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Diagnosis of Nutrient Imbalances with Vector Analysis in Agroforestry Systems

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Agricultural intensification has had unintended environmental consequences, including increased nutrient leaching and surface runoff and other agrarian-derived pollutants. Improved diagnosis of on-farm nutrient dynamics will have the advantage of increasing yields and will diminish financial and environmental costs. To achieve this, a management support system that allows for site-specific rapid evaluation of nutrient production imbalances and subsequent management prescriptions is needed for agroecological design. Vector diagnosis, a bivariate model to depict changes in yield and nutritional response simultaneously in a single graph, facilitates identification of nutritional status such as growth dilution, deficiency, sufficiency, luxury uptake, and toxicity. Quantitative data from cocoa agroforestry systems and pigeonpea intercropping trials in Ghana and Tanzania, respectively, were re-evaluated with vector analysis. Relative to monoculture, biomass increase in cocoa (*Theobroma cacao* L.) under shade (35–80%) was accompanied by a 17 to 25% decline in P concentration, the most limiting nutrient on this site. Similarly, increasing biomass with declining P concentrations was noted for pigeonpea [*Cajanus cajan* (L). Millsp.] in response to soil moisture availability under intercropping. Although vector analysis depicted nutrient responses, the current vector model does not consider non-nutrient resource effects on growth, such as ameliorated light and soil moisture, which were particularly active in these systems. We revisit and develop vector analysis into a framework for diagnosing nutrient and non-nutrient interactions in agroforestry systems. Such a diagnostic technique advances management decision-making by increasing nutrient precision and reducing environmental issues associated with agrarian-derived soil contamination.

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Agricultural intensification has greatly increased global crop production but has had unintended environmental consequences, including increased nutrient leaching and surface runoff and other nonpoint source agrarian-derived pollutants (Tilman et al., 2001). The main source of this problem is excessive mineral inputs, with subsequent disruption of localized biogeochemical processes under intensively managed monoculture systems (Drinkwater and Snapp, 2007). However, increasing agro-ecosystem diversity restores nutrient cycling processes, resulting in increased capture and transfer of nutrients and hence less reliance on external inputs and lower pollution risk (Tilman et al., 2001; Udawatta et al., 2002; Drinkwater and Snapp, 2007). These beneficial effects of agrodiversity have been demonstrated for agroforestry systems in temperate and tropical climates (Schroth et al., 2001; Gathumbi et al., 2002; Thevathasan and Gordon, 2004; Isaac et al., 2010).

The higher resource use efficiency in agroforestry relative to monoculture systems is primarily a result of structural and functional diversity within agroforests (Nair et al., 2008). For instance, partitioning of light within the canopy (Isaac et al., 2007a) and soil nutrient utilization zones between trees and crops (Allen et al., 2004) are key mechanisms for increasing nutrient and non-nutrient resource use efficiency (Wojtkowski, 2004). Accordingly, the design and management of agroforestry systems needs to embrace this system complexity to optimize positive (facilitation and complementarity) and minimize negative (competition) interactions. These conditions will consequently reduce agrarian-derived soil and water contamination while increasing ecosystem services. To achieve this, a management support system that allows for site-specific rapid evaluation of nutrient-production imbalances and subsequent management prescriptions is needed for appropriate agroforestry design.

This paper illustrates and advances a diagnostic tool—vector analysis—to assess nutrient and non-nutrient requirements in agroforestry systems. Traditionally, vector analysis has been used to diagnose plant nutrient interactions in forests, and more recently agroforests, based on relative changes in biomass, nutrient concentrations, and nutrient content in response to nutrient supply through fertilization (Gregoire and Fisher, 2004; Salifu and Jacobs, 2006) or natural recycling processes from functional tree species (Isaac et al., 2007a) or after tree fallowing (Kimaro et al., 2008). However, ameliorated moisture or light conditions can also stimulate biomass production when plant growth is not limited by nutrients, as documented in agroforestry and other intercropping systems (Wojtkowski, 2004;

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Abbreviations: LER, Land Equivalent Ratio.

Jose et al., 2004; Clinch et al., 2009). Despite increases in nutrient content, biomass increases under these conditions are usually accompanied by a decline in nutrient concentrations, a phenomenon known as growth dilution (Haase and Rose, 1995; Imo and Timmer, 1997). Frequently cited growth dilution responses in vector analysis are those related to declining concentrations of nonlimiting nutrients after the addition of the most limiting nutrients (i.e., nutrients that drive plant growth) (Imo and Timmer, 2000; Salifu and Jacobs, 2006; Isaac et al., 2007b; Kimaro et al., 2008).

