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

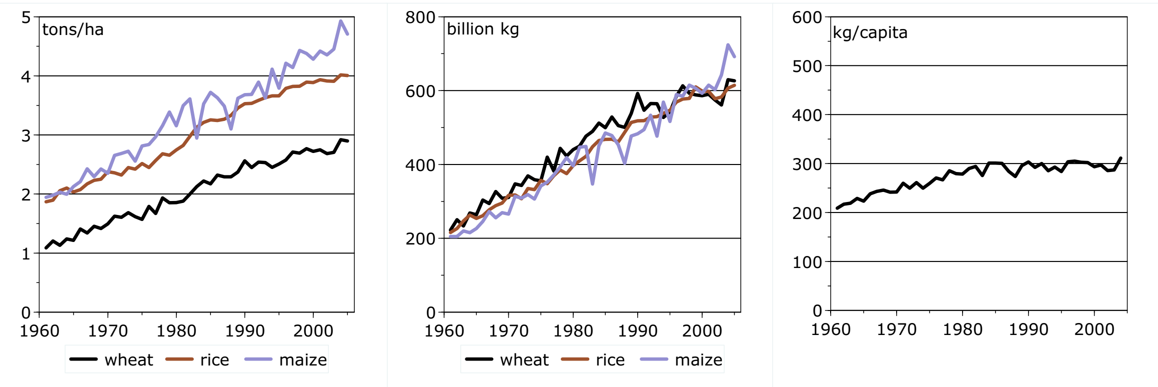
1.2.1 The crop yield gap and food security

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

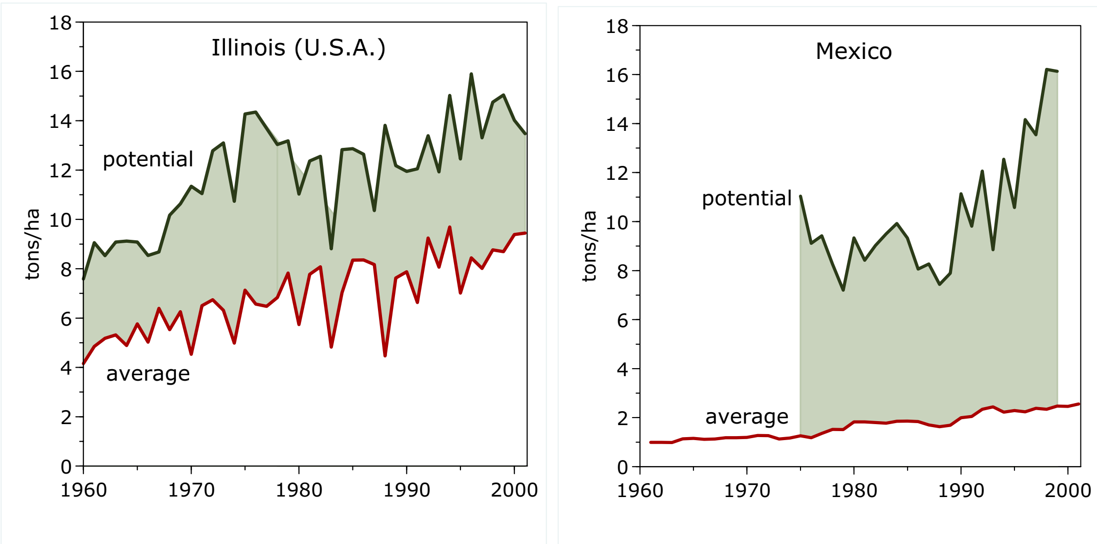
1.2.2 The crop yield potential

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

Illinois has closely followed the growth in yield potential at the state's experiment stations. Not only are the trends the same but also the variations around the trends resemble one another. Average yields in the beginning of the 1960s reached 4 tons but doubled to 8 tons by 2000 with the yield gap being—a more or less permanent—2 tons/ha. The picture for Mexico strongly contrasts that of Illinois. Mexican average yields also doubled in the same period but remain at a low average of about 2.5 tons/ha. The yield gap has, however, widened considerably since the early 1990s from about 6 tons/ha to more than 12 tons/ha.

