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# Agroforestry with N<sub>2</sub>-fixing trees: sustainable development's friend or foe?

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Legume tree-based farming systems sit at a crucial nexus of agroecological sustainability. Their capacity to support microbial N<sub>2</sub> fixation can increase soil nitrogen (N) availability and therefore improve soil fertility, crop yields, and support long-term stewardship of natural resources. However, increasing N availability oftentimes catalyzes the release of N into the surrounding environment, in particular nitrous oxide (N<sub>2</sub>O) — a potent greenhouse gas. We summarize current knowledge on the agroecological footprint of legume-based agroforestry and provide a first appraisal of whether the technology represents a pathway toward sustainable development or an environmental hazard.

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## Too little nitrogen

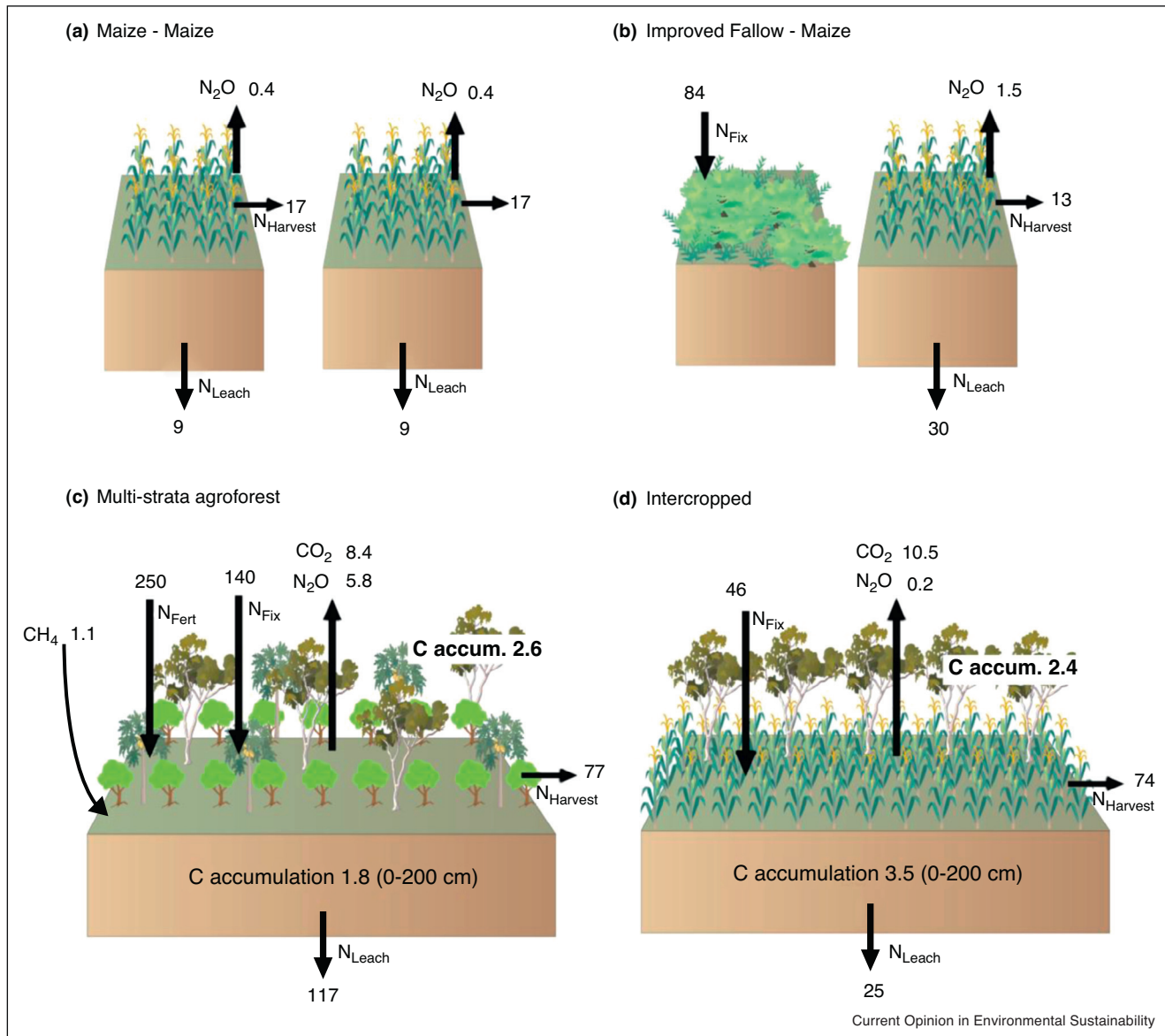
Nitrogen constrains plant productivity in terrestrial ecosystems, including agricultural fields [1]. Farmers typically overcome nitrogen (N)-limitation by supplementing

