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Agroforestry with N_2-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_2 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_2O) — 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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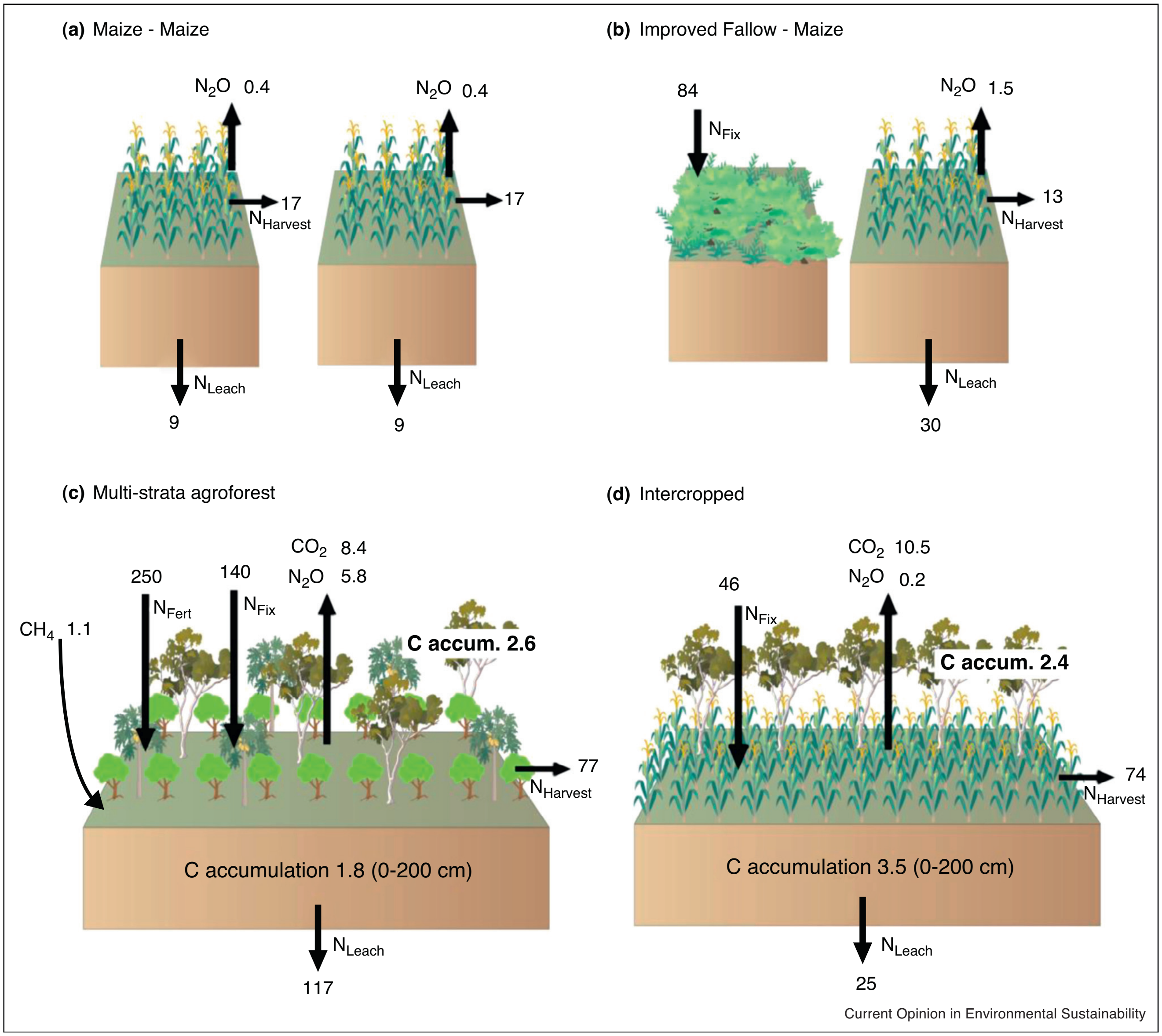
Too little nitrogen

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^{-1}, if any at all [3], and the lack of availabile 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_2 from the atmosphere to the biosphere. This biologically 'fixed' N_2 becomes available to crop plants when plant tissues (e.g. root and leaf litter) decompose. Though the entire amount of fixed N_2 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_2 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

