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The biophysical and socio-economic dimension of yield gaps in the southern Amazon – A bio-economic modelling approach

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ABSTRACT

Farmers in the State of Mato Grosso are among Brazil's most productive soybean, maize and cotton producers, but are still far away from achieving potential yields as measured on experimental sites. The objective of this study was to decompose yield gaps in the Southern Amazon into their biophysical and socio-economic dimensions. In order to achieve this, the process-based **MO**del of **NI**trogen and **C**arbon dynamics in **A**gro-ecosystems (MONICA) was coupled with the Mathematical Programming-based Multi-Agent Systems (MPMAS) software. Soybean, maize and cotton yield gaps were simulated for five macro-regions in Mato Grosso considering different climatic, edaphic and crop management conditions. The impact of socio-economic constraints on crop yields was assessed in form of full factorial design in which each factor was set to a baseline and unconstrained level. The simulation results show that biophysical yield gaps (due to water and nutrient deficit) account for 24% of potential yields (Y_p), whereas an unrestricted access to machinery, labour, credit and technological innovation would lead to a reduction of yield gaps by 6.1% and an expansion of cropland by 22%. Yield gaps can be reduced through improved water- and nutrient management, appropriate cultivar-sowing date combinations and in part by a removal of socio-economic constraints. However, each solution comes with its own limitation either in form of increased pressure on limited environmental resources or incompatibility with individual farmer objectives. Future yield gap closure will depend on the access to arable land, environmental regulations preventing further deforestation as well as political and economic incentives for sustainable intensification.

1. Introduction

The agricultural sector faces immense challenges: it is confronted with the task of producing sufficient food and biomass for an increasing world population and the conservation of natural resources on which it depends on (FAO, 2009; UN DESA, 2015). Currently, it is responsible for one quarter of global greenhouse gas emissions (IPCC, 2014) and contributes to the loss of biodiversity through cropland expansion and the degradation of soil and water resources through an excessive use of fertilizers and pesticides (Tilman et al., 2011). Foley et al. (2011) found that global food production can be increased by 2.3 billion tonnes if the gap between potential yields (Y_p) and actual yields (Y_a) was closed to 95%. According to Müller et al. (2012), large production increases (45% to 70%) will be possible through yield gap closure if nutrient imbalances and inefficiencies are reduced. However, the scope for further yield gap reductions varies from region to region: while farmers in Western Europe, the United States, China and South America are close to attain Y_p, farmers in Eastern Europe and Sub-Saharan Africa face large intensification opportunities as those are the regions with the largest yield gaps (Licker et al., 2010; Müller et al., 2012).

Over the past two decades, Brazil has emerged as a global player on the agricultural world market and is nowadays leading the exportation of soybean, corn, sugar, meat, coffee and ethanol (IMF, 2017). Large parts of Brazil's agricultural commodities are produced in the state of Mato Grosso (MT) in the Southern Amazon (CONAB, 2016), where intensive double-cropping systems were adapted to local climatic conditions (Arvor et al., 2014). However, with about one third of the total deforested area in the Legal Amazon (INPE, 2017), MT is also a hotspot

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of deforestation. Despite recent intensification processes and technological advances, farmers in the state of MT are still far away from obtaining yield potentials as measured on experimental sites. Between 1987 and 2013, the average maize yield obtained on experimental sites of the Brazilian Agricultural Research Corporation (EMBRAPA, 2016) in Central-West Brazil was 53% higher than the average maize yield reported by farmers in MT (IBGE, 2015). In a study on soybean yield gaps in Brazil, Sentelhas et al. (2015) found that the yield gap (Y_g) between Y_p and actual yields (Y_a) in two locations in MT amounts to 1.2 t ha^{-1}, corresponding to 27%, and is mainly caused by water deficit and low soil fertility.

Biophysical and management related factors of yield gaps have been studied at the local (Soltani et al., 2016; Stuart et al., 2016), regional (Grassini et al., 2015; Henderson et al., 2016; Monteiro and Sentelhas, 2013) and global (Foley et al., 2011; Licker et al., 2010; Müller et al., 2012; Neumann et al., 2010) scale. A comprehensive ongoing research project on yield gaps is the Global Yield Gap and Water-Productivity Atlas (GYGA) that aims at providing estimates of exploitable yield gaps for all major food crops and countries. While time-intensive and costly field experiments have been used in the past to assess the magnitude and possible causes of Y_g, nowadays, crop simulation models provide flexible tools to simulate the effects of interacting constraints on yields (Affholder et al., 2003; Boling et al., 2010). Suboptimal nutrient and water management, inappropriate sowing dates, insufficient crop protection and low soil fertility were identified as key biophysical and management related factors explaining the yield gap (Beza et al., 2016).