the soil N pool with organic material (e.g. manures or residues) or chemical fertilizer to stimulate crop growth. Farming, without replenishing the N exported as crop harvest, depletes soil nutrient reserves and degrades the long-term productive capacity of the land. Nutrient mining from continuous farming is of particular concern in sub-Saharan Africa (SSA) where N fertilizer use, in any form, is extremely limited [2]. Farmers typically use less than 10 kg of mineral N ha<sup>-1</sup>, if any at all [3], and the lack of available land and labor limits the application of organic fertilizers [4]. Low N use, poor prospects for increasing application, and the consequential soil degradation threaten regional food security and agricultural-based development.

Unequivocally, SSA farmers must apply more N to increase food production and improve livelihoods, and some development organizations and governments have initiated fertilizer subsidy and distribution programs to achieve this goal. This approach may represent the most rapid way to introduce plant available N into fields at the rate and scale necessary to match population growth and food demand. However, the long-term sustainability of such schemes remains questionable. For example, fertilizer subsidies helped Malawi transition to a net food exporter by raising maize yields country-wide [5]; however, the high maintenance costs of the program coupled with elevated governmental oversight at the expense of other sectors threaten its continuation. Concerns over chemical fertilizer use extend beyond economic considerations. In developing regions where inorganic fertilizer is readily available at low costs (e.g. China), its overuse is ubiquitous [3,6]. Excess fertilizer use contributes to a suite of negative environmental outcomes including climate change, eutrophication, tropospheric ozone depletion, and loss in biodiversity and species extinctions [7].

The integration of legume trees into agricultural systems offers an alternative strategy to increase N availability in cropping systems without increasing mineral N additions. Legumes, in association with root symbionts, transfer N<sub>2</sub> from the atmosphere to the biosphere. This biologically 'fixed' N<sub>2</sub> becomes available to crop plants when plant tissues (e.g. root and leaf litter) decompose. Though the entire amount of fixed N<sub>2</sub> is not readily crop-available instantaneously, the amount that is can equal or exceed that needed by associated crop plants [8\*,9]. Rates of N<sub>2</sub> fixation by legume trees can vary greatly by species as well

Figure 1



Partial nutrient balances in select cropping and agroforestry systems with N-fixing trees. Data sources for A and B [11,51], C [27,41\*\*,50], and D [8\*,32,51,52].  $NO_3^-$  leaching for C and D estimated as 30% of N inputs [8\*,32]. The proportion of litterfall N that came from N-fixation was 57% in *Inga* [53] and 50% in *Gliricidia* [54]. All N fluxes are reported in  $kg\ N\ ha^{-1}\ yr^{-1}$ . C accumulation,  $CO_2$  and  $CH_4$  are reported in  $Mg\ C\ ha^{-1}\ yr^{-1}$ . All mass values pertain to the N or C component of  $N_2O$ ,  $CH_4$ , and  $CO_2$ .

as soil N status, and can range from 5 to greater than  $300\ kg\ N\ ha^{-1}\ yr^{-1}$  [4,10] (Figure 1). Despite variable  $N_2$  fixation rates, legume trees provide a mechanism for increasing N in farming systems.