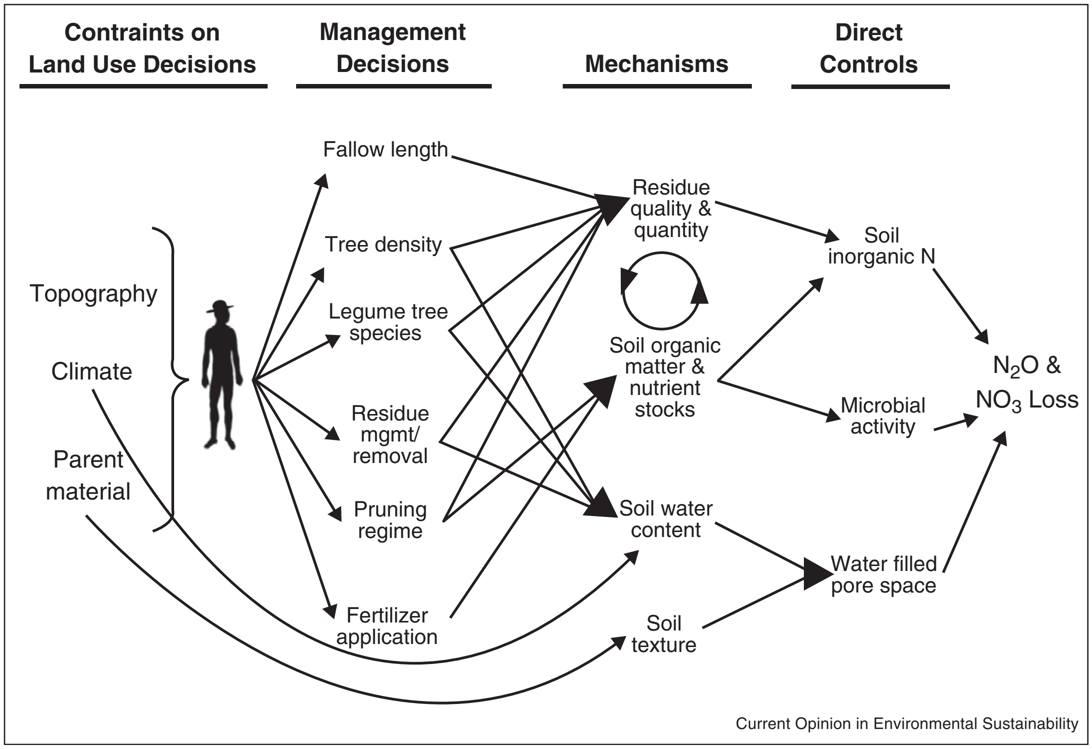
Select legume-based agroforestry systems.

Characteristic	Agroforestry system		
	Intercropped	Multi-strata	Improved fallow
Climate	Arid to wet tropics	Wet tropics	Semi-arid to humid sub tropics
Common legume species	*Faidherbia, Acacia, Gliricidia, Caleandra*	*Inga, Erythrina, Eucalyptus*,	*Acacia, Sesbania, Gliricidia, Tephrosia*
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[a]	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

[a] 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_2O — 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_2O 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_2) and methane (CH_4) — and to nitrate (NO_3^-) 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_2O and NO_3^- loss from N_2-fixing production systems and management decisions that drive these N losses.

