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Assessing Cross-disciplinary Efficiency of Soil Amendments for Agro-biologically, Economically, and Ecologically Integrated Soil Health Management

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Abstract: Preventive and/or manipulative practices will be needed to maintain soil's biological, physiochemical, nutritional, and structural health in natural, managed, and disturbed ecosystems as a foundation for food security and global ecosystem sustainability. While there is a substantial body of interdisciplinary science on understanding function and structure of soil ecosystems, key gaps must be bridged in assessing integrated agro-biological, ecological, economical, and environmental efficiency of soil manipulation practices in time and space across ecosystems. This presentation discusses the application of a fertilizer use efficiency (FUE) model for assessing agronomic, economic, ecological, environmental, and nematode (pest) management efficiency of soil amendments. FUE is defined as increase in host productivity and/or decrease in plant-parasitic nematode population density in response to a given fertilizer treatment. Using the effects of nutrient amendment on *Heterodera glycines* population density and normalized difference vegetative index (indicator of physiological activities) of a soybean cultivar 'CX 252', how the FUE model recognizes variable responses and separates nutrient deficiency and toxicity from nematode parasitism as well as suitability of treatments designed to achieve desired biological and physiochemical soil health conditions is demonstrated. As part of bridging gaps between agricultural and ecological approaches to integrated understanding and management of soil health, modifications of the FUE model for analyzing the relationships amongst nematode community structure, soil parameters (eg. pH, nutrients, %OM), and plant response to soil amendment is discussed.

Key words: fertilizer use efficiency model, normalized difference vegetative index, nutrient amendment, soil amendments, soil degradation, soybeans, soybean cyst nematode.

Healthy soil in natural, managed, and disturbed ecosystems is the foundation for meeting the food, fiber and living environment needs of the increasing world population, and overall global ecosystem welfare. As used here, soil health refers to biological, physiochemical, nutritional, and structural integrity of the soil in question. Natural refers to pristine forests and other vegetation, disturbed or degraded refer to an environment where aboveground vegetation and belowground biota (and potentially biological functions and processes), and soil nutrients are expected to be minimal, and managed refers to an ecosystem that has low nutrient and belowground biological activity. Managed and disturbed ecosystems are likely to be dominated by arable and/or pastoral landscapes, where severe soils degradations within and across ecosystems and landscapes in large regions have resulted in loss of habitat and biodiversity, food insecurity, malnutrition, and forced population migration (Lal, 2007; Tillman, 1999; Vagen et al., 2005). Unless soil health can be restored on a regional scale, vital ecosystem services are unlikely to return to levels that can sustain populations of humans, plants and animals (Lal, 2007).

The degrees of biological, physiochemical, nutritional, and structural degradations in natural, managed and disturbed soil ecosystems, however, present many and complicated agricultural and ecological adaptation and/or mitigation challenges. These include empirical data lagging behind theoretical work, gaps in multidisciplinary knowledge base, links between basic and applied sciences, scale of application, and integration models (Allesina and Pascual, 2009; Caron-Lormier et al., 2009; Melakeberhan and Avendaño, 2008; Proulx, 2007; Richter et al., 2007). Against this background and with a focus on stressing the need for cross-disciplinary and integrated approaches to solving soil degradation challenges, this manuscript highlights the following points: 1) ecological and 2) agricultural approaches to understanding and/or amending soil ecosystems, 3) necessary paradigm shifts, and 4) agro-ecologically integrated soil amendment use efficiency analyses.

Understanding terrestrial ecosystem structures and functions: Ecological network theory, employing species biomass and abundance properties and their interactions, has been widely used to understand terrestrial ecosystem structure, with significant influence on species conservation policies (Caron-Lormier et al., 2009). Use of *n*ematodes, the most abundant metazoan and indicator for identifying soil biological conditions and nutrient cycling processes in rehabilitating soil degradations and maintaining healthy ecosystems is one example (Bongers and Ferris, 1999). For detailed description of the role of nematodes in the ecosystem, see Ferris (this issue). However, many disciplinary and science gaps exist, primarily due to ecological complexities and empirical data lagging behind theoretical work (Proulx, 2007). For example, a more complete way of explaining a terrestrial ecosystem's biological structure and function will be to enumerate all

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life forms (microbes to trees) and their roles in influencing the ecosystem behavior along a continuum, which is not feasible. On the other hand, when single or multiple species are enumerated in a given ecosystem, applying the data across environmental conditions becomes less reliable because of what the different environments represent as well as due to the lack of group models (Allesina and Pascual, 2009; Allison and Martiny, 2008; Proulx, 2007).