Legume-based agroforestry encompasses a diverse array of farming systems; the only common denominator being the inclusion of leguminous shrubs or trees with crops or in crop rotations. We categorized legume-based agroforestry systems into three main types: (1) intercropped, (2) multi-strata agroforests, and (3) improved fallows (Table 1;

Figure 1). Within these classes, farmer decisions alter the crop, legume species, and extent of tree management, which in turn influence carbon (C) and N cycling, retention, and loss [11] (Figure 2). Despite such nuances, our simple typology provides a useful lens through which to examine agricultural development and natural resource trade-offs.

Introduction of additional N into the plant-soil-microbe system via legume trees is not devoid of environmental consequences. Legume-derived N, once converted into

Table 1

## Select legume-based agroforestry systems.

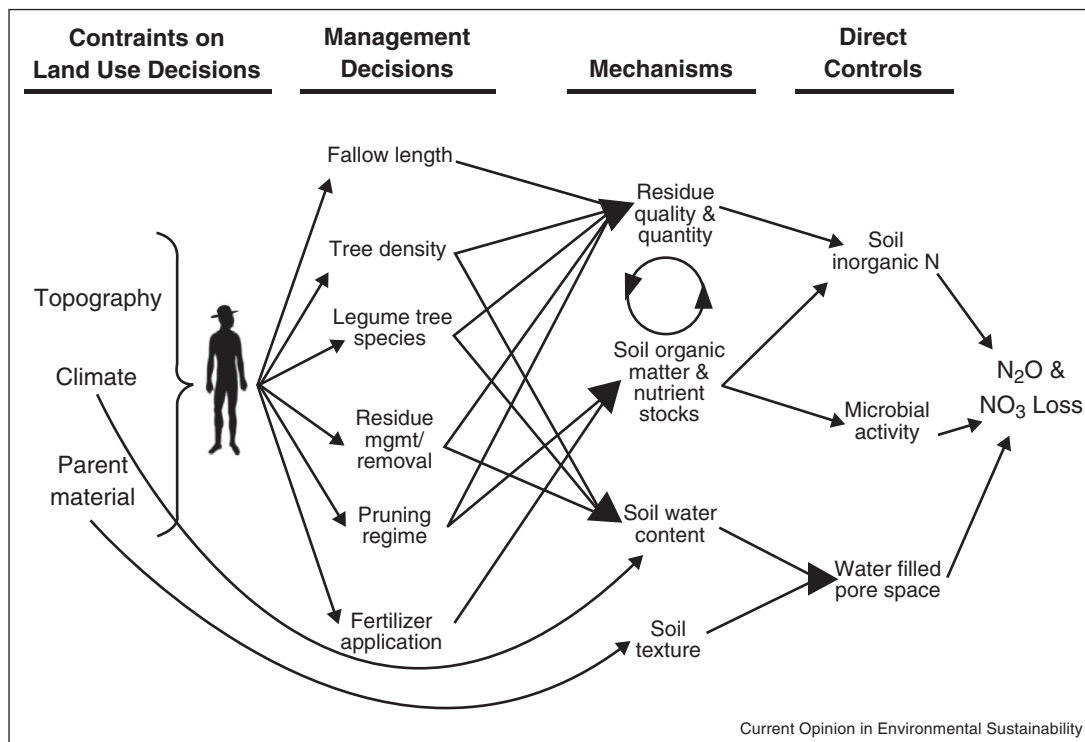
Characteristic	Agroforestry system		
	Intercropped	Multi-strata	Improved fallow
Climate	Arid to wet tropics	Wet tropics	Semi-arid to humid sub tropics
Common legume species	<i>Faidherbia</i> , <i>Acacia</i> , <i>Gliricidia</i> , <i>Caleandra</i>	<i>Inga</i> , <i>Erythrina</i> , <i>Eucalyptus</i> ,	<i>Acacia</i> , <i>Sesbania</i> , <i>Gliricidia</i> , <i>Tephrosia</i>
Primary crop species	Maize, Sorghum, Shea	Cocoa, Coffee, Vanilla, Spices, Tree-fruit	Maize, beans
Key C and N cycling interaction	Accumulates C in biomass, coppiced to affect N releases and	Accumulates C in biomass, pruning affects N releases	N released before significant crop development
Management intensity <sup>a</sup>	High	Moderate	Low
Geographic distribution	Sahel Sub-Saharan Africa India	Latin America, Southeast Asia, Highlands East Africa, Forested West Africa	Sub-Saharan Africa Latin America
Production orientation	Subsistence	Markets, Subsistence	Subsistence