Trade-offs with N_2-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 *Gliricida sepium*-maize yields were 42% greater than non-fertilized fields and similar in magnitude to fertilized maize yields (receiving 92 kg mineral N ha^{-1}). Moreover, yields were more stable over time at the *Gliricidia sepium*-maize sites [8•] 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•,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^{-1} yr^{-1} to the cropping system (Figure 1b–d). Nevertheless, introduction of recycled N into soils may stimulate emissions of N_2O 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^{-1} yr^{-1} (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_2O evolution varies considerably, most investigations report fluxes toward the lower end of the range (e.g. less than 2 kg N ha^{-1} yr^{-1}, [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•,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_2O measurements in agroforestry systems with N_2-fixing trees from tropical regions — and data from improved fallows in SSA suggest that N_2O emission 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_2O 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_2O 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_4 exchanges too. Increased soil N availability can suppress CH_4 consumption in aerobic soils [38] or stimulate CH_4 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_2O 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••]. 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••] but has yet been applied in tree-based systems (see partial application in [43•]). Future research investigating emissions in agroforestry systems with N_2-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_2O evolution from N_2-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_2-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_3^- 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^{-1} yr^{-1} following improved fallows, and this additional N may be subject to leaching losses [45]. Movement of NO_3^- 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_3^- losses by scavenging available N once it passes below the rooting depth of crops [19,47]. Thus, while surface soil NO_3^- may be elevated in legume-based agroforests, it is unlikely that this NO_3^- will ultimately be lost from the system. Nevertheless, in comparison to gaseous losses of N_2O, NO_3^- 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_2O and NO_3^-) from tropical soils planted with N_2-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_2O 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_2-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_2-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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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA: **Transformation of the nitrogen cycle: recent trends, questions, and potential solutions**. *Science* 2008, **320**:889-892.
2. Sanchez PA: **Soil fertility and hunger in Africa**. *Science* 2002, **295**:64-65.
3. Vitousek PM, Naylor RL, Crews TE, David MB, Drinkwater LE, Holland EA, Johnes PJ, Katzenberger J, Martinelli LA, Matson PA *et al.*: **Nutrient imbalances in agricultural development**. *Science* 2009, **324**:1519-1520.
4. Vanlauwe B, Giller KE: **Popular myths around soil fertility management in sub-Saharan Africa**. *Agric Ecosystems Environ* 2006, **116**:34-46.
5. Denning G, Kabambe P, Sanchez P, Malik A, Flor R, Harawa R, Nkhoma P, Zamba C, Banda C, Magombo C *et al.*: **Input subsidies to improve smallholder maize productivity in Malawi: toward an African green revolution**. *PLoS Biol* 2009, **7**:e23.

6. Erisman JW, Sutton MA, Galloway JN, Klimont Z, Winiwarter W: **How a century of ammonia synthesis changed the world**. *Nat Geosci* 2008, **1**:636-639.

7. Erisman JW, Galloway JN, Seitzinger SP, Bleeker A, Butterbach-Bahl K: **Reactive nitrogen in the environment and its effect on climate change**. *Curr Opin Environ Sustain* 2011, **3**:281-290.

8. • Sileshi GW, Debusho LK, Akinnifesi FK: **Can integration of legume trees increase yield stability in rainfed maize cropping systems in Southern Africa?** *Agron J* 2012, **104**:1392-1398.

This paper suggests that intensively managed intercropped legume tree-maize system can significantly outperform nonfertilized maize counterparts and similarly to fertilized maize under some conditions.

9. Chikowo R, Mapfumo P, Nyamugafata P, Giller KE: **Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe**. *Plant Soil* 2004, **259**:315-330.

10. Ajayi OC, Place F, Akinnifesi FK, Sileshi GW: **Agricultural success from Africa: the case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe)**. *Int J Agric Sustain* 2011, **9**:129-136.

11. Mapfumo P: **Comparative analysis of the current and potential role of legumes in soil fertility in management in Southern Africa**. In *Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management.* Edited by Bationo *et al.*: Amsterdam: Springer; 2011.

12. Mutuo PK, Cadisch G, Albrecht A, Palm CA, Verchot LV: **Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics**. *Nutr Cycling Agroecosyst* 2005, **71**:43-54.

13. Verchot LV, Van Noordwijk M, Kandji ST, Tomich TP, Ong C, Albrecht A, Mackensen J, Bantilan C, Anupama KV, Palm CA: **Climate change: linking adaptation and mitigation through agroforestry**. *Mitigation Adapt Strategies Global Change* 2007, **12**:901-918.

14. Sumberg J: **The logic of fodder legumes in Africa**. *Food Policy* 2002, **27**:285-300.

15. Aranguren J, Escalante G, Herrera R: **Nitrogen cycle of tropical perennial crops under shade trees. I. Coffee**. *Plant Soil* 1982, **67**:247-258.

16. Glover N, Beer J: **Nutrient cycling in to traditional Central American agroforestry systems**. *Agroforestry Systems* 1986, **4**:77-87.

17. Verchot LV, Brienzajunior S, Deoliveira V, Mutegi J, Cattânio JH, Davidson EA: **Fluxes of CH_4, CO_2, NO, and N_2O in an improved fallow agroforestry system in eastern Amazonia**. *Agric Ecosyst Environ* 2008, **126**:113-121.

18. Hall NM, Kaya B, Dick J, Skiba U, Niang A, Tabo R: **Effect of improved fallow on crop productivity, soil fertility and climate-forcing gas emissions in semi-arid conditions**. *Biol Fert Soils* 2005, **42**:224-230.

19. Tully KL, Lawrence D: **Closing the loop: nutrient balances in organic and conventional coffee agroforests**. *J Sustain Agric* 2011, **35**:671-695.