The objectives of this paper are to demonstrate nutrient and non-nutrient interactions in agroforestry with the application of vector techniques and to extend this tool to a management support system. We revisit two case studies (Isaac et al., 2007a; Kimaro et al., 2009) in which we re-examine data using vector analysis to quantify nutrient and non-nutrient interactions in agroforestry and illustrate the application of this analysis for managing agroforestry systems. Improved diagnosis of on-farm nutrient application is needed to minimize soil and water contamination, and vector analysis may prove to be an appropriate system for comparing management options.

Materials and Methods

Site Descriptions and Sampling Protocols

This paper is based on two case studies on cocoa (*Theobroma cacao* L.) and pigeonpea [*Cajanus cajan* (L). Millsp.] conducted in the Western region, Ghana and in the Dodoma region, Tanzania, respectively. In the Western region, the research was conducted in the moist semideciduous tropical zone in the Sefwi Wiawso district (06°12′ N and 02°29′ W; altitude of 300 m). The soils of the study region are dominated by ochrosol–oxisol intergrades (Rhodic Ferralsol) and are highly leached soils that are acidic (pH 5.9 ± 0.07) and relatively low in fertility. This region typically has a mean annual precipitation of 1100 mm in bimodal rainy seasons (April–July and September–November) and an average aboveground temperature of 26.0°C. The cocoa-shade study was conducted in an 8-yr-old cocoa plantation (~2 ha in size) with three shade tree species: *Albizia zygia* (D.C.), *Milicia excelsa* (Welw.), and *Newbouldia laevis* (Seem.). Cocoa biomass and nutritional response were compared under each of the three tree species as well as in monoculture. Details on the experimental design and treatments can be found in Isaac et al. (2007a).

In Dodoma, the research was conducted at Ihumwa (6°10′ S, 35°53′ E; altitude of 640 m) located in a semiarid zone. This site receives a mean annual rainfall of 560 mm and has a dry period of 7 to 8 mo. Soils are acidic (pH 4.6 ± 0.10), classified as ferric acrisols according to FAO classification, and have a sandy loamy texture (Kimaro et al., 2009). The pigeonpea study was established to examine yield and nutritional responses of maize (*Zea mays* L.) and pigeonpea to fertilizer and cattle manure additions under monoculture and intercropping arrangements. Details of the experimental design and treatments can be found in Kimaro et al. (2009). Aboveground biomass was derived from destructively sampled individuals or estimated from a pre-established allometric biomass equation. Samples of plant tissue (leaf and stem) were collected and analyzed for total N, P, and K, among other macronutrients. Nutrient concentration was then multiplied by dry mass to determine nutrient content. Relative changes in these three variables (nutrient concentration, nutrient content, and biomass) were plotted simultaneously on a single graph as detailed in the Vector Analysis section. Although initial vector analysis on this data was conducted in Isaac et al. (2007a) and Kimaro et al. (2009), we reposition the analysis and interpretation of the original data to examine non-nutrient interactions in these systems.

Vector Analysis

Vector analysis was developed as a diagnostic method for determining the nutritional status of tree seedlings in boreal plantation systems (Timmer, 1991; Malik and Timmer, 1996; Imo and Timmer, 1997). This method uses a bivariate model to depict vectors associated with changes in biomass and nutrients, as compared with a sole-species plantation system (i.e., a competition-free system [control]). Dry mass and nutrient status of plants within systems can be examined by vector analysis to assess nutritional response associated with plant interactions (Haase and Rose, 1995; Imo and Timmer, 1997). As we know from the literature, plant nutrition is a function of nutrient concentration and biomass. However, testing the changes in plant nutrient concentration alone does not provide evidence for relationships between plant growth and uptake because concentration can change due to biomass changes or nutrient uptake (Imo and Timmer, 1997). Growth response is curvilinear in relationship to nutrient supply (Fig. 1) because increasing nutrient supply corresponds to increases in growth during deficiency to a point of sufficiency when growth and nutrition are maintained (Salifu and Jacobs, 2006). If tissue nutrient concentration continues to

