Global and Planetary Change 122 (2014) 107–121

Contents lists available at ScienceDirect

Global and Planetary Change

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

# Global wheat production potentials and management flexibility under the representative concentration pathways

Juraj Balkovič [a,b,*], Marijn van der Velde [c], Rastislav Skalský [a,d], Wei Xiong [e,f], Christian Folberth [a], Nikolay Khabarov [a], Alexey Smirnov [a], Nathaniel D. Mueller [g], Michael Obersteiner [a]

[a] International Institute for Applied Systems Analysis (IIASA), Ecosystem Services and Management Program, Schlossplatz 1, A-2361 Laxenburg, Austria
[b] Department of Soil Science, Faculty of Natural Sciences, Comenius University in Bratislava, 842 15 Bratislava, Slovak Republic
[c] European Commission, DG JRC, Institute for Environment and Sustainability, Ispra, 21027, Italy
[d] National Agricultural and Food Centre, Soil Science and Conservation Research Institute, 827 13 Bratislava, Slovak Republic
[e] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32600-0570, USA
[f] Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Science, Beijing 100081, China
[g] Harvard University Center for the Environment, Harvard University, Cambridge, MA 02138, USA

ARTICLE INFO

*Article history:*
Received 4 November 2013
Received in revised form 7 August 2014
Accepted 12 August 2014
Available online 20 August 2014

*Keywords:*
EPIC
RCP
wheat yield
wheat yield gap
wheat yield potential
wheat management
world wheat production

ABSTRACT

Wheat is the third largest crop globally and an essential source of calories in human diets. Maintaining and increasing global wheat production is therefore strongly linked to food security. A large geographic variation in wheat yields across similar climates points to sizeable yield gaps in many nations, and indicates a regionally variable flexibility to increase wheat production. Wheat is particularly sensitive to a changing climate thus limiting management opportunities to enable (sustainable) intensification with potentially significant implications for future wheat production. We present a comprehensive global evaluation of future wheat yields and production under distinct Representative Concentration Pathways (RCPs) using the Environmental Policy Integrated Climate (EPIC) agro-ecosystem model. We project, in a geographically explicit manner, future wheat production pathways for rainfed and irrigated wheat systems. We explore agricultural management flexibility by quantifying the development of wheat yield potentials under current, rainfed, exploitable (given current irrigation infrastructure), and irrigated intensification levels. Globally, because of climate change, wheat production under conventional management (around the year 2000) would decrease across all RCPs by 37 to 52 and 54 to 103 Mt in the 2050s and 2090s, respectively. However, the exploitable and potential production gap will stay above 350 and 580 Mt, respectively, for all RCPs and time horizons, indicating that negative impacts of climate change can globally be offset by adequate intensification using currently existing irrigation infrastructure and nutrient additions. Future world wheat production on cropland already under cultivation can be increased by ~35% through intensified fertilization and ~50% through increased fertilization and extended irrigation, if sufficient water would be available. Significant potential can still be exploited, especially in rainfed wheat systems in Russia, Eastern Europe and North America.

## 1. Introduction

In the coming years the agricultural sector will face a challenge to feed an increasingly growing human population while simultaneously facing a need to avoid additional deforestation and land degradation. This challenge requires the sustainable intensification of underperforming agricultural systems that can cope with climate change. With a current production of ~700 Mt, wheat is the third largest crop globally, and an essential source of calories in human diets. Wheat will remain a crucial component of human nutrition and increasing its production is therefore an important requirement for food security. Two main aspects of securing and sustaining future world wheat production are being discussed. Firstly, sustainable intensification of wheat systems to satisfy rising food demands (Cassman, 1999; Cassman et al., 2003; Foley et al., 2011;

---

*Abbreviations:* N-AM, Northern America; CS-AM, Central and South America; W-EU, Western Europe; S-EU, Southern Europe; E-EU, Eastern Europe; N-EU, Northern Europe; RFED, Russian Federation; W-AS, Western Asia; C-AS, Central Asia; S,SE-AS, Southern and South-Eastern Asia; E-AS, Eastern Asia; A-NZ, Australia and New Zealand; N-AF, Northern Africa; S-AF, Sub-Saharan Africa.

