Agricultural Systems 148 (2016) 159–168

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Accounting for interannual variability in agricultural intensification: The potential of crop selection in Sub-Saharan Africa

P. Bodin [a,*], S. Olin [a], T.A.M. Pugh [b,c], A. Arneth [b]

[a] *Department of Physical Geography and Ecosystem Science, Sölvegatan 12, Lund University, Lund, Sweden*
[b] *Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Karlsruhe Institute of Technology, Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany*
[c] *School of Geography, Earth & Environmental Science and Birmingham Institute of Forest Research, University of Birmingham, B15 2TT, United Kingdom*

ARTICLE INFO

Article history:
Received 10 March 2016
Received in revised form 13 July 2016
Accepted 22 July 2016
Available online 7 August 2016

Keywords:
Climate change
Yield
LPJ-GUESS
Crop model
Modern Portfolio Theory

ABSTRACT

Providing sufficient food for a growing global population is one of the fundamental global challenges today. Crop production needs not only to be increased, but also remain stable over the years, in order to limit the vulnerability of producers and consumers to inter-annual weather variability, especially in areas of the world where the food consumed is mainly produced locally (e.g. Sub Saharan Africa (SSA)).

For subsistence agriculture, stable yields form a crucial contribution to food security. At a regional to global scale dynamical crop models can be used to study the impact of future changes in climate on food production. However, simulations of future crop production, for instance in response to climate change, often do not take into account either changes in the sown areas of crops or yield interannual variability. Here, we explore the response of simulated crop production to assumptions of crop selection, also taking into account interannual variability in yields and considering the response of agricultural productivity to climate change. We apply the dynamic global vegetation model LPJ-GUESS, which is designed to simulate yield over large regions under a changing environment. Model output provides the basis for selecting the relative fractions of sown areas of a range of crops, either by selecting the highest yielding crop, or by using an optimization approach in which crop production is maximized while the standard deviation in crop production is kept at below current levels.

Maximizing simulated crop production for current climate while keeping interannual variability in crop production constant at today's level generates rather similar simulated geographical distributions of crops compared to observations. Even so, the optimization results suggest that it is possible to increase crop production regionally by adjusting crop selection, both for current and future climate, assuming the same cropland cover as today. For future climates modelled production increase is >25% in more than 15% of the grid cells. For a small number of grid cells it is possible to both increase crop production while at the same time decreasing its interannual variability. Selecting the highest yielding crop for any location will lead to a large potential increase in mean food production, but at the cost of a very large increase in variability.

1. Introduction

Global food security is a fundamental challenge for Earth's current and future population. Currently around 840 million people in the world are under-nourished (Food and Agricultural Organisation, 2013). Due to an increasing global population and changes in food consumption patterns, it is expected that crop production needs to double by 2050, for which several options exist in principle. On the production side this entails either increasing the extent of agricultural land or increasing production on existing cropland. In this context, reducing the difference between actual and potential yield (closing the so-called yield gap) through improved management (including irrigation and fertilizer use) and by selection of appropriate cultivars (Foley et al., 2011; Licker et al., 2010; Mueller et al., 2012) is fundamental.

A second option, somewhat less discussed, would be to select different crop *species* (as opposed to different cultivars of the same crop) that give a higher yield locally (Franck et al., 2011; Koh et al., 2013). For example, Koh et al. (2013) found that global cereal crop production could increase by 46% when selecting the highest yielding cereal (in terms of mass) for each location. But selecting the highest yielding crop in all locations is not rational if one wishes to ensure stability in the global crop production. Already the risk of an increasing volatility, as a consequence of agricultural systems becoming more homogenous, is being debated, since a few dominating crops can be vulnerable to episodic events such as extreme weather or disease (Khoury et al., 2014). Moreover, in many parts of the developing world, such as in Sub-Saharan Africa (SSA), people are largely dependent on local crop production for their sustenance and lack the means to compensate for years of poor

---

* Corresponding author.
E-mail address: per.e.bodin@gmail.com (P. Bodin).

http://dx.doi.org/10.1016/j.agsy.2016.07.012

production by buying food on global markets (Devereux and Maxwell, 2001; Funk and Brown, 2009). This means that local crop production is a critical aspect for establishing local food supply (Garrity et al., 2010), but making local population highly vulnerable to the effects of extreme weather events and crop failure. In addition, SSA is also a region where the effects of climate change on agriculture are expected to be most adverse (Barrios et al., 2008; Kotir, 2011), including an increased vulnerability in the majority of the region's rain-fed cropland area, which constitutes 97% of the total cropland area (Rockström et al., 2004).

In regions where food security is closely linked to local food production, the inter-annual variability in yields also needs to be taken into account. In a changing future climate, one key question is whether farmers in a more variable future climate will still aim to "optimise productivity under increased climate variability or adopt strategies and management practices that are more risk averse, and aim to achieve consistent, but potentially lower, productivity" (Matthews et al., 2013). In theory, crops could thus be selected in order to maximize crop production while keeping interannual variability in production at an acceptable level. Although it must be considered that in reality, other factors also affect the selection of the crops sown, such as food preferences and market drivers.