Figure 1.2: Maize yield gaps for Illinois and Mexico



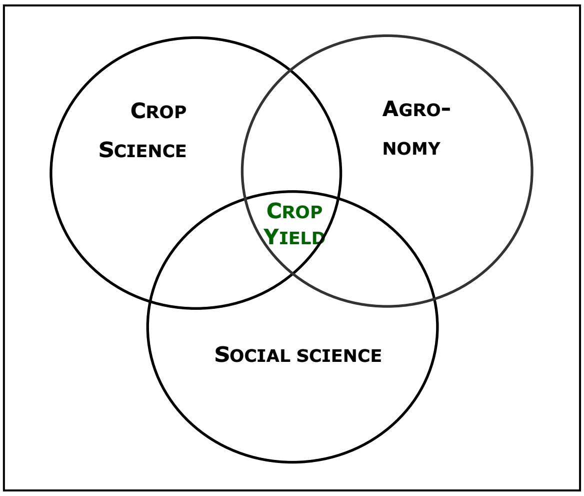
Sources/notes: The Illinois yield gap is based on the maximum over three trial locations: DeKalb, Urbana, and Brownstown, and the average state yield (which is slightly above the United States average maize yield) (Illinois Experiment Station 1960-2001, USDA 2002). Similarly, the Mexico yield gap is based on the three best yielding CIMMYT cultivars and the corresponding national average yield (CIMMYT 2002; FAO 2006).

The stark contrast between the two pictures is the only reason for showing them here. A multitude of factors determines the width of a yield gap. Farmers in Illinois rapidly adopt higher yielding varieties, yet the situation in Mexico seems to be much more complex. A weak linkage between yields at experiment stations and yields in farmers' fields can result from a lack of agricultural service provision, lack of knowledge among farmers, insufficient adaptation of crop varieties to farmers' conditions, missing or incomplete input markets including credit, high levels of risk impeding adoption, or a misalignment of researchers' and farmers' objectives. It is, however, not the intention to go into much detail at this stage. Yet, one hypothesis would be that crop yield gap dynamics for most developing countries come closer to the Mexican than to the Illinoisan picture.

1.2.3 Need for integrated approaches

The concept of crop yield is situated at the fault lines between three scientific disciplines: crop science, agronomy, and social science. Each of these disciplines has a strong interest in crop yields but from a different point of view. That is not to say that these scientific disciplines can be delineated neatly; they are more like a Venn diagram, as in **Figure 1.3**, with crop yield at its center.

Figure 1.3: Positioning the yield gap



The debate on yield gaps can largely be brought back to a difference in scientific perspectives on the factors determining crop yield. Biophysical sciences tend to focus on proximate factors—such as genes, soil nutrients, and energy—while social sciences tend to focus on underlying determinants—such as markets and institutions. The figures below illustrate these three contrasting perspectives.

First, **Figure 1.4** illustrates the determinants of crop yield from a crop science perspective (*i.e.*, crop physiology). Crop yield, in this view, is a function of total biomass and harvest index. Crop breeders generally concentrate on the absolute size of the yield difference between a new variety and farmers' varieties (Sanders and Lynam, 1982: 99). This yield difference can be widened either by an increase in total biomass—*i.e.*, increasing the size of all parts of the plant, or by an increase in harvest index—*i.e.*, increasing the proportion of grain in the total biomass. This perspective focuses on the level of the individual crop and the increase in crop yield is very much an objective in itself.