[*] Corresponding author at: International Institute for Applied Systems Analysis (IIASA), Ecosystem Services and Management Program, Schlossplatz 1, A-2361 Laxenburg, Austria. Tel.: +43 2236/807 385; fax: +43 2236/807 599.

*E-mail addresses:* balkovic@iiasa.ac.at, balkovic@fns.uniba.sk (J. Balkovič), marijn.van-der-velde@jrc.ec.europa.eu (M. van der Velde), skalsky@iiasa.ac.at, r.skalsky@vupop.sk (R. Skalský), wei.xiong@ufl.edu (W. Xiong), folberth@iiasa.ac.at (C. Folberth), khabarov@iiasa.ac.at (N. Khabarov), smirnov@iiasa.ac.at (A. Smirnov), nmueller@fas.harvard.edu (N.D. Mueller), oberstei@iiasa.ac.at (M. Obersteiner).

http://dx.doi.org/10.1016/j.gloplacha.2014.08.010
0921-8181/© 2014 Elsevier B.V. All rights reserved.

Lobell, 2012; Mueller et al., 2012) and, secondly, the impacts of future climate on wheat yields (Lobell et al., 2008, 2011; Asseng et al., 2011).

Global fertilizer and pesticide use has increased significantly during the last decades leading to an increase in wheat yields in many countries. Yet, approximately 70% more wheat could still be produced if the cropland already under cultivation met its current climatic potential, which can mainly be achieved through improved fertilization and irrigation (Mueller et al., 2012). A large geographic variation in wheat yields across similar climates points to sizeable yield gaps in many nations, and indicates a regionally variable flexibility to increase wheat production (Licker et al., 2010; Mueller et al., 2012). For example, substantial progress is still lacking in Africa (Ejeta, 2010). On the other hand, certain signs of stagnation in wheat yield development have already been reported for some of the leading producers, including Western Europe, Western U.S., China or India (Hafner, 2003; Lin and Huybers, 2012; Ray et al., 2012). Therefore, a geographically explicit assessment of actually achieved and potentially achievable yields is desired to identify the flexibility for future yield developments (Lobell et al., 2009; van Ittersum et al., 2013).

Climate change will alter growing conditions and thus impact future wheat production and management opportunities for sustainable intensification. Wheat is expected to be especially sensitive to rising temperature since it has been among the crops most affected in an already changing climate (Schlenker and Lobell, 2010; Lobell et al., 2011). Warming is likely to reduce wheat yields due to a shorter grain filling period caused by a more rapid development (van Oijen and Ewert, 1999). On the other hand, increased growth rates during winter or a shift of the grain filling period into a wetter part of the season may result in rising wheat yields in some regions (Ludwig and Asseng, 2006; Xiao et al., 2010). In addition, precipitation is expected to become an important driver for crop production in many regions, such as in South and West Asia (Lobell and Field, 2007; Lobell and Burke, 2008). Recent simulations have also indicated that the negative effect of global warming may be offset by the direct $CO_2$ fertilization effect (Long, 2006). Therefore, a comprehensive and spatially explicit approach is needed to evaluate the impacts of future climate on global wheat production and intensification opportunities.

Given the complexity of crop responses to climatic and management drivers, simulation models are essential to evaluate how much the drivers matter in different regions (Lobell et al., 2011). Large-scale implementations of crop and ecosystem simulation models are increasingly used for these purposes at regional to global scales, including EPIC (Liu et al., 2007; Folberth et al., 2012; Van der Velde et al., 2012, 2014; Balkovič et al., 2013), DayCent (Stehfest et al., 2007), PEGASUS (Deryng et al., 2011), DSSAT (Nelson et al., 2010), GLAM (Osborne et al., 2007), LPJmL (Bondeau et al., 2007) or WOFOST (Boogaard et al., 2013). Such implementations are commonly based on a crop growth model spatially integrated with available datasets on climate, soils and land use. However, together with the rising popularity of large-scale crop models, certain limitations related to the up-scaling of models have been emphasized (e.g. Hansen and Jones, 2000; Niu et al., 2009; van Ittersum et al., 2013). Foremost, integration of spatially heterogeneous and granular weather, soil and management data leads to aggregation errors resulting in spatial and temporal bias (Hansen and Jones, 2000). A thorough model calibration, which should be a prerequisite for its reliable application, cannot be performed since there are no comprehensive experimental or independent data available that allow for testing of the entire set of variables and their interactions represented in the integrated models. Therefore, a careful validation or evaluation against historical yield observations must be performed when using a crop growth model at larger scales (e.g. Balkovič et al., 2013). In addition, interaction and transfer of uncertainties through the climate to crop model chain introduce another concern specific for climate change studies (Asseng et al., 2013).