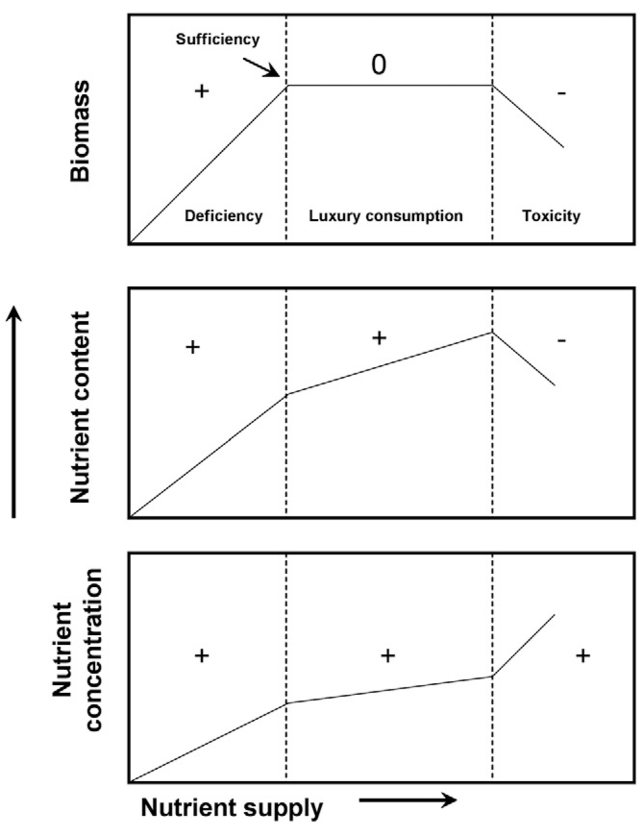


Fig. 1. Growth and nutrient supply curves showing biomass, nutrient content, and nutrient concentration response to increasing nutrient supply. Dashed vertical lines separate deficiency, sufficiency, luxury consumption, and toxicity resulting from increasing nutrient uptake.

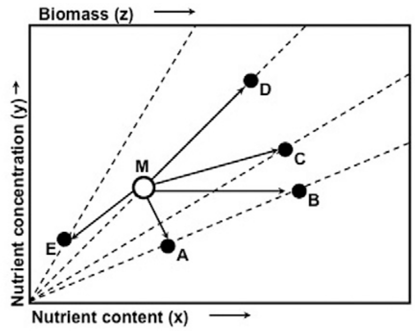
increase relative to nutrient supply but without a corresponding increase in biomass, luxury consumption of nutrients occurs, and a subsequent toxic effect on plant growth may also occur (Salifu and Jacobs, 2006). Nutrient content response is also curvilinear in form with increasing nutrient supply (Timmer, 1991; see Fig. 1). Therefore, concurrent examination of all three plant response variables to nutrient supply in a single diagram is required.

Vector diagrams (nomograms) reflect the following function: Nutrient content (or amount) in a plant (bottom horizontal *x* axis) is the product of its nutrient concentration (vertical *y* axis) multiplied by its biomass (top horizontal *z* axis) (Fig. 2). Changes in these parameters relate to two key processes driving plant growth—nutrient uptake and dry matter production—that characterize differing treatment responses. Plant responses are expressed relative to the control (normalized to 100) to facilitate comparisons between various treatments and nutrients. In this approach, differences associated with plant size and nutrient status are eliminated. Relative values, instead of absolute values, in association with the normalized controls allow for comparisons to be made between multiple nutrients and trials (Haase and Rose, 1995).

Individual response is depicted by vectors that may differ in length and direction (Fig. 2, arrows). Vector length represents response magnitude, and vector direction identifies specific nutritional responses. Thus, a treatment-induced increase in nutrient uptake and dry biomass with decreased nutrient concentration (Shift A) would reflect a dilution of this nutrient due to accelerated growth. A similar response without change in concentration (Shift B) signifies sufficiency of this nutrient because concentration was stable and kept up with increased growth and nutrient uptake. Increased biomass, nutrient concentration, and nutrient content reflect an enrichment response to a nutrient deficiency (Shift C) insofar as growth and nutrient uptake improve with increasing supply of a deficient element. A similar response but without a biomass change (Shift D) would suggest luxury consumption because nutrient uptake was enhanced without growth increase. Other vector shifts depict antagonism responses (Shift E, declines in the three parameters) (Haase and Rose, 1995; Imo and Timmer, 1997). The term "dilution" is also often applied to stable isotopes; however, this term has traditionally been applied to plant nutrition, and therefore we continue with this term in our context of vector analysis.

Vector analysis concurrently compares plant biomass, nutrient concentration, and nutrient content on a single diagram, unlike the critical level approach and other diagnostic techniques that are based on a single measure of nutrient concentration. This graphical interpretation is based on site-specific comparisons of plant response to nutrient supply (native and external inputs) relative to control, making the diagnosis independent of published critical ratios or levels (Gregoire and Fisher, 2004). Moreover, examining yield and nutritional responses simultaneously in a single graph facilitates identification of specific nutritional status, such as growth dilution, deficiency, sufficiency, luxury uptake, toxicity, and multinutrient interactions, which tend to complicate conventional diagnostic techniques (Salifu and Jacobs, 2006).