20. • Tscharntke T, Clough Y, Bhagwat Sa, Buchori D, Faust H, Hertel D, Hölscher D, Juhrbandt J, Kessler M, Perfecto I *et al.*: **Multifunctional shade-tree management in tropical agroforestry landscapes — a review**. *J Appl Ecol* 2011, **48**:619-629.

This paper provides a good survey of the positive and negative affects agroforestry species in general and in some cases leguminous trees have on ecosystem function.

21. Harmand J-M, Ávila H, Dambrine E, Skiba U, Miguel S, Renderos RV, Oliver R, Jiménez F, Beer J: **Nitrogen dynamics and soil nitrate retention in a *Coffea arabica—Eucalyptus deglupta* agroforestry system in Southern Costa Rica**. *Biogeochemistry* 2007, **85**:125-139.

22. Dick J, Skiba U, Wilson J: **The effect of rainfall on NO and N_2O emissions from Ugandan agroforest soils**. *Phyton* 2001, **41**:73-80.

23. Hergoualc'h K, Skiba U, Harmand J-M, Oliver R: **Processes responsible for the nitrous oxide emission from a Costa Rican Andosol under a coffee agroforestry plantation**. *Biol Fert Soils* 2007, **43**:787-795.

24. Verchot LV, Hutabarat L, Hairiah K, Van Noordwijk M: **Nitrogen availability and soil N_2O emissions following conversion of forests to coffee in southern Sumatra**. *Global Biogeochem Cycles* 2006, **20**:1-12.

25. Baggs EM, Chebii J, Ndufa JK: **A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya**. *Soil Tillage Res* 2006, **90**:69-76.

26. Millar N, Ndufa JK, Cadisch G, Baggs EM: **Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics**. *Global Biogeochem Cycles* 2004, **18**.

27. Hergoualc'h K, Skiba U, Harmand J-M, Hénault C: **Fluxes of greenhouse gases from Andosols under coffee in monoculture or shaded by Inga densiflora in Costa Rica**. *Biogeochemistry* 2008, **89**:329-345.

28. Veldkamp E, Purbopuspito J, Corre MD, Brumme R, Murdiyarso D: **Land use change effects on trace gas fluxes in the forest margins of Central Sulawesi, Indonesia**. *J Geophys Res* 2008, **113**:1-11.

29. Hall NM, Kaya B, Dick J, Skiba U, Niang A, Tabo R: **Effect of improved fallow on crop productivity, soil fertility and climate-forcing gas emissions in semi-arid conditions**. *Biol Fert Soils* 2006, **42**:224-230.

30. Dick J, Kaya B, Soutoura M, Skiba U, Smith R, Niang a, Tabo R: **The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali**. *Soil Use Manage* 2008, **24**:292-301.

31. Stehfest E, Bouwman L: **N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions**. *Nutr Cycling Agroecosyst* 2006, **74**:207-228.

32. Makumba W, Akinnifesi FK, Janssen B, Oeneme O: **Long-term impact of a gliricidia-maize intercropping system on carbon sequestration in southern Malawi**. *Agric Ecosyst Environ* 2007, **118**:237-243.

33. Montagnini F, Nair PKR: **Carbon sequestration: an underexploited environmental benefit of agroforestry systems**. *Agroforestry Systems* 2012, **61**:281-295.

34. Takimoto A, Nair PKR, Nair VD: **Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel**. *Agric Ecosyst Environ* 2008, **125**:159-166.

35. Tonucci RG, Nair PKR, Nair VD, Garcia R, Bernardino FS: **Soil carbon storage in silvopasture and related land-use systems in the Brazilian cerrado**. *J Environ Quality* 2011, **40**:833-841.

36. Verchot LV, Dutaur L, Shepherd KD, Albrecht A: **Organic matter stabilization in soil aggregates: understanding the biogeochemical mechanisms that determine the fate of carbon inputs in soils**. *Geoderma* 2011, **161**:182-193.

37. Jensen ES, Peoples MB, Boddey RM, Gresshoff PM, Hauggaard-nielsen H, Alves BJR, Morrison MJ: **Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review**. *Agron Sustain Develop* 2011, **32**:329-367.

38. Steudler P, Bowden R, Melillo J, Aber J: **Influence of nitrogen fertilization on methane uptake in temperate forest soils**. *Nature* 1989, **341**:314-315.

39. Bodelier PLE, Laanbroek HJ: **Nitrogen as a regulatory factor of methane oxidation in soils and sediments**. *FEMS Microbiol Ecol* 2004, **47**:265-277.

