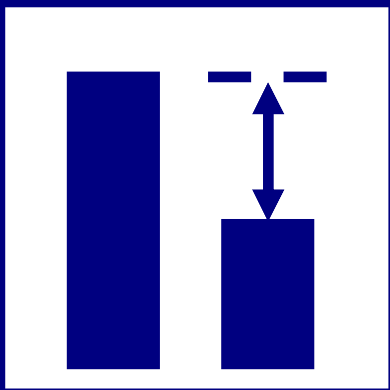
Pepijn Schreinemachers

The (Ir)relevance of the Crop Yield Gap Concept to Food Security in Developing Countries

With an Application of Multi Agent Modeling to Farming Systems in Uganda



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Summary

Introduction

The crop yield gap is defined as the difference between the yield potential and the average yield of a crop, in which the yield potential is the maximum yield achieved under optimal conditions with all stresses from nutrients, pests, and water controlled. Pointing to an observed diminishing growth in global rice and wheat yields, many studies have argued that the exploitable gap between potential and average yields is too narrow and shrinking and that this endangers food security. Such observations often lead to the claim that increasing the yield potential is the best strategy we have to combat food insecurity and that the growth in yield potential should at least keep pace with the growth in population to avert hunger.

Objective

It is the objective of this thesis to take a critical look at the relationship between the crop yield gap and food security in developing countries. The thesis first scrutinizes the crop yield gap concept at global and national levels and then zooms in at the farm household level using an innovative methodology based on multi-agent systems that integrates the biophysical and socioeconomic factors driving the width of the yield gap. This integrated model is then used to decompose the yield gap in proximate and underlying factors, to assess its relationship with food security, and to explore how improved varieties with a higher yield potential could affect the well-being of farm households.

Methodology

Multi-agents systems (MAS) were used as a framework to integrate three model components: an economic model simulating farm household decision-making; a biophysical model simulating crop yields and soil property dynamics; and spatial layers of soil properties representing the physical landscape.

The methodology was applied to two villages in southeast Uganda. Maize yields in Uganda are notoriously low while maize plays a central role in the strategies of the government and several NGOs to increase food security. High population density, a

diversified farming system, and a strong reliance on manual labor characterize the study area, while the use of external inputs such as improved seeds and mineral fertilizer is infrequent.

Each farm household was represented by an individual agent in the model so that there were as many agents as there were farm households in reality. Agents were parameterized by applying Monte Carlo techniques on a random sample of farm households. A mathematical programming (MP) model, with non-separable production and consumption decisions, was used to simulate agent decision-making. The MP model included more than 2,000 activities and over 500 constraints and agents optimized a three-dimensional utility function of cash income, food, and future income from investments. MP models were solved in a recursive fashion over a period of 15 years.

The biophysical part of the model was based on Mitscherlich-type of crop yield equations with explanatory variables being available nutrients (nitrogen, phosphorus, and potassium), soil organic carbon, acidity, labor use, and a factor capturing the yield effect of intercropping. Soil fertility was specified as a function of initial soil conditions as altered by both management (crop choice, input use, livestock numbers, harvest removal) and natural processes (decomposition, deposition, leaching, erosion).

Model integration was implemented at a pixel level, 0.5 ha in size, which captured much of the heterogeneity in environmental conditions. Survey data were used to calibrate and validate the decision model while soil samples and secondary data from literature were used to parameterize the landscape and biophysical model.

In four ways did the thesis advance existing methodologies: First, the thesis showed how MAS can be parameterized from survey data, which is unique as most MAS are based on experimental or hypothetical data. Second, the thesis developed a non-separable three-stage decision model of investment, production, and consumption that realistically captured the economic trade-offs in the allocation of scarce resources over time. Third, a three-step budgeting system, including an Almost Ideal Demand System, was included in an MP model to simulate poverty dynamics in terms of food energy consumption. Fourth, coping strategies to food insecurity were included that gave agents a limited, yet realistic, capacity to adapt to food crises.