Paradigm shifts: In order to effectively prevent degradation and/or restore ecosystem services in degraded soils to the point of making a global impact, at least two paradigm shifts will be required: a) The extent of soil degradations cannot be resolved without simultaneous consideration of the effects of direct (physical and biological) and/or indirect (anthropogenic) ecosystem change drivers (Lal, 2007; Richter et al., 2007; Vagen et al., 2005). For example, the combined effect of the direct and indirect ecosystem change drivers on soil health, further exacerbated by drought and poor water resource management, continue to confound efforts to sustain human and other life forms in vast regions of the world. b) The same science and other actions applied in multiple locations to match the scale and heterogeneity of degradations. The paradigm shifts will need a science foundation that integrates understanding of the degrees of soil degradations in natural, managed and degraded, scale of degradations, and the complexity of the ecosystem change drivers in agricultural and non-agricultural landscapes.

The agricultural approach of dealing with soil degradations: Agricultural soils probably represent the most degradation of soil conditions because of the population pressure and demand for food on an ever decreasing arable landmass (Fink et al., 1999; Baligar et al., 2001; Good et al., 2004; Loneragan, 1997). For the most part, the agricultural approach to dealing with soil biotic and abiotic limitation to high crop yield has been to change the soil to fit the plant and/or change the plant to fit the soil (Baligar et al., 2001). Changing soil primarily involves adding fertilizer or adjusting pH to improve soil quality and/or suppress biotic yield limiting factors. For example, over 140 million t/year of fertilizer are applied globally (Anon, 2006) and annual pesticide application increased from 50,000 t/year in 1945 to 2.5 million t/year in 2005 (Sundquist, 2005).

Changing the plant includes breeding for resistance biotic yield limiting factors and/or environmental stresses. Developing lasting solutions, however, remains challenging because of lack of integrated approaches to the problems (Melakeberhan and Avendaño, 2008). For example, breeders may be concerned with developing specific traits like high yield or resistance to a particular biotic or abiotic factor, all of which are likely to end up in fields where many unaccounted for limitations exist. Soil scientists may be looking at physical and chemical constraints while, the often overlooked, biological constraints are not as integrated into changing soil conditions as should be. While necessary to increase yield, therefore, agricultural inputs need to be considered carefully because they have many long-term biological and agro-environmental implications (Fink et al., 1999; Good et al., 2004; Wickham et al., 1997).

As illustrated in Table 1 and Fig. 1, there are data analyses and conceptual challenges to overcome when amending soils. The data in Table 1 are a snapshot at a vegetative (V5) and reproductive (R1/R2) stages of soybean (Fehr et al., 1971) in a study designed to test a hypothesis that *nutrient amendment will result in better physiological activity of soybean and suppress soybean cyst nematode (SCN,* Heterodera glycines*) population dynamics than in none amended soil.* Normalized difference vegetative index (NDVI, indicator of physiological activities)) and SCN population densities were measured at two points during V5 to R1/R2 stages. NDVI was measured using a portable GreenSeeker Hand Held™ optical sensor unit (NTech Industries, Ukian, CA) and calculated as: NDVI = (NIR-R)/(NIR+R), where NIR = near infrared (0.76 to 0.99 μm) and R = red (0.63 to 0.69 μm) (Royle and Lathrop, 2002). SCN population density (eggs/100 cc of soil) was determined as described in Melakeberhan (2007).

Using a standard ANOVA, there is no statistical effect on SCN or on NDVI (Table 1). The difference in SCN numbers over time may be explained by life cycle; whereas, the lack of difference may be attributed to uncontrollable and natural factors often associated with field studies. Overall, leading one to conclude that the soil amendments did not work under the experimental conditions, and leaving many of the problems unanswered. Under these circumstances, soil amendment may either be abandoned or continue repeating the study in time and space in search of the desired outcomes. This will potentially lead to economic loss and environmental hazard from repeated amendment applications (Melakeberhan, 2006).

TABLE 1. The effects of amending soil with none (check), 112.1 kg^{-1} ha^{-1} of 06-15-40 (N-P-K) containing urea (+N), 112.1 kg-1 ha-1 of 0-15-40 (N-P-K) (-N) on SCN population density (eggs/100 cc of soil) and NDVI at two points during V5 and R1/R2 stages of CX 252 soybean cultivar under field conditions expressed as measured values (left side) and as percent of control (right side).