Vector analyses can have comparative advantages over Land Equivalent Ratio (LER), the prominent approach in agriculture for evaluating ecological interactions in multispecies systems



Vector	z	y	x	Interpretation	Possible diagnostic
A	+	-	+	Dilution	•Growth dilution
B	+	0	+	Sufficiency	•Steady-state
C	+	+	+	Deficiency	•Limiting
D	0	+	+	Luxury consumption	•Accumulation
E	-	-	-	Excess	•Antagonistic

Fig. 2. Nomogram of relative response in biomass (z), nutrient content (x), and nutrient concentration (y). The reference condition (M) is normalized to 100. (A–E) Diagnosis is based on shifts (increase [+], decrease [–], or no change [0]) in plant growth, nutrient concentration, and nutrient content response to treatment effect (modified from Imo and Timmer 1997). Vector interpretation and possible diagnosis are given in the associated table.

(Vandermeer, 1989; Wojtkowski, 2004). The basis of LER is a comparison of the land requirements for intercrops versus monocultures. Simply put, LER is the sum of the relative yields of each species (Mead and Willey, 1980; Vandermeer, 1989; Anderson and Sinclair, 1993; Nair, 1998). Although LER established a method to diagnose productivity in agroforestry systems, this approach is strictly based on yields and does not provide sufficient analysis to determine mechanisms of interactions that occur simultaneously in intercropping systems (Ashton, 2000).

As known from principles of nutrient supply and biomass production, growth response to progressively available nutrients is curvilinear in form (Timmer, 1991). This well known, single-variable model of growth in relation to nutrient uptake does not take into consideration non-nutrient resource limitations (e.g., light, moisture, and micro-climate) on growth, which can be particularly active in agroforestry systems. A primary goal of multispecies assemblages in production systems is to strategically promote growth and nutrition of a target species by using nutrient and non-nutrient facilitative effects of a secondary species. That is, the secondary species may have a beneficial effect on limiting resources in the local environment. For instance, a secondary species may alter the light environment through shading, particularly for shade-tolerant species, or moisture availability through microclimate amelioration. If these facilitative effects on local resources occur, accelerated growth presumably follows, demonstrating a positive biomass response in the absence of external nutrient supply. As such, increasing growth without nutrient addition may result in declining plant tissue nutrient concentration, indicating growth dilution (Timmer, 1991; Gastel and Lemaire, 2002; Marino et al., 2004). By linking biomass increase to nutrient uptake and concentrations, vector analysis allows for rapid identification and ranking of principal factors (nutrient and non-nutrient) driving plant growth as discussed for the cocoa and pigeonpea case studies.

Results and Discussion

Evaluating Non-Nutrient Resources on Cocoa Biomass: Light Effects

Growth and nutrient data from the 8-yr-old plantation indicated that higher cocoa (a shade-tolerant species) biomass production near shade trees (35–80% greater than in monoculture), presumably a result of improved light conditions, was associated with significantly lower P concentration values (17–25% less than in monoculture). In contrast, cocoa grown in monoculture resulted in lower biomass production but significantly higher P concentration (Isaac et al., 2007a). Vector nomograms isolating the dilution response of P under all three shade species (*A. zygia*, *M. excelsa*, and *N. laevis*) in the 8-yr-old plantation are presented in Fig. 3. These data support the hypothesis that an improvement to non-nutrient resources induces accelerated growth and nutrient dilution of a potentially limiting nutrient of the target species in multispecies systems. This reinforces the need to evaluate all plausible causes of nutritional response.

This trend was not consistent for all nutrients, presumably due to variations in preexisting soil resources, natural nutrient supply from decomposition fluxes, and the age of the study plants and sites resulting in varying levels of limitation (Isaac et al., 2007a). For instance, in this older site, efficient nutrient cycling may have increased N nutrient supply, thus providing a natural source of N and avoiding dilution of this element with accelerated growth. Therefore, dilution effects due to accelerated growth during increased access to a non-nutrient resource may occur but may be offset by improved natural nutrient supply or may occur when nutrients are not limiting. Further research is required to elucidate the scope of dilution effects from regulated light in agroforestry systems.