Main results

A comparison of maximum yields of CIMMYT international wheat and maize trials with average national yields showed that yield gaps for most developing countries are very wide. This can be taken as *prima facie* evidence that factors other than the genetic potential are constraining average yields. Four major misconceptions were identified from a review of literature on the relationship between the yield potential and food security; these misconceptions were that a higher yield potential is wanted by farmers, that it is needed to meet future demands, that it increases food security, and finally, that it is needed to keep food prices low. Each of these claims was disarmed by case studies from literature. In addition, data for 19 Indian states on the width of the rice yield gap and three outcome indicators of food insecurity showed significant and positive correlations – indicating that states with a wider yield gap (read: lower yields and/or a higher potential) tend to be more food insecure. The thesis argues that this does not point to deficiencies in technology but more likely to non-technological factors that make the people in some states poorer than in others. To understand better what these factors are, the analysis turned to the farm household level using a case study of two villages in southeast Uganda.

Based on computational experiments with the multi-agent system, the maize yield gap was decomposed in proximate factors such as crop variety choice and low fertilizer use. Two additional factors that reduce yields, but are not usually considered in agronomic studies, were included: low labor use and intercropping. The results revealed the importance of the last two factors in explaining low maize yields in Uganda. The size and composition of the yield gap do, however, not indicate any inefficiencies or food insecurity.

Turning to the issue of performance, land and labor productivity were plotted against the width of the yield gap, which – not so surprisingly – showed that agents with lower maize yields have wider yield gaps. Yet a strong correlation also appeared between wide yield gaps and food security, indicating that smaller farms attain greater yields but are also more likely to be food insecure due to relatively low returns to labor. In land-constrained systems, prominence is often given to yield enhancing technologies, yet the simulation results showed that even under land scarcity, raising labor productivity, and not yields, is the most important for poverty alleviation. Scenario analyses showed that poverty levels could be reduced drastically be relatively straightforward interventions related to a better access to short-term credit and existing technologies.

That maize occupies about 20 percent of arable land in Uganda is often taken as a measure for its importance to food security. This claim was assessed by comparing the present situation with two rather synthetic scenarios: one without maize and one with only maize. Results showed that poverty levels would double in the 'maize only scenario' while poverty levels would be only 4 percent lower in the 'no maize scenario'. This indicates that the importance of a crop cannot be assessed from the area it occupies, but also, that the promotion of maize – as is currently done by several NGOs – might be counterproductive beyond a certain point as it reduces the diversification of the farming system, which is important for food security.

The effect of two improved maize varieties was assessed by comparing the present situation with two hypothetical scenarios in which only one of these varieties was available. In the first scenario, a hybrid maize variety gradually replaced a traditional variety. The hybrid maize variety had a high yield potential, required more labor, was unsuitable for intercropping, and required agents to purchase new seeds annually. A second scenario simulated the diffusion of an open pollinated improved variety, which had a lower yield potential than the hybrid, but which was suitable for intercropping, had lower labor needs, and seeds could be re-used for five years. The results showed that maize yields and total maize output would be substantially greater if only hybrid maize was introduced as this gave a more complete diffusion of the hybrid. Yet in spite of this, it appeared that simulated poverty levels were about equal for all three scenarios. This suggests that albeit it's higher yield potential, the hybrid maize variety is not better than the improved open pollinated maize, which could explain the in reality observed low adoption rate of hybrids in Uganda. Varieties with a higher yield potential might hence not have the desired effect if they require more labor and more cash. Researchers would need to consider labor needs, and the effect on labor productivity, more explicitly when breeding for improved varieties.

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Stuttgart, May 2006

Abbreviations

AIDS	Almost Ideal Demand System
CIMMYT	International Maize and Wheat Improvement Center
FAO	Food and Agriculture Organization of the United Nations
HIV/Aids	Human Immunodeficiency Virus / Acquired Immune Deficiency Syndrome
IFPRI	International Food Policy Research Institute
IRRI	International Rice Research Institute
MAS	Multi-agent systems
MILP	Mixed integer linear programming
MP	Mathematical programming
MP-MAS	Mathemetical programming based multi-agent systems
SD	Standard deviation of the mean
TSPC	Tropical Soil Productivity Calculator
UBOS	Uganda Bureau of Statistics
UNHS	Uganda National Household Survey (conducted in 1999-2000)
USDA	United States Department of Agriculture
Ush	Ugandan shilling (1,000 Ush ≈ 0.63 Euro on 01.01.2001)
ZEF	Center for Development Research in Bonn

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1 Introduction

1.1 Introduction

This thesis discusses the relevance of the concept of crop yield gaps with respect to food security in developing countries. It applies a novel methodology based on multi-agent systems (MAS) to decompose and simulate crop yield gaps while simultaneously measuring the economic well-being and food security of farm households in a developing country context. This first chapter introduces the crop yield concept and methods used to analyze it. The chapter is organized in six sections. Section 1.2 describes the problem background and introduces the concept of crop yield gaps; Section 1.3 defines the objectives of the study, while Section 1.4 introduces the methodological approach and Section 1.5 outlines how the remainder of the thesis is organized.