<sup>a</sup> Relative among systems.

mineral form, cannot be differentiated from mineral-derived N, and is therefore subject to the same pathways for loss. In particular, concerns have been raised about its potential to increase biogenic soil emissions of N<sub>2</sub>O — a powerful greenhouse gas [12,13]. Thus, the use of legume trees may induce a trade-off between competing livelihood and environmental objectives in tropical developing countries. Economic concerns have also been raised as several efforts to introduce legume trees in agricultural system have low rates of farmer-adoption

due to small returns on labor and issues of land tenure [14]. Here, we synthesize information on the evolution of N<sub>2</sub>O from agricultural systems intercropped with legumes to evaluate these prospective trade-offs. We then extend our assessment to the major agricultural greenhouse gases — carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) — and to nitrate (NO<sub>3</sub><sup>-</sup>) leaching because of the cascading effects legume trees can have on C and N cycling and the potential for unintentional environmental harm.

Figure 2



Factors contributing to N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup> loss from N<sub>2</sub>-fixing production systems and management decisions that drive these N losses.

### Trade-offs with N<sub>2</sub>-fixing trees

Leguminous agroforestry — through deposition and decomposition of litter and biomass — can increase soil mineral N and hence improve soil health [15,16]. The expected extent of soil N change is species-dependent and environment-dependent and thus may not always increase in the presence of legumes [17]. However, when soil N increases, leguminous agroforestry tends to generate higher yields than farmers' (non-fertilized) practice. A 13-year trial on sites in Malawi and Zambia found intercropped *Gliricidia sepium*-maize yields were 42% greater than non-fertilized fields and similar in magnitude to fertilized maize yields (receiving 92 kg mineral N ha<sup>-1</sup>). Moreover, yields were more stable over time at the *Gliricidia sepium*-maize sites [8<sup>\*</sup>] compared to the fertilized sites. Integrating legume trees into fallow periods between crops (known as improved fallows; Figure 1b) also increases production in some systems. Sorghum yields increased by 55% in the two seasons following *Gliricidia* by comparison to traditional fallows (where native vegetation is allowed to cover the field when not cultivated) [18]. However, yield is not always the appropriate metric for evaluating the benefits of leguminous agroforestry. For example, in Latin America, crop yields are lower in coffee agroforests compared to highly fertilized monocultures [19]. However, agroforests retain greater ecosystem function such as increased soil organic matter, higher biodiversity, reduced soil compaction, and higher N retention [20<sup>\*</sup>,21].

In comparison to monoculture maize, which receives no fixed N (Figure 1a), legume trees in the three focal agroforests add between 46 and 140 kg N ha<sup>-1</sup> yr<sup>-1</sup> to the cropping system (Figure 1b–d). Nevertheless, introduction of recycled N into soils may stimulate emissions of N<sub>2</sub>O via nitrification and denitrification [17,22,23]. Emissions from legume-based agroforests tend to be three to seven times greater than natural forest or non-fertilized non-forested cropped systems due to more rapid N cycling [24,25] and reported values range from less than 1 to 5.8 kg N ha<sup>-1</sup> yr<sup>-1</sup> (or 0.1–1.9% of N inputs) depending on residue quality and quantity, temperature and soil water content [9,24,26,27]. The large variation is not surprising, as legume-based agroforests span species, soil types, climatic, and management regimes. Though the rate of N<sub>2</sub>O evolution varies considerably, most investigations report fluxes toward the lower end of the range (e.g. less than 2 kg N ha<sup>-1</sup> yr<sup>-1</sup>, [9,17]).