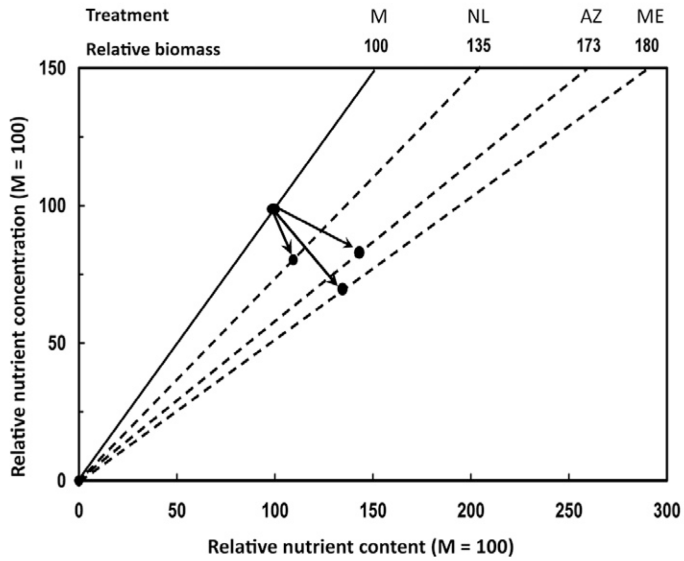


Fig. 3. Nomogram depicting isolated phosphorus dilution response of cocoa after 8 yr in monoculture (M), normalized to 100, and under *Newbouldia laevis* (NL), *Albizia zygia* (AZ), and *Milicia excelsa* (ME).

Evaluating Non-Nutrient Limitation on Pigeonpea Biomass Yield: Soil Moisture Effects

As noted for cocoa under shade trees, biomass and uptake of fallowed pigeonpea without fertilization shown in a vector nomogram (Fig. 4) affirmed a growth dilution under a natural supply of resources (i.e., soil nutrients and water in semiarid conditions for this case study). Without fertilization (–IF), relative increase in pigeonpea biomass and nutrient uptake in the fallow treatment compared with intercropping treatment was associated with reduced concentrations of all nutrients tested (Fig. 4) (Kimaro et al., 2009). This growth dilution response indicates that uptake of native soil nutrients did not keep pace with stimulated biomass increase, implying that alleviated soil moisture competition through sequential cropping of pigeonpea and maize was responsible for this increase. Similar soil N and P levels in the intercropping and fallow treatments at 2 wk after onset of the growing season also affirmed that yield differential growth response between these treatments cannot be attributed to soil nutrient supply (Kimaro et al., 2009).

Figure 4 also indicates that a combination of soil moisture control, through sequential cropping and fertilizer inputs, further stimulated biomass increase. The addition of N and P fertilizers (+IF in Fig. 4) increased pigeonpea biomass yield relative to the unfertilized intercropping treatment (control) by 239% (339 – 100%) and was associated with a 33% improvement in P nutrition. This vector shift (Shift C in Fig. 2) may indicate P deficiency resulting from P fixation by aluminum (Kimaro et al., 2009). These results also demonstrate fertilizer-by-moisture interactive effects that are typical in most semiarid areas in the tropics due to low and sporadic precipitations and infertile soils (Vohland and Barry, 2009).

Framework for Evaluating Non-Nutrient Resource Effects Using Vector Analysis

Our analysis of the pigeonpea and cocoa case studies demonstrates that vector techniques can simultaneously depict nutrient and non-nutrient interactions on a single graph to provide rapid and site-specific diagnosis of plant growth response (Fig. 3 and 4). Tree–crop interactions were reassessed with resultant vector shifts, providing interpretations of multispecies interactions, including nutrient and non-nutrient effects. However, the current vector analysis model does not consider non-nutrient resource effects on growth. Because secondary species in

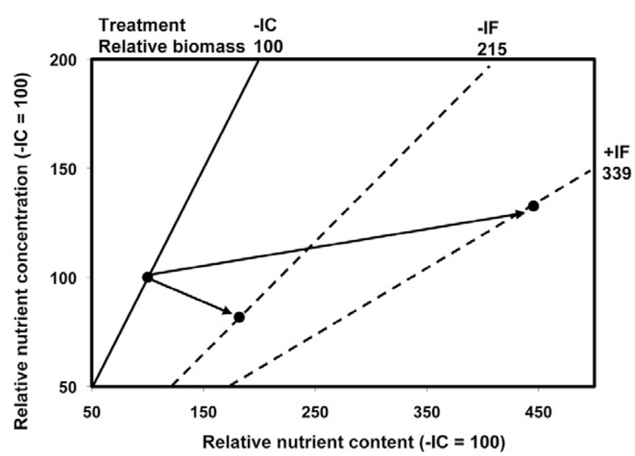


Fig. 4. Nomogram depicting phosphorus dilution and deficiency responses of pigeonpea to unfertilized (–IF) and fertilized (+IF) fallow treatments in semiarid Dodoma, Tanzania (Unfertilized intercropping [–IC] = 100). Application rates were 80 kg N ha^{-1} and 40 kg P ha^{-1} for N and P fertilizers, respectively.

a multispecies system can affect nutrient and non-nutrient environmental conditions, such as light (Fig. 3) and soil moisture (Fig. 4) resources, diagnostic accuracy of plant nutrition should be reconsidered.

