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Forecasting technological change in agriculture—An endogenous implementation in a global land use model

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ABSTRACT

Technological change in agriculture plays a decisive role for meeting future demands for agricultural goods. However, up to now, agricultural sector models and models on land use change have used technological change as an exogenous input due to various information and data deficiencies. This paper provides a first attempt towards an endogenous implementation based on a measure of agricultural land use intensity. We relate this measure to empirical data on investments in technological change. Our estimated yield elasticity with respect to research investments is 0.29 and production costs per area increase linearly with an increasing yield level. Implemented in the global land use model MAgPIE ("Model of Agricultural Production and its Impact on the Environment") this approach provides estimates of future yield growth.
Highest future yield increases are required in Sub-Saharan Africa, the Middle East and South Asia. Our validation with FAO data for the period 1995–2005 indicates that the model behavior is in line with observations. By comparing two scenarios on forest conservation we show that protecting sensitive forest areas in the future is possible but requires substantial investments into technological change.

1. Introduction

More than 200 years ago Thomas Malthus published his rather pessimistic population essay, in which he stated that population growth would be restricted by a slow growth rate in food production [1]. Now the world is inhabited by almost seven billion people, which marks an increase by about 600% since Malthus' times. One of the main shortcomings of his essay was the underestimation of technological change (TC) in agriculture [2].

However, during Malthus' times technological change was negligible and higher food production was almost exclusively due to an increase in production factors [3]. Important innovations in agriculture from the 19th century onwards changed this pathway [4]. Since then land-saving technological change has been the main driver for growth in agricultural output [5,6]. Fig. C.1 shows the strong correlation between agricultural output and population during the last 200 years. Agricultural output has increased considerably, paving the way for strong population growth. Most of such increases in agricultural output have been the result of technological change induced by investments in Research & Development (R&D). One example is the so called "Green Revolution" in Asia and Latin America, initiated by international agricultural research institutes [7].[2]

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[1] Equal contribution.

[2] During the 1960s and 1970s the International Maize and Wheat Improvement Center (CIMMYT) and the International Rice Research Institute (IRRI) developed high-yielding wheat and rice seeds.

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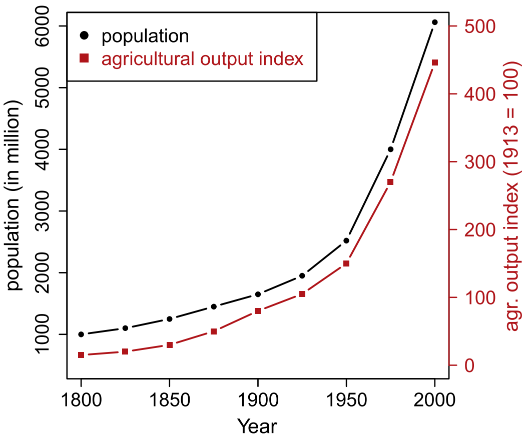

Fig. C.1. Historic development of agricultural production and population [own illustration based on Federico [3] and United Nations [64]].

The importance of TC for the agricultural sector is widely acknowledged in the scientific literature. For instance, some recent studies document the need of agricultural innovation and progress for satisfying global food demand and keeping food prices at tolerable levels [8,9]. Thirtle et al. [10] point out that growth in the agricultural sector has a much higher impact on poverty reduction in Africa and Asia than growth in other sectors. Sub-Saharan Africa particularly profits from R&D investments mostly in terms of increases in agricultural productivity and poverty alleviation [11].

Notwithstanding, in agricultural sector models or models of land use change, TC is implemented as an exogenous driver [12–16]. In these models, projections primarily depend on a fixed technology path rather than on internal model dynamics. This may lead to serious biases in model results due to an underestimation of the adaptability in the agricultural sector, especially in the longer run.

The main reason for using an exogenous TC path in most models is that although the relationship between R&D investments in agriculture and technological change is well documented [8,11,10,17,18], the exact influence of R&D on technological change is still unknown. Several reasons exist for this knowledge gap. First, available time series of R&D investments are still relatively short (less than 30 years) and often incomplete [19]. Second, as Evenson [20] showed, spillover effects are of major importance in agricultural research and hamper the correct attribution of R&D investments to their impact. Third, success in R&D is hard to predict. High investment may fade away without producing any output, whereas in other instances low investment may create marvelous results. Finally, no clear boundary exists between R&D investments in different sectors. In many cases inventions in one sector are based on inventions in other sectors. In a sectoral analysis of a specific R&D sector, e.g. agricultural R&D, these cross-connections cannot be considered.

Due to improved data on agricultural R&D investment [21] and a measure for agricultural land use intensity, we are able to present a new attempt of implementing endogenous technological change in a land use model, which uses a deterministic investment-improvement ratio and ignores possible spillovers from other sectors. Within a sectoral model and with the current data availability to analyse the relationship of R&D investments and agricultural productivity this is the only option to endogenise technological change. With the new approach presented here, the model can freely decide on the optimal rate of technological change, which is of central importance for long-term projections over several decades and dynamics under increasingly limited production resources. For this purpose, we relate investments in technological change and corresponding yield growth to agricultural land use intensities. As a second step, we estimate empirically how the level of agricultural production costs per area evolves with the yield level. The methods are implemented in the global land use optimisation model MAgPIE ("Model of Agricultural Production and its Impact on the Environment") [22–24] and the resulting technological change rates are validated with independent data. Finally, in order to illustrate the importance of the dynamic behaviour of TC, we compare two extreme scenarios on forest conservation which reflect the trade-off between agricultural land expansion and technological change.

2. Methodological framework

The endogenous implementation of agricultural TC is based on production costs and the effectiveness of R&D investments on yield changes (investment–yield ratio, IY) (see Table C.1 for definitions). The IY ratio, describing TC investments required per unit of yield growth, evolves with the agricultural land use intensity. Accordingly, production costs (i.e. for use of inputs) are based on yield levels. For the purpose of measuring agricultural land use intensity we use the τ-factor developed by Dietrich et al. [25]. The τ factor is an output-related measure of land use intensity and captures the full spectrum of yield increasing technology and management options. It is the ratio of actual yields and reference yields under a spatially and temporally fixed land use intensity.

2.1. Investment–yield ratio

Based on the τ factor it is possible to link investment costs for generating technological change directly to the level of land use intensity. We differentiate between two types of investment costs which influence the rate of technological change: first, public and private investments in agricultural R&D, and second,

Table C.1
Concepts and terms used in this paper.

Concept	Description
Agricultural land use intensity	Degree of yield amplification caused by human activities [25]
τ-factor	Measure proportional to agricultural land use intensity [25]
Technological change (TC)	More efficient usage of the input factors land, labour or capital [65]
TC investments	Composite of annual investments in R&D and infrastructure (e.g. transport and telecommunication) [US$/year]
Investment–yield ratio (IY ratio)	TC investments required per human-induced unit yield growth and area [US$/ha]