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Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—A review

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ABSTRACT

Climate change implies higher frequency and magnitude of agroclimatic extremes threatening plant production and the provision of other ecosystem services. This review is motivated by a mismatch between advances made regarding deeper understanding of abiotic stress physiology and its incorporation into ecophysiological models in order to more accurately quantifying the impacts of extreme events at crop system or higher aggregation levels.

Adverse agroclimatic extremes considered most detrimental to crop production include drought, heat, heavy rains/hail and storm, flooding and frost, and, in particular, combinations of them.

Our core question is: How have and could empirical data be exploited to improve the capability of widely used crop simulation models in assessing crop impacts of key agroclimatic extremes for the globally most important grain crops? To date there is no comprehensive review synthesizing available knowledge for a broad range of extremes, grain crops and crop models as a basis for identifying research gaps and prospects.

To address these issues, we selected eight major grain crops and performed three systematic reviews using SCOPUS for period 1995–2016. Furthermore, we amended/complemented the reviews manually and performed an in-depth analysis using a sub-sample of papers.

Results show that by far the majority of empirical studies (1631 out of 1772) concentrate on the three agroclimatic extremes drought, heat and heavy rain and on the three major staples wheat, maize and rice (1259 out of 1772); the concentration on just a few has increased over time. With respect to modelling studies two model families, i.e. CERES-DSSAT and APSIM, are clearly dominating for wheat and maize; for rice, ORYZA2000 and CERES-Rice predominate and are equally strong. For crops other than maize and wheat the number of studies is small. Empirical and modelling papers don't differ much in the proportions the various extreme events are dealt with – drought and heat stress together account for approx. 80% of the studies. There has been a dramatic increase in the number of papers, especially after 2010.

As a way forward, we suggest to have very targeted and well-designed experiments on the specific crop impacts of a given extreme as well as of combinations of them. This in particular refers to extremes addressed with insufficient specificity (e.g. drought) or being under-researched in relation to their economic importance (heavy rains/storm and flooding). Furthermore, we strongly recommend extending research to crops other than wheat, maize and rice.

1. Introduction

1.1. Background and objectives

Sustainably increasing crop production to meet the projected increase in food demand of > 60% by 2050 compared to present (Alexandratos and Bruinsma 2012), in the face of climatic change, is a major challenge of the 21 st century (Godfray et al., 2010; Wheeler and von Braun, 2013). Increased occurrence and magnitude of adverse and extreme agroclimatic events are considered a major threat to global food security (Lobell and Gourdji, 2012; Trnka et al., 2014; Chenu et al., 2017).

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Some authors have estimated that the annual costs of adaptation in the agriculture, forestry and fishery sectors will amount to at least US$ 14 billion annually by 2030 to cope with the adverse impacts of climate change – though that figure could be two to three times greater (see, Fankhauser, 2010).

Extreme weather is usually defined as the extremes of temperature, precipitation, winds and other phenomena of their historical distribution—i.e. the range that has been seen in the past (Field et al., 2012). Hence, "an extreme event can be typified by its physical intensity, duration or frequency of occurrence." (Rummukainen, 2012;). For this paper, we focus on such adverse and extreme agroclimatic events that are considered most detrimental to crop production – including drought, heat, heavy rains/storm, flooding and frost, or a combination of them (Cattivelli et al., 2008; Battisti and Naylor, 2009; Schlenker and Roberts, 2009; Hakala et al., 2012; Trnka et al., 2011, 2014). This specification implies that we also consider sequences of weather and climate events which are not necessarily extreme by themselves but bring about extreme (cumulative) effects (Hegerl et al., 2011; Rummukainen, 2012)., such as a number of dry spells over the growing season leading to substantial water deficits and substantial yield loss or flooding which may occur as on-side effect of heavy rain happening somewhere else.

Climate change implies higher frequency of extreme weather events (Coumou et al., 2015; IPCC, 2013; Field et al., 2014; Mann et al., 2017) such as heat waves (e.g. Christidis et al., 2015), drought (Dai, 2013; Sheffield and Wood, 2008; Schauberger et al., 2017) or hail (Brimelow et al., 2017) – to name a few – causing reduced crop yields and plant production and threatening the provision of other ecosystem services (Field et al., 2012; Powell and Reinhard, 2016; Rummukainen, 2014).