40. Grosso S Del, Parton W, Mosier A, Ojima D, Potter CS, Borken W, Brumme R, Butterbach-Bahl K, Crill PM, Dobbie K *et al.*: **General CH4 oxidation model and comparisons of CH4 oxidation in natural and managed systems**. *Global Biogeochem* 2000, **14**:999-1019.

41. Hergoualc'h K, Blanchart E, Skiba U, Henault C, Harmand J-M: •• **Changes in carbon stock and greenhouse gas balance in a coffee (*Coffea arabica*) monoculture versus an agroforestry system with Inga densiflora, in Costa Rica**. *Agric Ecosyst Environ* 2012, **148**:102-110.

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_2O emissions than the monoculture when considering N_2O alone. But the net radiative forcing effect of the agroforestry systems was less when taking CO_2, CH_4, and N_2O exchanges into account

42. Linquist B, Groenigen KJ, Adviento-Borbe MA, Pittelkow C, Kessel C: •• **An agronomic assessment of greenhouse gas emissions from major cereal crops**. *Global Change Biol* 2012, **18**:194-209.

This paper introduces the indicator yield-scaled global warming potential to rice, wheat, and maize. This indicator is well suited for multi-criteria assessment and evaluation of livelihood and climate trade-offs.

43. Schellenberg DL, Alsina MM, Muhammad S, Stockert CM, • Wolff MW, Sanden BL, Brown PH, Smart DR: **Yield-scaled global warming potential from N_2O emissions and CH_4 oxidation for almond (*Prunus dulcis*) irrigated with nitrogen fertilizers on arid land**. *Agric Ecosyst Environ* 2012, **155**:7-15.

This article is the first (partial) application of yield-scaled global warming potential in a tree crop. It however does not include carbon dioxide fluxes, leguminous trees, complex agroecosystems, nor is in a tropical climate or developing country.

44. Tully KL, Wood Sa, Lawrence D: **Fertilizer type and species composition affect leachate nutrient concentrations in coffee agroecosystems**. *Agroforestry Systems* 2013. doi:10.1007/s10457-013-9622-0.

45. Hartemink A, Buresh R, Van Bodegom P, Braun A, Jama B, Janssen B: **Inorganic nitrogen dynamics in fallows and maize on an Oxisol and Alfisol in the highlands of Kenya**. *Geoderma* 2000, **98**:11-33.

46. Recha JW, Lehmann J, Walter MT, Pell A, Verchot L, Johnson M: **Stream water nutrient and organic carbon exports from tropical headwater catchments at a soil degradation gradient**. *Nutr Cycling Agroecosyst* 2013, **95**:145-158.

47. Chintu R, Mafongoya PL, Chirwa TS, Mwale M, Matibini J: **Subsoil nitrogen dynamics as affected by planted coppicing tree legume fallows in Eastern Zambia**. *Exp Agric* 2004, **40**:327-340.

48. Chikowo R, Mapfumo P, Leffelaar Pa, Giller KE: **Integrating legumes to improve N cycling on smallholder farms in sub-humid Zimbabwe: resource quality, biophysical and environmental limitations**. *Nutr Cycling Agroecosyst* 2007, **76**:219-231.

49. Crews TE, Peoples MB: **Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review**. *Nutr Cycling Agroecosyst* 2005, **72**:101-120.

50. Siles P, Harmand J-M, Vaast P: **Effects of Inga densiflora on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica**. *Agroforestry Systems* 2009, **78**:269-286.

51. Akinnifesi FK, Makumba W, Kwesiga FR: **Sustainable maize production using gliricidia/maize intercropping in Southern Malawi**. *Exp Agric* 2006, **42**:441-457.

52. Kim DG: **Estimation of net gain of soil carbon in a nitrogen-fixing tree and crop intercropping system in sub-Saharan Africa: results from re-examining a study**. *Agroforestry Systems* 2012, **86**:175-184.

53. Leblanc HA, Mcgraw RL, Nygren P: **Dinitrogen-fixation by three neotropical agroforestry tree species under semi-controlled field conditions**. *Plant Soil* 2007, **291**:199-209.

54. Sanginga N, Danso SKA, Zapata F, Bowen GD: **Field validation of intraspecific variation in phosphorus use efficiency and nitrogen fixation by provenances of *Gliricidia sepium* grown in low P soils**. *Appl Soil Ecol* 1994, **1**:127-138.