Data characterizing soil emissions from systems where leguminous trees have been introduced in SSA are limited in terms of species, farming system, and length of study and thus it is difficult to draw conclusions about emission outcomes. For example, there are no flux data from the multi-strata agroforestry systems that dominate coffee and cocoa growing regions of West and East Africa and only a few from tropical climates globally

[20<sup>\*</sup>,24,27,28]. Other studies rely on short-term, seasonal investigations or laboratory incubations [25,29,30] that may not mimic field dynamics. However, N<sub>2</sub>O measurements in agroforestry systems with N<sub>2</sub>-fixing trees from tropical regions — and data from improved fallows in SSA suggest that N<sub>2</sub>O emissions are approximately equal to or often less than that from mineral fertilizer, ~1% of N inputs [31]. We therefore conclude that legume-based agroforestry is unlikely to contribute an *additional* threat to increasing atmospheric N<sub>2</sub>O concentrations, by comparison to the alternative (e.g. mineral fertilizers). More data, however, are required to determine their impact on regional greenhouse gas budgets in absolute terms.

By modifying nutrient cycles, legume trees amplify and/or suppress exchanges of greenhouse gases other than N<sub>2</sub>O between the biosphere and the atmosphere. First, leguminous agroforestry systems accumulate C in woody biomass (when conserved in situ) [32,33], store C deeper in the soil profile and in more stable soil aggregates [34–36], and enhance soil C sequestration by stimulating growth [37] (Figure 1c,d). Second, legume tree systems may affect biosphere-atmosphere CH<sub>4</sub> exchanges too. Increased soil N availability can suppress CH<sub>4</sub> consumption in aerobic soils [38] or stimulate CH<sub>4</sub> oxidation in formerly N limited soils [39], though the rates are driven by soil texture, soil moisture and soil disturbance [40].

The multitude and counterbalancing effects of C and N cycling suggest it is appropriate to use full-accounting approaches inclusive of all greenhouse gas effects when evaluating the climate outcomes of legume-based agroforestry systems. Unfortunately, N and C emissions, uptake, and accumulation in soils, atmosphere, and biomass are typically investigated in isolation. Calculating a robust balance is largely not feasible with current data because the calculus would require extrapolation across sites and systems that differ in the major drivers of flux (e.g. N availability, species composition, legume tree management, soil type, climate, among others; Figure 2). A recent study highlights the need for wider adoption of full accounting approaches. Soil N<sub>2</sub>O fluxes were 35% greater in coffee agroforests shaded by legume trees versus monocultures. However, the agroforests' net annual radiative forcing was 280% less than the monoculture when considering C accumulation in biomass and soils [41<sup>\*\*</sup>]. The evaluation of farming systems should be taken one step further still to include productivity assessments when identifying sustainable agricultural innovations is the goal. Global warming potential can be 'yield-scaled' to internalize and quantify production and climate trade-offs enabling multi-gas, multi-impact and multi-system comparisons. Yield-scaled global warming potential is an increasingly common indicator to analyze system level outcomes in agronomy [42<sup>\*\*</sup>] but has yet been applied in tree-based systems (see partial application in [43<sup>\*</sup>]). Future research investigating

emissions in agroforestry systems with N<sub>2</sub>-fixing trees should apply such compound metrics to better represent livelihood-environmental trade-offs.