Figure 1.4: Crop yield as studied in crop physiology

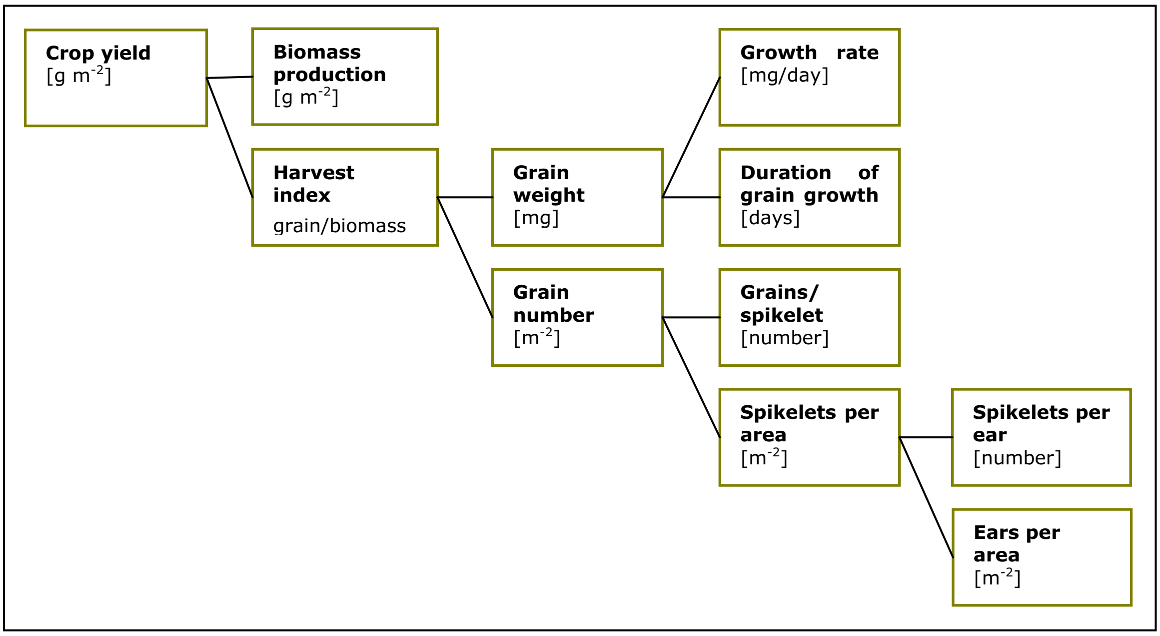
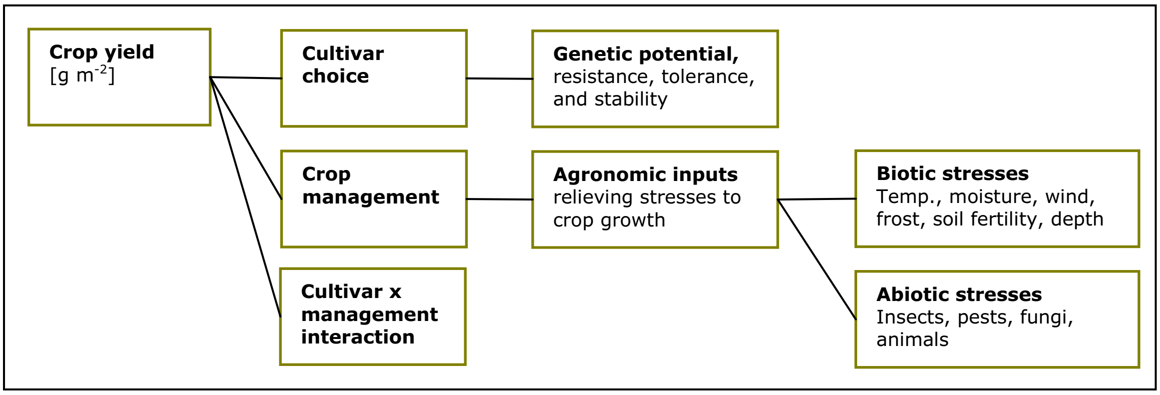