Recently, a new generation of emission scenarios called the Representative Concentration Pathways (RCPs), following up on the IPCC SRES scenarios, has been developed (Moss et al., 2010). Together with improvements in Global Circulation Model (GCM) simulations, the new RCPs provide higher spatial and temporal resolution in climate change scenarios, more consistent land-use and land-cover information and projections. In addition, globally consistent agricultural management data on wheat cultivation are increasingly available, including the new dataset on crop-specific fertilization and achievable yields by Mueller et al. (2012). The expanding availability of wheat management data, together with the release of the RCP climate data (cf. Hempel et al., 2013), motivated us to this study.

Although quite a few studies on climate change impacts in agricultural sector have been published (Tan and Shibasaki, 2003; Deryng et al., 2011; Tatsumi et al., 2011; Liu et al., 2013), a global assessment of both actual and potential wheat yields and production quantifying the intensification potential under climate change is still lacking. In this study we build and test a geographically explicit global implementation of the EPIC (Environmental Policy Integrated Climate model; Williams, 1995) crop growth model, that is driven by RCP climate data, and set up and evaluated by the most recent and complete information on global wheat cultivation currently available. The main objective of this article is to evaluate, in a spatially explicit manner, global and regional wheat yield developments under current and fertilization/irrigation-intensive managements to estimate management flexibility for future intensification under the RCP scenarios. To achieve the main objective, several specific objectives were identified: (1) to evaluate the ability of our global EPIC implementation to capture historical wheat yields and production under various management systems (current input intensity, rainfed potential, potentials with current irrigation infrastructure, and potential not limited by nutrients or water), (2) to estimate future wheat yield development under the RCP climates and various management systems, and (3) to evaluate the impacts of the RCPs on future wheat production, and the flexibility that fertilization and irrigation management can provide to maintain or increase total global wheat production.

## 2. Material and methods

### 2.1. The EPIC model

EPIC is one of the most widely used crop models for studies on climate change impacts in the agricultural sector (White et al., 2011). It was originally developed to quantify effects of erosion on soil productivity in the U.S. (Williams et al., 1984) and has been continuously extended into a complex agro-ecosystem model (Sharpley and Williams, 1990; Williams, 1995). It contains routines for simulating crop growth, yield and competition, hydrological, nutrient and carbon cycle, weather simulation, soil temperature and moisture, soil erosion and a wide range of crop management options, including tillage, fertilization, irrigation, liming and pesticides. EPIC operates on a daily time step and can be used for long-term assessments spanning decades to centuries. The EPIC model has been extensively calibrated and validated against observations under various climatic conditions in the U.S. and other regions (cf. Gassman et al., 2005). It has been used for assessments of crop production (Balkovič et al., 2013), climate change (Tan and Shibasaki, 2003; Niu et al., 2009; Liu et al., 2013), water resources use (Liu et al., 2007; Liu and Yang, 2010) as well as carbon sequestration, GHG mitigation and biofuel studies (cf. Izaurralde et al., 2012).

Potential plant growth is calculated with a daily time step based on intercepted solar radiation, conversion of $CO_2$ to biomass and vapor pressure deficit. The daily potential growth is decreased by stresses caused by temperature, shortage of water and nutrients (N and P), salinity, aluminium toxicity, soil strength or inadequate soil aeration. Only the stress with the highest impact on potential plant growth on a given day is considered. Temperature stress occurs each day when