On the basis of the available information, we suspect that concerns over N<sub>2</sub>O evolution from N<sub>2</sub>-fixing trees (in the context of the sustainable development conversation) are unwarranted due to: (1) the relative similarity among fluxes arising from soils planted with N<sub>2</sub>-fixing trees and those fertilized with mineral N, (2) the potential for some legume-based agroforests to represent a net sink for greenhouse gases, specifically due to the positive effect of leguminous trees on biomass C and soil C sequestration, and (3) the potential boost in yield as a result of higher N-inputs.

Still, N intensification in any form can have environmental consequences. Mineral N is lost from the plant-soil-microbe system in many ways and alternative loss pathways might present additional threats, especially for local populations. Leguminous trees elevate surface NO<sub>3</sub><sup>-</sup> concentrations in soils and soil water due to the decomposition of high quality biomass [44]. Soil N (0–200 cm) can increase by 136 kg N ha<sup>-1</sup> yr<sup>-1</sup> following improved fallows, and this additional N may be subject to leaching losses [45]. Movement of NO<sub>3</sub><sup>-</sup> through the soil system contaminates local drinking water supplies and ecosystems. Recent work in W. Kenya suggests that N losses to surface waters persist for decades following conversion to agriculture and increase over time [46]. However, unlike shallow-rooted annuals, trees (leguminous and not) can buffer against NO<sub>3</sub><sup>-</sup> losses by scavenging available N once it passes below the rooting depth of crops [19,47]. Thus, while surface soil NO<sub>3</sub><sup>-</sup> may be elevated in legume-based agroforests, it is unlikely that this NO<sub>3</sub><sup>-</sup> will ultimately be lost from the system. Nevertheless, in comparison to gaseous losses of N<sub>2</sub>O, NO<sub>3</sub><sup>-</sup> losses from legume trees have received little attention [48]. Given the potential environmental and human health effects, more attention should be paid to solution N losses from legume trees.

### Toward multi-impact management

Though relatively few data are available about N loss (N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup>) from tropical soils planted with N<sub>2</sub>-fixing trees, we can identify the mechanisms driving loss such as residue quantity and quality and soil moisture (Figure 2). Accordingly, we should be able to identify, with reasonable certainty, the systems and factors that create conditions conducive to N losses. This information can guide the design of integrated management strategies that balance agricultural and environmental trade-offs. Strategies should focus on synchronizing legume-N availability with crop demand [49] and may include such techniques such as (1) delaying pruning until only weeks before planting, (2) planting diverse legume mixes to maximize residue decomposition profiles [25], and (3)

abandoning practices where N release is poorly timed [48]. Since the factors that regulate gaseous and leaching losses are congruent (e.g. moisture, N availability), there is a strong probability that win-win-win systems can be created. However, identifying practices and management systems that create a triple-win across productivity, climate, and water quality will require a fundamental departure from the historic trajectory of agroforestry and environmental impact research that have largely focused on productivity gains or single media (e.g. air or water) alone.

Even in legume-based agroforestry systems there are trade-offs between crop production and environmental impacts. Concerns of excessive N<sub>2</sub>O production and disruption of regional greenhouse gas balances should be taken seriously; however, in light of the growing need to produce more food and introduce N into cropping systems in resource-challenged regions, the integration of N<sub>2</sub>-fixing trees on farms represents a viable option in many systems and it is worth determining whether these systems can contribute to low-emission agricultural development. Perhaps equally crucially, legume-based agroforestry has the potential to transfer substantial amounts of nitrate into local water supplies increasing concentrations above the safe drinking levels, however data are scarce. Advocates of agroforestry with N<sub>2</sub>-fixing trees would do well to orient their attention to global environmental services (e.g. climate regulation) and locally relevant services (e.g. food production and water quality) simultaneously.

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Results of this paper demonstrate the importance of using a full accounting approach when evaluating the GHG impacts of leguminous agroforestry systems. The multi-strata agroforestry system produced more N<sub>2</sub>O emissions than the monoculture when considering N<sub>2</sub>O alone. But the net radiative forcing effect of the agroforestry systems was less when taking CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O exchanges into account

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