	SCN	NDVI	SCN	NDVI
Factor	Measured values		As % of control	
Nutrient				
Check	2420 a[1]	0.373 a	na	na
−N	991 a	0.411 a	36.9 a	110.3 a
+N	2269 a	0.333 a	82.3 a	89.8 a
Time (DAP)				
V5	3062 a	0.348 a	74.3 a	108.3 a
R1/R2	725 b	0.396 a	44.9 a	91.9 a
Nutrient*Time	0.5398	0.6988	0.6205	0.9296

na = Not applicable because data are expressed as percent of the respective controls.

[1] Means within a column followed by the same or no letters are not significant different ($P \leq 0.05$).

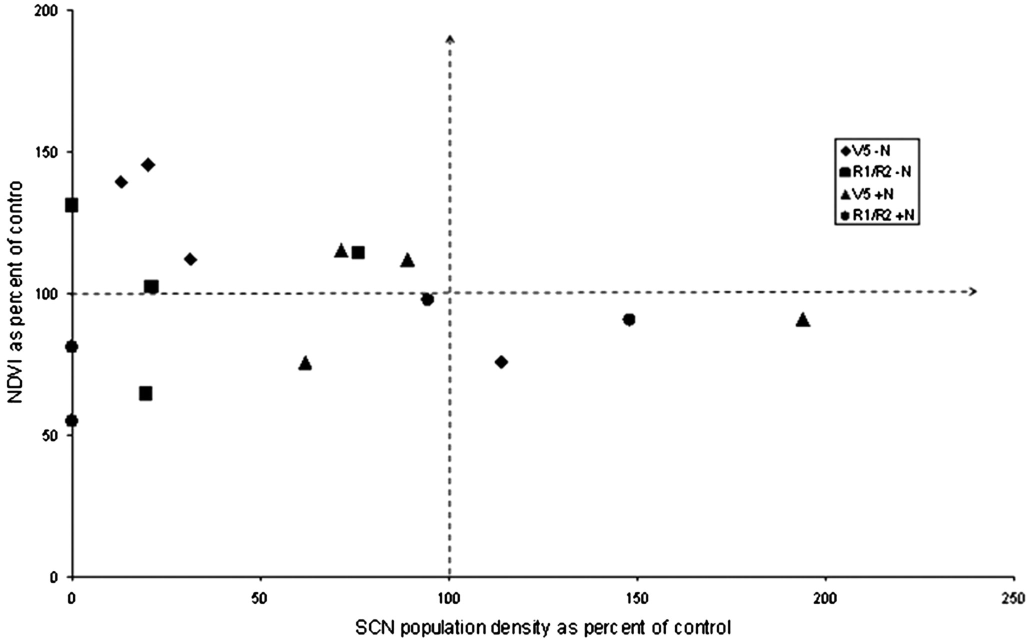

Fig 1. The data that produced Table 1 expressed as a percent of control per the FUE model to determine agro-biological efficiency of nutrient amendment with or without nitrogen.

What is clear from the data in Table 1 is that there is high degree of variability that may not be adequately explained by simply attributing them to natural and/or uncontrollable field conditions. For example, it is generally accepted that soil with high N will be less favorable to herbivore nematodes than low N, which seems to contradict the 18% and 63% reduction of SCN population density in the respective treatments (Table 1). It is not that either the data analyses or the hypothesis were wrong as much as there is a conceptual challenge. i.e. The hypothesis testing is limited to SCN and NDVI response to soil amendment. In doing so, the potential of multi-dimensional accounting of the effects of soil amendment on the environment, agro-ecological, biological, economic, and etc. response to soil amendment, key to bridging the ecology and agriculture approaches to addressing and understanding the complex issues of ecosystems, are missed (see next section).