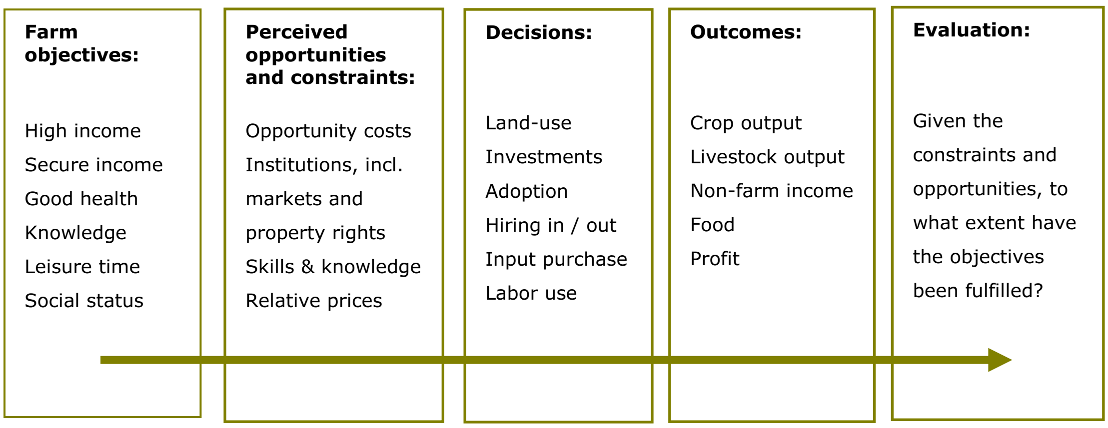
Figure 1.5 shows an agronomist's perspective. Agronomists focus on the field rather than the plant level. The yield of a crop can be increased by using higher yielding cultivars, improving crop management, or improving the interaction between these two (Evans and Fischer 1999). Similar to crop physiology, increasing crop yield and maximizing agronomic response is an objective in itself.

Figure 1.5: Crop yield as studied in agronomy



In the socioeconomic perspective, farm households—unlike crop scientists—do not usually attempt to obtain maximum crop yield. Farm households maximizing crop yields are destined to bankruptcy in any functioning market economy. Farm households have different objectives, such as meeting the food needs of the household, attaining a high level of income, having a stable income over time, increasing their knowledge, and having leisure time. **Figure 1.6** conceptualizes the socioeconomic perspective on the farm household. It shows that crop yield is one particular outcome of farm decision-making, rather than an objective in itself. In their decision-making, farm households are guided by their objectives and their perceptions of the environment, such as the availability and price of inputs, the sale of output, the security of their land tenure, the amount and distribution of rainfall, and the fertility of their soils. When evaluating their decisions, farm households will assess the extent to which their expectations with respect to objectives have been met and compare their performance with other farms.

Figure 1.6: Socioeconomic view on crop yield



Household objectives seldom overlap with attaining maximum crop yields, yet they may come close under certain conditions: (a) if land is the scarcest factor of production and land rents are therefore high; (b) if labor or mechanization is in ample supply; (c) if yield risks and price risks are low or covered by insurance; (d) if variable inputs such as fertilizers and agrochemicals are relatively cheap, supply is certain, and credit is available; and (e) if farmers are well-informed about the characteristics of improved varieties. These conditions apply more to agriculture in Illinois than to agriculture in most developing countries.

The three disciplinary perspectives on crop yield complement rather than substitute each other. Each perspective focuses on a different scale, from the plant, to the plot, to the farm level. Though the above contrast between disciplines is rather simple and incomplete, it helps to highlight two issues. First, caution is needed when linking determinants of crop yield at the plant level to factors at higher levels, such as the link between increasing the harvest index of wheat on the one hand and the food security of farm households on the other hand. Second, the understanding of crop yields and the relevance of crop yield gaps requires an integrated approach. Neither economic nor biophysical models alone can explain the level of and variation in average crop yields.

