestation activities. Improved tree fallows do provide substantial GWP offsets through the higher C stocks from AGB compared to baseline and the other scenarios. The food production component of improved fallows might be increased by increasing the length of the cropping relative to that of the fallow phase; time-averaged yields have been higher than unfertilized controls even when tree fallows are shortened to 7 months in higher rainfall areas such as Sauri (21). The benefits of higher yields would have to be weighed against reduced mitigation. This analysis illustrates that, in landscapes already dominated by agricultural production, managing tree fallows for biomass production could play an important role in mitigating GHG emissions without compromising food production.

It is inevitable that intensification scenarios will result in N_2O emissions higher than the baseline situation, because of higher amounts of N added to the crops. The magnitude of that trade-off with increased food production differs across the intensification scenarios. Although there is little data comparing N_2O emissions from mineral fertilizers and legume cover crops or improved tree fallows, some short-term monitoring shows higher emissions from the organic sources (12); similar trends were found by using the Intergovernmental Panel on Climate Change (IPCC) or *Davidson* factors for N_2O emissions. This perhaps surprising result is because higher amounts of N are added from the legume sources, $\sim 110\ \mathrm{kg\,N\,ha^{-1}}$ for Mbola and $\sim 135\ \mathrm{kg\,N\,ha^{-1}}$ for Sauri compared to $80\ \mathrm{kg\,N\,ha^{-1}}$ with mineral fertilizer. There are indications that emissions from organic sources of N are lower than from mineral sources on a per added N basis, which would also lower the N_2O emissions in this analysis (12). As indicated by this partial GWP analysis, it is possible in some situations that these increased N_2O emissions could be offset entirely by reduced deforestation or reforestation.

Several other important factors were not considered in this analysis that could change the results or recommendations considerably. First, food security entails more than meeting the minimal caloric requirements as indicated for Mbola where high levels of undernutrition exist despite the apparent capacity to produce sufficient maize. This discrepancy could be because of many factors: Postharvest losses, which can be as high as 50% of yields, undermine food availability; undernutrition is not just addressed by meeting caloric requirements but also entails a diversified, protein- and nutrient-rich diet; and in Mbola, many farmers concentrate family labor on tobacco production and may divert labor from the maize crop. The factors underlying undernutrition are site specific, and understanding them is critical in appropriately addressing this issue; increasing food production is just the first step. Second, the analysis was for current population levels; in Sauri with its high population density and limited land availability, there is inadequate ability to even meet current needs, and other options such as cash crops and nonagricultural enterprises will be needed to meet food requirements. Third, the "carbon footprint" of fertilizers was determined on the basis of emissions for production and transport for industrial nations. Transport of fertilizers in SSA will require distances up to four times that in Europe and will result in substantially higher emissions. Even with a substantial increase in transport-related emissions, this analysis indicates that the relative contribution of emissions from fertilizers is still minor. Fourth, emissions from fuelwood consumption were not considered and could be equal to or greater than mitigation estimates at both sites. Including wood consumption further illustrates the connection between agricultural lands and the success of REDD because intensification reduces the need for land-use change but could also provide wood requirements with reforestation or tree fallows. Fifth, without proper incentives, higher yields may actually result in more land put into production (22). In fact, recent analyses of land sparing because of increased agricultural yields indicate that without policy and/or financial incentives increased productivity will not curb deforestation (22, 23). Sixth, this static analysis does not account for variability either spatially or temporally. Whereas there has been much work in temperate regions on the dynamic relationship between N_2O emissions and environmental conditions like rainfall and temperature or differences in soil types, there are only a few studies that have looked at this in the humid tropics (24). A better understanding of this relationship in the tropics is needed to model these scenarios with greater realism. Finally, other agroforestry technologies such as rotational woodlot fallows, multistrata perennial cropping, live-fencing, or hedgerows could further improve the mitigation potential of agricultural landscapes, often without compromising food production or acquisition.

Despite the encouraging results from these agricultural intensification scenarios in terms of both food security and climate mitigation, it is unlikely that they will be implemented on a wide scale without substantial changes in policy. The use of mineral fertilizers will remain low in most of SSA because of high costs, limited access, and an absence of subsidy programs. Malawi, an exception to this trend, recently demonstrated that a national fertilizer and improved crop germplasm program could meet the nation's food requirements (25). It is not clear yet whether these programs have had any impact on associated land cover change or reforestation activities.

Incorporation of legume cover crops and improved tree fallows is an important alternative or complement to mineral fertilizers, which have volatile prices and are likely to continue to increase in cost (26). Biological N sources also build soil organic matter and sequester C, which in turn can improve soil fertility, help ensure long-term productivity, and increase the farming system capacity to adapt to climate change. As with mineral fertilizers, widespread adoption of green manures and tree fallows remains low despite massive efforts by agricultural research and extension activities (27). The lack of adoption relates to a variety of factors, including land and labor requirements, forfeit of time and land to growing tree fallows, and land tenure (27). Without adequate financial incentives, these practices are unlikely to be adopted on a large scale regardless of their promised long-term impacts on production.