Agro-ecologically integrated soil amendment use efficiency analyses: When soil amendments are applied, it is rare for inter-disciplinary gaps (agronomic and biotic factor suppression) to be considered, let alone bridge the ecology and agricultural sides of the complex problems. One way to integrate the ecological approach to understanding ecosystem functions and processes and the agricultural approach to improving soil conditions through soil amendment is to be able to test the hypothesis that "*agro-biological, physiochemical, economic and environmental benefits from and responses to treatment are separable*". With the ability to separate responses comes the potential for identifying overlapping interactions and designing integrated solutions. These can be accomplished with the use of a fertilizer efficiency (FUE) model (Melakeberhan, 2006). Defined as increase in host productivity and/or decrease in plant-parasitic nematode population density in response to a given fertilizer treatment, the FUE model separates nutrient deficiency and toxicity from nematode parasitism as well as suitability of treatments designed to achieve desired biological and physiochemical soil health conditions. The FUE model is derived from expressing data on the same scale (as a percentage of a control) as expressed in the following equation (using variables in Table 1):

$$\begin{aligned}&\text{Percent SCN or NDVI}\\&= ((\text{values of SCN or NDVI in amended soil})/\\&(\text{average values of SCN or NDVI in non-amended soil}))\\&\times 100 \qquad [1]\end{aligned}$$

and plotting percent SCN (X-axis) and percent NDVI (Y-axis) to elicit four clusters of data set (Fig. 1).

When soil is amended to improve yield and soil quality while suppressing biotic yield-limiting factors, the responses measured may show an increase, decrease, or no change. For example, as shown in Table 1, there was no significant change in SCN population density and NDVI values. However, by expressing the data that lead to the means shown on Table 1 on the same scale (as a percentage of the unfertilized controls) and plotting the relationships based on the FUE model, one can elicit four distinct categories of responses and come to different conclusion than based on Table 1 (Fig. 1). It is worth noting that SCN population density increased only 19% of the time in response to soil amendment (right side of vertical dashed line), and the increases were in situations where soil amendment would be considered toxic for plant growth (lower right box, Melakeberhan, 2006). Where SCN population decreased (left of the vertical dashed line), NDVI values (host efficiency) increased 61% of the time (top left box). These conclusions and interpretations are far different from saying that nutrient amendment has no effect on SCN or NDVI based on Table 1 results, making it possible to explore the mechanisms and processes of why and how the observed interactions can be explained.

The multi-dimensional interpretations derived from the FUE model are significant and have many cross-disciplinary applications. For example, breeders looking for multi-traits such as nutrient use and nematode (biotic factor) suppression efficiency can cut down the process by selecting from interactions that result in the upper left box or best case scenario (Fig. 1). If the plan is to add nematode suppression traits to high nutrient use efficiency, look for interactions that fall in the upper right box. If the plan is to added nutrient use efficiency to nematode suppression traits, look for interactions that fall in the lower left box. Interactions that fall in the lower right box represent the worst case scenario (Melakeberhan, 2006). If biotic pests increase and host productivity decrease in response to soil amendment, it is likely that the soil amendments are leading to environmental hazard and economic loss as well. The model is applicable to other biotic suppressing systems as well as scalable.

The FUE model has since been modified to include nematode community structure-based bio-ecological indices and broad range of agro-biological parameters, including the development of agro-biologically sustainable soil nutrient management using nematode community structure as driver of soil health (Melakeberhan and Avendaño, 2008). Let's assume that soil amendments (organic or inorganic) are applied and nematode trophic groups (TG) excluding herbivores, soil parameters (SP) (nutrients, pH, %O.M) and crop yield are measured. Response of herbivores (if present) to the soil amendments will be analyzed as described for Fig. 1. The relationships among the other parameters can be described as follows (Melakeberhan and Avendaño, 2008):

$$\text{Percent yield} = ((\text{yield in amended soil})/(\text{average yield in non-amended soil})) \times 100. \qquad [2]$$

$$\text{Percent TG} = ((\text{TG \#s in amended soil})/(\text{average TG \#s in non-amended soil})) \times 100. \qquad [3]$$

$$\text{Percent SP} = ((\text{SP value in amended soil})/(\text{average SP value in non-amended soil})) \times 100. \qquad [4]$$

The difference between Fig. 1 (biotic suppression) and TG (without herbivores) is that the positions of the best- and worst-case scenario boxes have moved one box clockwise in the latter (Melakeberhan and Avendaño, 2008). In this case, data points that fall in the upper right box will be ideal and those in lower left box, environmental and economic disaster. Data points that fall in the upper left and lower right will require complimentary treatments to improve the numbers of trophic group or host productivity, respectively. These modifications are key bridges that tie nematology and cross-disciplinary gaps to agricultural and ecological approaches to developing agrobiologically sustainable soil health management practices (Melakeberhan and Avendaño, 2008).

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