The relation of socio-economic factors to yield gaps is less straight forward. According to Penning de Vries (1990), socio-economic factors never interact directly with plant growth, but constitute important boundary conditions, which determine farmers' decision-making process and hence the management choices they make. The price of fertilizers, for example, is not directly linked to crop growth, but defines how much fertilizer is applied, particularly if input costs are high. Limited access to credit, machinery and transportation costs, labour shortage, risk aversion, poor infrastructure, insecure land tenure rights, adverse land management policies and political instability are some of the major socio-economic and institutional hurdles of yield gap closure (Duwayri et al., 2000; Liu et al., 2016; Lobell et al., 2009; Müller et al., 2012; van Dijk et al., 2012; Michiel van Dijk et al., 2017; Zhang et al., 2016).

In a review on yield-gap explaining factors, Beza et al. (2016) found that biophysical factors are more often considered in yield gap analysis than farm characteristics or socio-economic factors, but the latter often explain large parts of the yield gap. Yield gap studies that address both the biophysical and socio-economic dimension of yield gaps are scarce as well as yield gap studies for the Southern Amazon. We seek to address this research gap by decomposing the yield gap in the Southern Amazon into its biophysical and socio-economic dimensions. The objectives of this study are to

(i) simulate potential, water-limited and actual soybean, maize and cotton yields in response to different climatic conditions, soil types, sowing dates, crop rotation schemes and fertilisation rates in five survey sites in MT;
(ii) estimate the magnitude of the biophysical yield gap in MT and identify its explaining factors;
(iii) assess the main effects of socio-economic constraints on yields in MT.

Yield gaps were decomposed into their biophysical and socio-economic components by coupling the process-based **Mo**del of **Ni**trogen and **C**arbon dynamics in **A**gro-ecosystems (MONICA) with the Mathematical Programming-based Multi-Agent Systems (MPMAS) software, which simulates decision-making at the farm household level (Nendel et al., 2011; Schreinemachers and Berger, 2011). Coupling two simulation models from different disciplines (agronomy and agricultural economics) helps to "improve results, raise the number of alternatives for management […] and expand area to which the new model is applicable" (Penning de Vries, 1990). In fact, neither crop growth nor agro-economic models alone can adequately explore the full dimension of yield gaps: While crop models find it difficult to represent farmers` decisions regarding the use of purchased inputs, agro-economic models fail to capture how biophysical determinants affect yield levels (Schreinemachers et al., 2007; Vera-Diaz et al., 2008). The integrated MONICA and MPMAS model system allows for a detailed representation of crop growth under different climatic and crop management conditions as well as the assessment of socio-economic constraints on farm household decision making. This interdisciplinary approach enables us to address a much larger range of yield gaps-related determinants than common disciplinary approaches can do.

2. Material and methods

2.1. The models

2.1.1. The MONICA model

MONICA is a process-based crop growth model that was initially developed to account for the combined effects of changing climate variables and soil processes in Central Europe (Nendel et al., 2011; Nendel et al., 2014). It consists of several interrelated modules that are able to simulate crop growth, soil hydrology and temperature, nitrogen uptake and organic matter turnover in the soil. The crop growth process is simulated as a function of temperature, solar radiation and atmospheric CO_2 concentration. In a simplified process of photosynthesis, light energy is converted into carbohydrate molecules, which, in turn, are distributed among crop organs (root, shoot, leaf and fruit), while the plant evolves through several development stages from sowing to harvest maturity. In early development stages, root and leaf growth is fostered, whereas shoot and fruit growth is enhanced in later development stages. The duration of each development stage depends on the number of growing degree days (GDD), which are calculated as the difference between daily average temperature and a crop-specific base temperature (Nendel, 2014).

MONICA has been widely tested and benchmarked in international model inter-comparisons, including simulations of maize (Durand et al., 2017) and soybean (Battisti et al., 2017a; Battisti et al., 2017b) and their response to climate factors and management. These tests included soil (pseudo-sand aggregated ferralsols) and climate environments (hot and humid winters, warm and dry summers) that are comparable to the conditions in MT. MONICA considers the sand-like water transport alongside the micro-aggregates, while reproducing the water storage behaviour of the clay aggregates, as it is typical for ferralsols in this region. However, soil surface charge-induced deviations from standard temperate nitrate and ammonia transport formalisms, as could be expected for tropical acid soils, are not implemented in MONICA. Also, as MONICA considers only nitrate uptake in plants and not ammonia, the typically elevated ammonia-to-nitrate ratio in tropical soils may be a factor that attenuates MONICA's ability to reproduce N response of crops in tropical environments. Within the scope of the German-Brazilian research project Carbiocial (Carbon Sequestration, Biodiversity and Social Structures in the Southern Amazon), MONICA was calibrated to crop cultivars grown in a sub-tropical environment (Carauta et al., 2017a; Carauta et al., 2017b). An evaluation of the predictive performance of MONICA at farm-level is shown in the supplementary material.

2.1.2. MPMAS software

MPMAS is a software package for dynamic modelling of agricultural holdings, which are represented by computational agents (Schreinemachers and Berger, 2011). For modelling farm investment, production and consumption decisions, MPMAS employs mathematical programming (MP), an optimisation method originating from