To study potential future changes in regional to continental and global crop production, large-scale agricultural models have become useful tools for predicting future changes in crop yield over large regions (Berg et al., 2011; Bondeau et al., 2007; Deryng et al., 2011; Di Vittorio et al., 2010; Drewniak et al., 2013; Gervois et al., 2004; Lindeskog et al., 2013; Lokupitiya et al., 2009; Sus et al., 2010; Tao et al., 2009). For example, many of these models have been applied within the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013b) including a model intercomparison study where the effect of global change on future crop yield globally was simulated using a large number of crop models (Rosenzweig et al., 2013a). However, to date most analyses have concentrated on the impact of climate on mean yields, while studies that have also investigated the effect of climate change on changes in yield variability are rare. Despite often being described as tools to support adaptation strategies, relatively few examples of studies in which crop models have been applied to these types of questions can be found in the literature (Webber et al., 2014).

The Modern Portfolio Theory (MPT) (Markowitz, 1959) is a theory within economics for selecting a portfolio of stocks taking into account not only the monetary return of the portfolio of these stocks, but also risk aversion. This has been extended into the realm of agriculture, looking at the return of a portfolio of different crop varieties of wheat and rice (Nalley et al., 2009; Nalley and Barkley, 2010). We broaden this approach here further by combining MPT with simulated yields for SSA from an agrological global dynamic vegetation model (LPJ-GUESS; Smith et al., 2001; Lindeskog et al., 2013). Rather than looking at maximizing financial return we here instead maximize the number of calories produced. In this study we explore the potential to increase crop production through crop selection for SSA while also taking into account interannual variability in production. This study is a stylised experiment, and not intended to represent the decision making of individual farmers, which is determined by many economic aspects beyond climate effect on yields such as food preference, market value, or access to markets.

The focus of the study is the potential increases in crop production that could be attained through crop selection while constraining to an acceptable level of variance in production. The increase in production in this study is thus assessed without extending agricultural land or through increased irrigation or fertilizer use.

Using the same acceptable level of crop production for future yield means that this study also takes into account limited climate adaptation. While performing the analysis we generate optimized relative cropland cover for each crop and grid cell.

The main purpose of the study is to:

1) Explore the potential to increase crop production through crop selection for SSA while also taking into account interannual variability in production using simulated yield and an optimization approach.
2) Explore changes in the optimized cropland fractions over time for a range of crops.
3) Compare the optimized geographical distributions of crops to observed distributions for current climate.

2. Methods

Here we use a state-of-the art agrological global dynamical vegetation model LPJ-GUESS (Lindeskog et al., 2013; Smith et al., 2001) to simulate current and future potential crop production in SSA. Simulated yields are then used as the basis for two different optimizations. The first one is to select the single highest yielding crop. The second option is based on MPT and here the relative sown areas for a range of crops are adjusted in order to maximize the number of calories produced while at the same time keeping the variance at a minimum level.

2.1. Model description

LPJ-GUESS is a deterministic, process-based dynamic global vegetation model designed to simulate patterns and dynamics of natural vegetation and corresponding fluxes of carbon and water (Lindeskog et al., 2013; Smith et al., 2001). It is driven by daily temperature, precipitation and short wave radiation and runs at a daily time scale, typically with a spatial resolution of 0.5°. Model processes include photosynthesis, respiration, water uptake, evapotranspiration, and carbon allocation and growth. The model has been evaluated against a broad range of observations, including for carbon fluxes in European forest ecosystems (Morales et al., 2005), seasonality of vegetation greenness in cropland regions in Africa (Lindeskog et al., 2013), interannual variability of terrestrial carbon uptake (Ahlström et al., 2012), CO_2 fertilisation response (Hickler et al., 2008), and yields and soil carbon response after land-use change (Pugh et al., 2015). Cropland processes have been recently introduced into LPJ-GUESS, with crops represented through 11 typologies of crops named Crop Functional Types (CFTs; Bondeau et al., 2007). Carbon allocation to various yield organs depends on summed heat units (degree-days above a crop-specific base temperature), also calculated at a daily time step. A dynamic Potential Heat Unit (PHU) sum needed to reach full maturity is calculated for each grid cell and each CFT based on the mean temperature of the last 10 years (Lindeskog et al., 2013). This approach means that the model assumes that varieties with growing periods adapted to the prevailing climate are always available and selected. As such, it represents the opposite approach to that commonly employed in global crop models of no cultivar adaptation to climate whatsoever (e.g. Rosenzweig et al., 2013a). A new sowing algorithm based on Waha et al. (2012) was also introduced where the timing of sowing depends on the variability in temperature or precipitation, rather than being specified from external datasets. Disturbance and mortality through extreme weather, pests and diseases are presently not yet accounted for in crops. Yields of CFTs are simulated separately for irrigated and rain-fed crops. Except for sowing and irrigation, crops are assumed to be grown under similar conditions regarding management, nutrients and pests across all grid cells in the model.

2.2. Modelling crop yield using LPJ-GUESS

Here we used the simulated rain-fed yield from the LPJ-GUESS model runs from the model intercomparison study performed as a part of AgMIP (Rosenzweig et al., 2013a). The model was driven by bias-corrected climate forcing data from 5 General Circulation Models (GCMs) (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) obtained from the Coupled Model Intercomparison Project Phase 5