In order to jointly address food security and climate mitigation in extensive areas of the tropics where deforestation and land degradation overlap with hunger and poverty, policies must address access, cost-benefit ratios, and incentives to increase the adoption of alternative sources of N, including mineral fertilizers, leguminous cover crops, and tree fallows. Preventing extensification into forests will likely require a combination of policy instruments including financial incentives, such as direct payments and fertilizer support, for climate-mitigating land management strategies, the regulation (and/or enforcement of regulations) of forest resources, and extension activities. REDD schemes that can incorporate these instruments may capitalize on the potential synergies between climate mitigation and food security objectives. Thus carbon credit payments for agricultural management practices could play a critical role in ensuring both human well-being and the success of proposed REDD programs.

Methods

Agriculture Scenarios. Estimation of areas under different land-use/cover, maize yields and total maize production, N inputs to maize crops, N_2O emissions, C sequestration, and partial GWP for the baseline and four alternative management scenarios were developed by using a combination of data collected for two MVP sites, data from the literature from locations representative of the MVP sites, and two approaches from the literature for estimating N_2O emissions. The alternative management scenarios were defined as follows:

1. Preintervention management (*baseline*): Baseline maize management assumed farmer practice prior to the MV fertilizer subsidy intervention. N additions to maize at baseline, 4 and 7 $\mathrm{kg\,N\,ha^{-1}}$ per crop for Mbola and Sauri, respectively, were obtained from a baseline survey administered to 300 randomly selected households in Sauri (2005) and Mbola (2006). Maize cropping was assumed to be annual; though in Sauri, two maize crops are often planted per year, the maize yields obtained during the second, short rainy season were small and not considered for this study.
2. Extensification with no increase in N application (*extensification*): If insufficient maize was produced in the baseline situation to meet minimal caloric requirements, then additional land was brought into maize by using the same management and N additions as baseline.
3. Intensification with mineral fertilizer (*fertilizer*): The amount of N fertilizer applied to the improved maize varieties was 80 $\mathrm{kg\,N\,ha^{-1}}$ per crop for both Mbola and Sauri and reflected local agricultural extension recommendations. As with *baseline*, maize cropping was assumed to be on an annual basis.
4. Intensification with legume cover crops (*green manure*): *Mucuna pruriens* is the most commonly used cover crop in the region. For this scenario, it is assumed that the cover crop is grown as a sole crop without fertilizers in the offseason in Mbola and interplanted with a maize crop in Sauri. Mucuna is incorporated into the soil for the subsequent cropping season, so that no cropping season is foregone to produce the cover crop. N inputs to the subsequent maize crop were based on literature values of N contents of *M. pruriens* after <5 months of growth. The average N added was 107 and 136 $\mathrm{kg\,N\,ha^{-1}}$ per crop for Mbola and Sauri, respectively (Table S3).
5. Intensification with agroforestry and the use of legume tree fallows (*improved tree fallow*): The improved tree fallow–maize rotations used in this scenario were based on those used more broadly in SSA (28). For Mbola, two years of improved tree fallow growth was followed by three years of maize cropping, and for Sauri, given the higher rainfall and productivity, one year of improved tree fallow was followed by three years of maize cropping. Total N added to the maize crop from the tree fallows were estimated from values in the literature, and the average N added was 185 $\mathrm{kg\,N\,ha^{-1}}$ for Mbola at the end of the two-year fallow or an average of 37.5 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ for the five-year crop–fallow rotation and 241 $\mathrm{kg\,N\,ha^{-1}}$ for Sauri at the end of the one year fallow or an average of 60.4 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ for the four-year rotation (Table S3).

Scenario Maize Yields, Basic Caloric Needs, and Land Area Requirements. Maize yields for the *baseline, extensification,* and *fertilizer* scenarios were estimated from field measurements on 30 or more randomly selected farms in the two MV sites that received recommended rates of fertilizer or were continuing to use baseline practices; maize was sampled from one to three quadrants of 3×3 m^2 randomly placed in fertilized or control maize fields. Maize yields for the *green manure* and *improved tree fallow* scenarios were estimated from the yield response ratios from an extensive meta-analysis from SSA (29). The response ratio compared to unfertilized maize was 1.3 and 1.8 for green manures and improved tree fallows, respectively. In the improved tree fallow scenario, maize is produced three out of five years in Mbola and three out of four years in Sauri; a time-averaged yield was calculated as the average per hectare annual maize yield multiplied by the three growing seasons and divided by the duration of the entire maize/fallow rotation.