1.3 Objectives

The general objective of this thesis is to scrutinize the concept and pitfalls of crop yield gaps with respect to developing country agriculture. More specifically, the objectives are:

1. To review the linkages between a higher crop yield potential on the one hand and an increase in average yields and food security on the other hand.
2. To build a dynamic simulation model that integrates the biophysical and socioeconomic factors driving the width of the crop yield gap, and use this model for three purposes: (a) to quantify yield gaps and yield gap dynamics at the farm household level and to decompose them in proximate and underlying factors; (b) to assess the relationship between the width of the crop yield gap on the one hand and farm household well-being and food security on the other hand; and (c) to analyze how improved varieties with a higher yield potential affect incomes and food security at the farm household level.

1.4 Approach

After an in-depth discussion on the (ir)relevance of crop yield gaps for developing country agriculture based on a review of literature in **Chapter 2**, the concept is analyzed at the farm household level in the remaining chapters. For this, a multi-agent system (MAS) is calibrated to two villages in southeast Uganda. The MAS is used as a framework for integrating three main model components: an agent component representing farm household decision-making, a landscape component, and a biophysical component simulating crop yields and soil property dynamics.

1.4.1 Main methodological contributions

The thesis makes the following four contributions to the methods of farm household modeling and MAS:

First, this thesis shows that it is possible to empirically parameterize multi-agent systems from farm household survey data by using Monte-Carlo techniques to extrapolate from survey estimates.

Second, the thesis describes a novel approach to simulate farm household decision-making with mathematical programming by sequentially simulating investment, production, and consumption decisions while treating consumption and production as non-separable. This three-stage sequence of decisions is a realistic way of representing farm household decision-making and is well able to capture economic trade-offs in the allocation of scarce resources over time.

Third, the consumption side is modeled using a three-step budgeting process involving savings, food expenditures, and expenditures on specific categories of food. A linear approximation of the Almost Ideal Demand System (LA/AIDS) is included in the third step. The inclusion of a complete and flexible expenditure system in MAS opens new opportunities for applying MAS to the analysis of poverty, food security, and inequality.

Fourth, coping strategies to food insecurity are included. Agents can choose to spend their monetary savings or sell off livestock if food consumption falls short of their needs. The inclusion of coping strategies in MAS gives a realistic representation of the strategies of food insecure farm households in developing countries.

1.4.2 Main collaborations

Thomas Berger (University of Hohenheim) wrote the source code for the multi-agent model. Jens B. Aune (Norwegian University of Life Sciences) calibrated the Tropical Soil Productivity Calculator (TSPC) for soil conditions and 11 crops in Uganda. The TSPC was adjusted and integrated into the MAS by the author together with Thomas Berger. Hosahng Rhew and Soojin Park (both from the University of Seoul) estimated continuous soil maps from soil samples that were collected by the author and Gerd Ruecker (ZEF/ German Aerospace Center, DLR). Johannes Woelcke (The World Bank) developed the first version of the mathematical programming matrix that served as a basis for the matrix developed for this thesis. Thorsten Arnold (University of Hohenheim) wrote the MatLab routines that collected the MAS output and compiled it into single data files, which were used for statistical analysis.

1.5 Outline of the thesis

The thesis consists of 10 chapters. **Chapter 2** introduces the yield gap debate and highlights four important misconceptions commonly voiced in this debate. These misconceptions concern the assumed linkages between an improvement in yield potential and an increase in average yields, food availability, and food security. The chapter will point to the microeconomic factors affecting the yield gap. To analyze these, the focus turns to the farm household level in the following chapters. A novel methodology is developed based on multi-agent systems to integrate dynamic models of biophysical processes and farm household behavior at a very fine spatial resolution. **Chapter 3** describes the conceptual frame of the study. The general methodology is outlined in **Chapter 4**. Four subsequent chapters describe the calibration of the main model components. These are respectively, the landscape component in **Chapter 5** and the biophysical component in **Chapter 6**. The agent decision component is split into two with the production part outlined in **Chapter 7** and the consumption part outlined in **Chapter 8**. Results of the study are presented in **Chapter 9**. Finally, **Chapter 10** highlights the strengths and limitations of the applied methodology.