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Review

Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa

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ABSTRACT

Despite the number of site-specific studies conducted on the effect of inorganic fertilizer and organic inputs on maize yield, information is lacking on the variation in yield risks with soils and climate in sub-Saharan Africa (SSA). Information on yield risk could give an idea of where a particular input may not work well, and thus has low potential for adoption by farmers. Using analytical methods combining features of meta-analysis, response surface regression and generalized additive models, this work synthesizes information on variation of maize yield gaps and risks with inorganic fertilizer and organic inputs in relation to soils and climate. The organic inputs included *in situ* green manure from sunhemp (*Crotalaria* spp.), velvetbean (*Mucuna* spp.), sesbania (*Sesbania* spp.), tephrosia (*Tephrosia* spp.) and gliricidia (*Gliricidia sepium*). Yield gap (YG) was defined as the difference in grain yield between maize grown using a given nutrient input and without external nutrient inputs (i.e. control) under a specific study condition. Yield risk was defined as the probability of obtaining yields lower than or equal to the control across similar conditions. Yield gaps with the recommended rate of inorganic fertilizer were significantly higher on farmers' fields compared with research stations, while with organic inputs such differences were smaller. With inorganic fertilizer, yield risks were higher (up to 22%) on Nitosols (one of the most fertile soils), compared with Luvisols (<5% risk). With sunhemp, yield risks were higher on Ferralsols (40%), which have low resilience to degradation and low sensitivity to yield decline, compared with Cambisols (<5%), which have high resilience and low sensitivity. Yield risks with velvetbean were higher on Acrisols (35%) and Lixisols (20%), which have very low resilience and high sensitivity, compared with Nitosols and Ferralsols (<15% risk). With sesbania higher yield risks were noted on Nitosols (53%) and Acrisols (39%) compared with Luvisols (17%), Ferralsols (20%) and Lixisols (22%). Response surface regression and generalized additive models indicated that yields and yield gaps with the different inputs vary with soil clay content, elevation and mean annual precipitation on the study sites. With all inputs, yield risks were lower on sites with 20–40% soil clay content, while the effect of elevation and precipitation differed widely with the type of input. It is conclude that yield gaps and yield risks vary with the soil fertility input, the sensitivity and resilience of soils and management. This study could not confirm the superiority of any of the legume species over the other across all locations. Therefore, blanket recommendation of species should be avoided. Instead, species should be targeted in niches where they can reduce yield risks and increase adoption by small-holder farmers.

Contents

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1. Introduction

Maize accounts for over 50% of the cropped area and the calories consumed in many countries in SSA (Byerlee et al., 1994). Despite the availability of improved varieties and agronomic practices, the average grain yield of maize in SSA has stagnated around 1–2 t ha^{-1} (FAO, 2008). Production has also not kept pace with consumption, and African countries import up to 10 million tonnes of maize each year (Cassman, 2007). The soils on which smallholder farms are so dependent have been subjected to erosion, loss of organic matter and hence low crop productivity (Sanchez, 2002; Stocking, 2006). Although mineral fertilizer can partly overcome the problem, rapid increases in world fertilizer prices have severely limited farmers' access to this input (Hargrove, 2008). In addition, opportunities for expansion of cultivated land are limited as rapid population growth has led to progressive encroachment upon marginal lands (Bojo, 1996), even against technical advice (Mubiru and Coyne, 2009). Therefore, improving maize production cannot come from area expansion but productivity gains through technological innovations that can narrow the yield gap.

The yield gap can be broken down into three components (Tran, 2004). The first component is the difference between the potential yield and the experiment station yield for which scientists breed varieties. The second component of yield gaps is the difference between the experiment station yield and the potential farm yield (Tittonell et al., 2008). The third component is the difference between the potential farm yield and the actual farm yield (Subedi and Ma, 2009), which is mainly caused by differences in land management practices and use of inputs (Tran, 2004). This type of yield gap can be narrowed by increasing efforts in research and extension in crop management or by appropriate institutional and policy interventions that improve access to inputs (Tran, 2004).