Often within agroforestry or intercropping studies, plant tissue nutrient concentration is used as an indicator for nutrient uptake. If nutrient concentration values are unusually low, this may lead to an interpretation of a false-negative interspecific interaction. However, this may be simply dilution. Improvement in resource availability via the presence of a secondary species is a desirable outcome in production systems; therefore, a dilution response may be particularly prevalent in agroforestry systems. Figure 5 depicts this conceptual inverse relationship between growth and nutrition; a secondary species (species 2) improves non-nutrient resources such that biomass production of target species 1 increases. Although different in magnitude, a corresponding dilution of nutrient concentration follows for both species. To account for this plausible relationship, the potential dilution effect is incorporated into a modified growth and nutrient supply model (Fig. 6) based on Timmer (1991), demonstrating the interactive effect of improving a limiting non-nutrient resource, such as light or moisture, on growth and nutrient uptake.

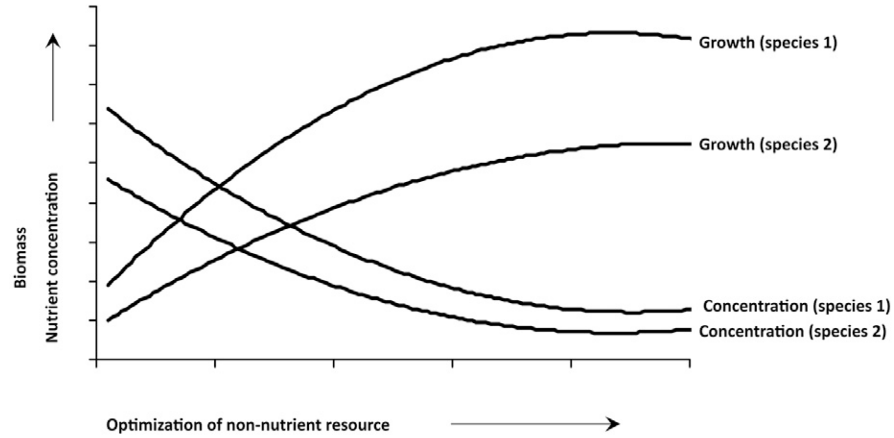


Fig. 5. Idealized graph depicting biomass and nutrient concentration in relation to increasing optimal levels of a non-nutrient resource, such as light or moisture resources. The growth of the target species in a multispecies assemblage increases while nutrient concentration declines. The secondary species may improve site conditions through facilitative effects for the target species. Growth and nutrient concentration of the secondary species show similar responses as the target species but to a lower magnitude.

Developing a Management Support System with Vector Analysis

Regulation of non-nutrient resources plays a significant role in increasing growth and nutritional response, and when nutrients are not limiting plant growth, optimization of non-nutrient resources may result in initial nutrient dilution. Our empirical findings support the need for integrating nutrient and non-nutrient resource effects on biomass and nutrition and subsequent favorable agroforestry management techniques. To do this, we revisit the vector analysis model and develop management prescriptions derived from a nutrient response that incorporated non-nutrient effects. Such advancements will enable interpretations of dynamic management practices on a temporal and spatial scale. New interpretations of vector shifts as well as prescriptions particular to agroforestry, including nutrient and non-nutrient manipulations, are illustrated in Fig. 7. We establish that ideal conditions for sustained productivity in agroforestry occur when nutrient supply is at sufficient level (vector B). Under field conditions, there are deviations from this vector due to insufficient or excessive nutrient supply (native or fertilization) as well as ameliorated light or moisture conditions, as noted in the case studies. We therefore present a series of management prescriptions to reposition agroforestry management strategies to achieve nutrient sufficiency and maintain