1.2 Problem background

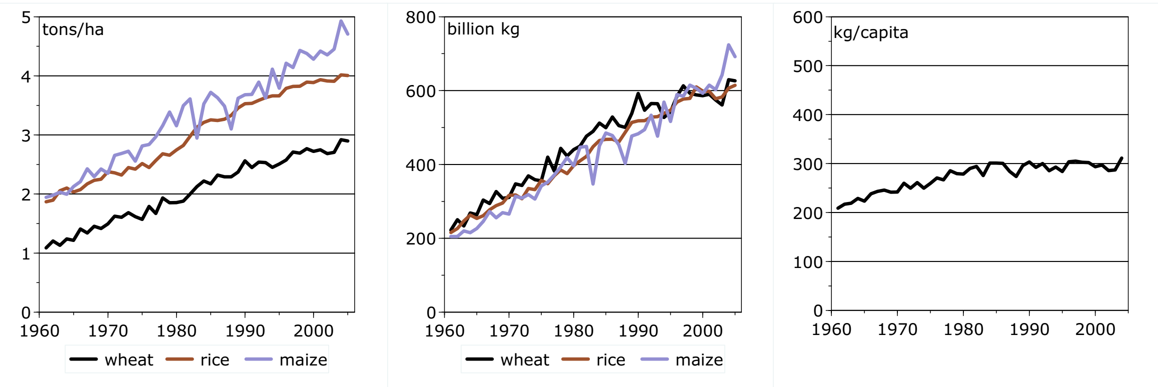
1.2.1 The crop yield gap and food security

A recent decline in the global growth rate of cereal production, production per capita, and cereal yield (see **Figure 1.1**) has intensified concerns about food sufficiency and food security. Cereal yields, many scientists have argued, need to be boosted to supply the growing human population with sufficient amounts of food (*e.g.*, Lampe 1995; Khush and Peng 1996; Pingali and Heisey 1999; Timsina and Connor 2001). An increase in yields is necessary because the possibilities to further expand the agricultural land area are being exhausted at a global level, and current land is rapidly being degraded and lost to expanding urban areas.

It is often written that growth in cereal yields is constrained by insufficient genetic gains in the yield potential and a subsequent narrowness of the yield gap (Peng *et al.* 1999; Reynolds *et al.* 1999; Timsina and Connor 2001). Technologies with a higher yield potential would therefore be required, especially in irrigated areas, to meet the increasing demand for food (*e.g.*, Reynolds *et al.* 1999).

The concern about yield gaps in relation to food security can be judged from the fact that much of the literature on the issue of crop yield potentials starts by summing up global population statistics (*e.g.*, Lampe 1995; Kush *et al.* 1996: 38; Reynolds *et al.* 1996: 1; Duvick 1999; Peng *et al.* 1999: 1552; Pingali and Rajaram 1999: 1; Rejesus *et al.* 1999: 1; Reynolds *et al.* 1999: 1611; Pingali and Pandey 2001: 1; Fischer *et al.* 2002: 1; Tiongco *et al.* 2002: 897). Several authors have called for more sustained efforts in 'beaking the yield barrier' (Cassman 1994; Reynolds *et al.* 1996). Raising the yield potential, in this respect, is implicitly assumed to increase actual cereal supply (*e.g.*, Peng *et al.* 1999; Reynolds *et al.* 1999). A reduction of the difference between yield potential and actual yield, often referred to as the narrowing of the yield gap, is interpreted as a worrying sign for long-term food security as farmers have less technological potential to exploit.

Figure 1.1: Global cereal yield trends and per capita availability, 1961-2005



Source: FAO 2006

1.2.2 The crop yield potential

The yield gap is commonly defined as yield potential minus average yields. This yield potential refers to the genetic maximum yield of a crop. Evans (1996: 292) defines this yield potential as "the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging and other stresses effectively controlled".

Figure 1.2 shows yield gaps for maize grown in Illinois (left pane) and Mexico (right pane). The yield potential is quantified as the average of the three highest yielding experiments in a particular year. This figure shows that the average maize yield in