Land degradation is one of the main biophysical causes of declining productivity in much of SSA (Sanchez, 2002; Stocking and Tengberg, 1999). The continuous cultivation of maize, which mines soil organic matter and nutrients, combined with decrease in intercropping and inadequate use of legume rotations has contributed to the steady decline in soil fertility (Mafongoya et al., 2006; Roose and Barthès, 2001). Soil fertility is linked to soil organic matter, whose status depends on inputs such as biomass management and outputs such as mineralization, erosion and leaching (Roose and Barthès, 2001).

Biomass from nitrogen-fixing legume trees (Akinnifesi et al., 2007; Mafongoya et al., 2006) and green manure/cover crops (GMCCs) has been widely used to improve maize yields in Africa (Sileshi et al., 2008a). These legumes, when integrated into maize cropping systems either as rotational fallows or relay intercrops, have been shown to provide considerable amounts of organic matter and nitrogen to the soil (Mafongoya et al., 2006; Mubiru and Coyne, 2009; Sileshi et al., 2008a). The organic matter thus added increases structural stability of the soil, resistance to rainfall impact, infiltration rates, and faunal and microbial activities (Mafongoya et al., 2006; Sileshi et al., 2008b). However, the potential impact of these legumes on crop yields is rarely realized on farmers' fields because of spatial variability in soil organic matter and nutrients, which in turn depend on the inherent resilience and sensitivity of the soil. Resilience is manifested through changes in specific degradation or erosion rates on different soils subject to the same erosive conditions, whereas sensitivity is a measure of how far the change induced in soil quality affects the soil's productive capability (Stocking, 2006).

Farmer's decision on whether to use a given input or not may depend on many factors (Ajayi et al., 2007), but the yield component of the decision will be based on the yield gain they expect on their farm (Sileshi et al., 2008a). Variation around the mean represents production risk, and it is one of the factors that influence farmers' decisions to adopt an innovation (Saha et al., 1994). Perception of yield risk can be a major factor that hinders the transfer of technologies including fertilizer (Simtowe, 2006). Although several site-specific studies exist, syntheses providing general principles that have application beyond the study sites are lacking in SSA. Therefore, we aim to assess the probability distribution of yield risks associated with inorganic fertilizer, legume trees and GMCCs in maize cropping systems. By gleaning information from site-specific studies and pooling the results, this study also attempts to address questions not posed by individual studies. The following are the main questions addressed in this study: Do yield gaps differ with management on research stations and farmer's fields? Do yield gaps and risks vary with the resilience and sensitivity of soils across sites? Do they vary with climate variables such as mean annual precipitation (MAP) and elevation of the site? This kind of information would have many potential benefits to both individual decision-makers and the society. Firstly, information on yield risk could give an idea of where a particular technology may work well and where it may fail, and thus may have low potential for adoption by farmers. Secondly, on the basis of such information researchers can set priorities for research, formulate recommendations to farmers and justify efforts to speed up adoption.

2. Materials and methods

Traditionally the performance of technologies has been judged based on mean yields. However, inference based on the mean can be misleading if the variance around the mean, and hence the probability distribution of the risk is not known. A more realistic approach is to use an appropriate effect size index (Sileshi et al., 2008a), which will allow one to model the probability distribution of yield gaps (YG) and hence yield risks. We defined YG as the mean difference in yield between maize grown with input X and maize grown without any external nutrient input (i.e. control), which is the *de facto* farmers practice in many regions of SSA. This represents the third type of yield gap described in Section 1. In this analysis we conceptualized each soil nutrient input as an investment to be compared with the control. Therefore, YG determines potential gains to be weighed against the required investment and input costs (Sileshi et al., 2008a). If a choice has to be made between two investments that have the same expected return but different variances, most people would choose the one with the lower variance and therefore, the lower risk. Therefore, farmers are expected to make decisions on investing in a given nutrient input using this common sense. If an external nutrient input is used as the 'experimental' and compared with the control, the YG is a realistic measure of the effectiveness of the input under