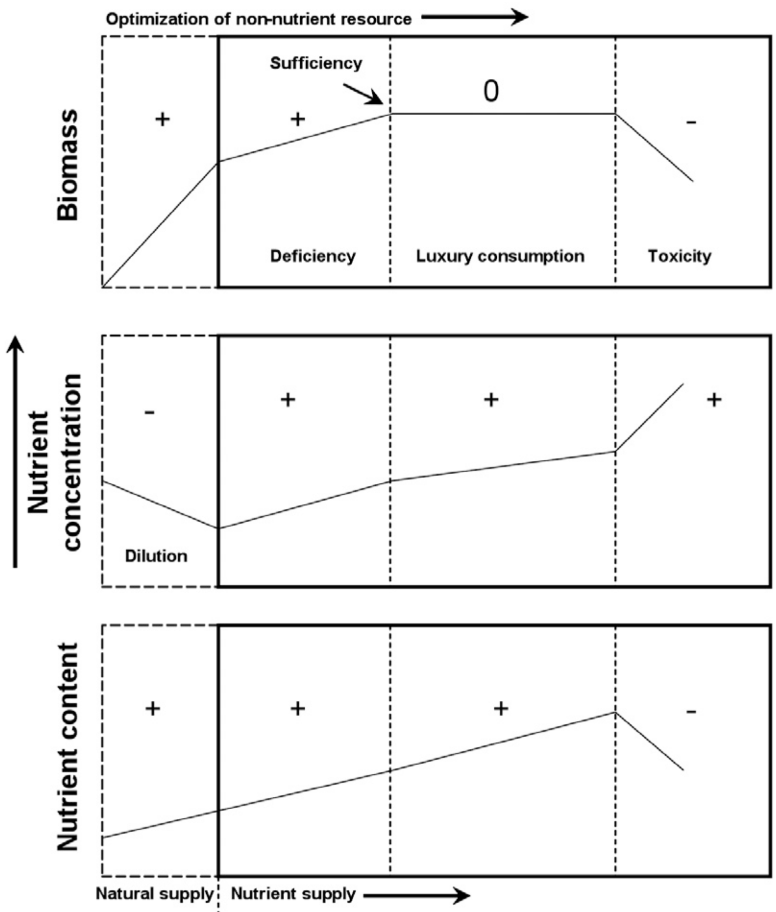


Fig. 6. Growth, nutrient content, and nutrient concentration response to nutrient supply (solid boxes) and no supply or natural supply (dashed boxes). Dashed vertical lines separate deficiency, sufficiency, luxury consumption, and toxicity resulting from increasing nutrient uptake. Curves in the dashed boxes include biomass and relative nutrient concentration and content response with favorable levels of non-nutrient resources without nutrient supply. The effect shown in the dashed box is the expected dilution effect resulting from accelerated growth due to favorable non-nutrient resources in the absence of nutrient supply.

the system at this condition. However, not all of these hypothetical scenarios can be found in a given agroforestry system or tested in one experimental design. Even with our two case studies, we were able to show only light and moisture effects based on P dilution. This concept is the foundation for the application of vector analysis as a management support tool. Details of silvicultural management practices to maintain nutrient sufficiency in agroforestry systems based on vector analysis of nutrient and non-nutrient interactions are provided below.

Mitigating Dilution: Vector Shift A to B

Vector A demonstrates nutrient dilution, where nutrient concentration declines with biomass production. Although biomass and nutrient content continue to increase, there is no corresponding increase in nutrient concentration, presumably due to insufficient availability. In an intercropped agroforestry system, this can indicate the occurrence of interspecific soil nutrient competition and over time may result in declining biomass production of the target species due to inadequate nutrition. Once dilution is diagnosed, prescriptions should focus on increasing nutrient concentration, thus arriving at sufficiency (shift B). Central to farm management is the reduction of belowground competition to ensure improved soil fertility for plant uptake; dilution is minimized through increased access to natural nutrient supply. This may be accomplished through decreasing the density of nontarget species or introducing function-based species, such as N_2 fixers.

Maintaining Sufficiency: Vector Shift B

Vector B demonstrates nutrient sufficiency, where nutrient uptake keeps pace with increasing biomass. This is the target situation for agroforestry systems; management regimes that achieve this level of interaction should be maintained, with a focus on sustaining non-nutrient resources such as appropriate light and soil moisture levels, and monitoring for the next limiting element. Selection of upper canopy species with adequate light infiltration or actions to manipulate light levels, such as pruning of shade trees, may be appropriate. Although soil resources are sufficient, biomass production may primarily be dependent on light availability.

Mitigating Deficiency: Vector Shift C to B

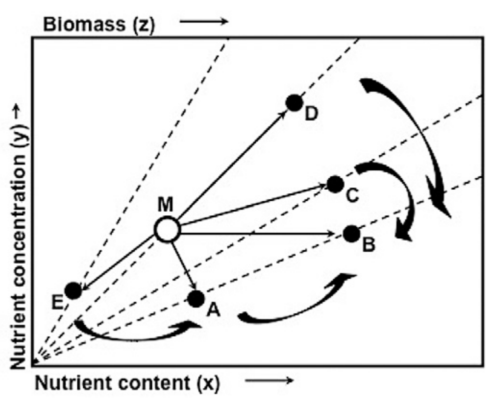
Vector C demonstrates nutrient deficiency, whereby nutrient concentration of the target species increases due to an enrichment response to growth. Diagnosis of deficiency indicates a potentially limiting nutrient. To shift nutrient deficiency to sufficiency, supply and use efficiency of the limiting nutrient, whether internal or external, should be increased to minimize the impacts of deficiency. In this scenario, farm management should focus on enhancing facilitative interactions, particularly through improved nutrient cycling to increase and maintain a potentially limiting nutrient. Careful management of functional species is essential in promoting long-term nutrient sufficiency.