The crop area required to meet basic caloric needs was estimated for baseline and each of the scenarios by first determining the maize production needed to meet village caloric requirements and then dividing by the yields produced by the various scenarios. Time-averaged maize yields were used in the case of improved legume tree fallows. Target per person grain yields of 219 kg of maize yr^{-1} were defined by the amount of maize needed to meet basic caloric requirements of 2,100 calories per day (30). In cases where yields and area cropped to maize were insufficient to meet basic caloric requirements, then it is assumed that other agricultural land, which includes natural fallows and other crops, would first be converted to maize production. If all the baseline agricultural lands were still insufficient, then "deforestation" or cutting areas under trees was necessary; conversely, if the yields and maize area were more than enough to meet basic caloric needs, then land in maize production at baseline was converted to woodlots.

The landscape considered for the baseline site description and for land-use/cover change is based on a 100-km^2 area encompassing each village site. The percent area under different land cover categories was assessed by sampling 160, 1, 000-m^2 plots stratified randomly in 10 blocks across the landscape. Plots were sampled by using a field protocol on the basis of the standard Food and Agriculture Organization Land Cover Classification System definition (31) that distinguishes: (*i*) *cropland*, defined as an area currently under cultivation, including annual and perennial food crops and short-term fallows. The area of cropland planted specifically to maize was estimated from the household surveys in the MV sites. (*ii*) The area with *dense woody cover*, defined as having >40% woody canopy cover. (*iii*) Land that did not fit these two categories was classified as *other*.

Carbon Sequestration. For this partial analysis, only aboveground C stocks in areas with dense woody vegetation cover (forests, woodlands, woodlots), C in improved tree fallows, and changes in these stocks were considered. C stocks in the Miombo woodlands of Mbola were 19.0 $\mathrm{Mg\,C\,ha^{-1}}$ (32); shrub and tree hedges in Sauri were 10.5 $\mathrm{Mg\,C\,ha^{-1}}$ (33). C accumulation rates and stocks in the improved tree fallows were estimated from studies in similar agroecological zones with mean values of 9.1 $\mathrm{Mg\,C\,ha^{-1}}$ at the end of a 2-year fallow for Mbola and mean of 12.1 $\mathrm{Mg\,C\,ha^{-1}}$ at the end of a 1-year fallow for Sauri (Table S3). Areas available for reforestation were assumed to be planted to woodlots; the C accumulation rates, rotation times, and C stocks at the end of these rotations were estimated to be 5.3 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ over the 5-year rotation for Mbola (34) and 12.2 Mg $\mathrm{C\,ha^{-1}\,yr^{-1}}$ for Sauri over the 2-year rotation (35). These rates and stocks were used to model C stored on maize lands planted to improved tree fallows and maize (and crop) land converted to woodlots for each scenario. Both the improved tree fallows and woodlots are rotations, so the average C stock, or time-averaged C, was used to represent the difference of growth minus harvest through time (19). C was assumed to be 50% of the woody biomass, and estimates for the stocks in each land-use/cover were reported for the entire landscape (100 km^2). Deforestation as a result of the conversion to agricultural land was assumed to result in the complete consumption and emissions of C from mature standing woodlots, woodlands, or hedgerows (e.g., fuelwood for cooking).

Nitrous Oxide Emissions. N_2O emissions following N additions were estimated by using two factors: (*i*) the IPCC protocol (18) and (*ii*) a method proposed by Davidson (17). The *IPCC* "bottom-up" method assumes 1% of applied N is directly emitted as N_2O-N with a given uncertainty range of 0.3–3% (18). Information needed to estimate the indirect emissions as outlined in the IPCC protocol is essentially not available for SSA. Alternatively, the Davidson "top-down" approach accounts for direct and indirect losses and estimates 2.2% (range of 1.5–2.4%) of applied N will result in N_2O-N emissions. N additions from the improved tree fallows occur only one out of five years in Mbola and one out of four years in Sauri; thus the N_2O emissions were adjusted as time-averaged values similar to that done for C stocks and N inputs in the *improved tree fallow* scenario.

Partial Global Warming Potential. A partial net GWP was estimated for all scenarios and includes preapplication fertilizer emissions, N_2O and CO_2 emissions, and C sequestration. Neither methane emissions nor changes in belowground C were considered. All GHG emissions and offsets were converted to CO_2e. Preapplication fertilizer emissions were derived from mean emission values per kilogram of applied N and phosphorus (P) fertilizers from the literature (36). Annual N_2O emissions were calculated from *Davidson* (17) on the basis of total N applied for the year. Emissions or offsets for land-use/cover change were estimated from changes in AGB resulting from deforestation, reforestation, or improved tree fallows. All partial GWP values are time-averaged and reported as an average for the entire landscape on a per hectare basis.

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