Minimizing Luxury Consumption: Vector Shift D to B

Vector D demonstrates luxury consumption where nutrient concentration increases without a corresponding increase in biomass production, indicating possible toxic uptake if accumulation continues. This response may occur in agroforestry systems when there is an abundance of nonlimiting nutrients, such as K, in the soil and subsequently transferred to intercrops through biogeochemical processes (Isaac et al., 2007a) or when non-nutrient resources limit plant growth. This unique situation calls for alternate management options, such as the redistribution of leaf litter to provide K nutrient supply to locations with low concentration levels or modification of non-nutrient resources (e.g., improving light and moisture availability to accelerate growth).

Mitigating Antagonism: Vector Shift E to B

Vector F demonstrates antagonism where nutrient concentration, content, and biomass decline in comparison to the control (typically monoculture), presumably the outcome of continuing dilution from insufficient nutrient supply due to competition. This suggests a significant limitation on resource availability, and extensive changes in management are necessary; eliminating agroforestry practices until soil resources are rehabilitated to sufficient levels may be required. Alternatively, management practices that reduce plant density (thinning) or increase the availability of a limiting resource (e.g., shoot pruning, fertilization, or irrigation) may be



Vector shifts	z	y	x	Initial diagnosis	Agroforestry prescription
A to B	+	- > 0	+	Short term yield response: limiting nutrient if in low supply	•Reduce belowground competition •Intercrop low density functional species
B	+	0	+	Sustained growth and nutrition	•Maintain system •Monitor for next limiting element
C to B	+	+ > 0	+	Accelerated growth response due to increase supply of a limiting nutrient	•Intercrop under high facilitation [nutrient availability through net inputs or resource partitioning]
D to B	0 > +	+	+	Accelerate nutrient uptake	•Modify non-nutrient resources
E to B	- > +	- > 0	- > +	Competition: low production under agroforestry	•Modify non-nutrient resources •Precise nutrient application

Fig. 7. Dynamic model of nutrient and non-nutrient effects on target species growth and nutrition in multispecies systems as compared with a monoculture (M) (normalized to 100): nomogram of relative response in biomass (z), nutrient content (x), and nutrient concentration (y). Vectors depict shifts (+, –, 0) in the three variables in comparison to a control (monoculture = 100). Vectors show initial diagnosis, and curved arrows show expected shifts over time with implementation of agroforestry management prescriptions in response to nutrient and non-nutrient diagnosis. Initial diagnoses for biomass and nutrition of the target species and subsequent agroforestry prescriptions are given in the associated table.

applied if they do not adversely affect the economic and social benefits of the system.

Conclusions

Empirically, biomass production and nutrition in multispecies systems exhibited typical responses as predicted by the conceptual model. Vector analysis confirmed these responses through analysis of vector shifts in comparison to a control. Subsequently, our recommended management prescriptions are based on original vector diagnosis and are deterministic in nature, such that the goal is to arrive at vector shift B in comparison to a control scenario (i.e., to maintain sufficient level of nutrients in the system). A comparative evaluation of multiple management schemes can be conducted simultaneously, allowing for comprehensive decision-making on farm design. Drawbacks to this system include misinterpretation of data sets typically confounded by incomplete data. Attention must be paid to the experimental design that allows separation of nutrient and non-nutrient effects on plant growth. If appropriate methodologies are followed, there is utility in using vector analysis as a management support system for agroforestry, particularly if multistrata agroforestry systems in which higher performance of a target species may be desired and in which paralleled nutrient and non-nutrient resource feedback are active. Accordingly, site-specific rapid evaluation of nutrient production imbalances that tend to complicate conventional diagnostic techniques and subsequent management prescriptions should include dynamic features during the life cycle of the farm.

Unintended environmental consequences of the inaccurate and overuse of fertilizer can have detrimental effects on nutrient leaching, surface runoff, and other nonpoint source pollutants. Linking crop performance to appropriate nutrient application, as well as quantifying existing nutrient cycles and interactions, will not only have the economic advantage of increasing yields but will also diminish financial and environmental costs. Such a diagnostic technique can advance management decision-making to reduce current environmental issues associated with agricultural intensification, particularly agrarian-derived soil contamination.

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