Whether in tropical or temperate regions, we are already observing more frequent and severe extreme weather events (Alexander et al., 2006; Coumou and Rahmstorf, 2012; Hakala et al., 2012; Lobell et al., 2011; Rummukainen, 2012; Tebaldi et al., 2006 Trenberth et al., 2015; Zheng et al., 2012), in particular increased droughts (Lesk et al., 2016); heat waves (Gourdji et al., 2013) and heavy rainfall events (Lehmann et al., 2015) that affect many important agricultural areas.

The overall picture emerging from the literature on shifts in extremes under a changing climate – summarized by Rummukainen (2012, p116) on the basis of the SREX (Field et al., 2012), as well as the AR4 and AR5 of the Intergovernmental Panel on Climate Change (Field et al., 2014) looks as follows:

- Increased frequency, intensity and duration of heat waves/extreme high temperature events, exceeding the changes in the mean temperature
- Increased heavy precipitation, exceeding the changes in the mean
- Increased drought in (many) different parts of the world
- Decreased cold extremes, exceeding the changes in the mean temperature

For assessing climate change impacts and *ex- ante* evaluation of a multitude of adaptation options, fairly complex and well-tested modelling tools are required, which go beyond empirical descriptions (Rötter et al., 2013a; Tao et al., 2017; Ruiz-Ramos et al., 2018). Process-based crop growth simulation models have proven to be the best available tools for this purpose, as they are capable of exploring genotype × environment × management interactions making them key tools for understanding the processes of the complex interconnections in cropping systems (Chenu et al., 2017; Glotter and Elliot, 2017; Hoffmann et al., 2018; Rötter et al., 2015; Schauberger et al., 2017).

This review paper is motivated by recognizing that though understanding of plant stress physiology has substantially advanced and some deficiencies in crop modelling approaches have been reduced (Cattivelli et al., 2008; Ewert et al., 2015; Lobell and Asseng, 2017; Maiorano et al., 2017; Rezaei et al., 2015; Rötter et al., 2011; Siebert et al., 2017a,b; Yin et al., 2017), the majority of crop models still do not capture the impacts of most relevant extremes for the major grain crops. On the one hand, not all the available knowledge has been incorporated to improve process descriptions in the crop models (Barlow et al., 2015; Rezaei et al., 2015); on the other hand, knowledge gaps with respect to the mechanisms leading to impacts by some extremes exist (see, e.g. Pagani et al., 2017; Moshelion et al., 2014). As a result, the impacts of specific weather extremes on crop performance might often not be quantified adequately at the crop system or higher aggregation levels (Barlow et al., 2015; Rötter et al., 2015; Wang et al., 2017a).

The core question addressed in this review is: How can empirical data be exploited to improve the capability of widely used crop simulation models in assessing impacts of key agroclimatic extremes for the globally most important cereal and legume crops? A related question is, how could they be utilized for future model improvements?

To explore this, we formulated three specific objectives: (i) to examine what relevant empirical data have been utilized to increase quantitative understanding of crop impacts of specific weather extremes, (ii) to inventory available modelling studies and approaches for assessing the impacts of extremes, and (iii) to identify studies demonstrating model improvements, specify datasets required and prioritize future research.

1.2. Brief literature review

Several reviews on the physiological mechanisms causing yield penalties by extremes have been conducted, usually for one or more major crops and for one or two extremes only – among others, by Barlow et al. (2015) on heat and frost for wheat, Rezaei et al. (2015) on heat for wheat, maize and rice, Bodner et al. (2015) on drought for several cereals and grain legumes, and Gardiner et al. (2016) for wind impacts on crop growth.

A common goal of the reviews by Barlow et al. (2015) and Rezaei et al. (2015) has been to draw conclusions for guiding future crop model improvements. A few of their main points are summarized here:

- for wheat, a heat shock module is proposed that specifically accounts for the reduction in grain number around anthesis (Barlow et al., 2015), while also describing advanced senescence and reduced duration of grain filling from cumulative heat load; it is suggested to follow the procedure of the crop models GLAM (Challinor et al., 2005) and MONICA (Nendel et al., 2011) which describe the percentage reduction in grain number as a function of temperature around anthesis.

- Barlow et al. (2015) proposed a frost shock module for wheat that follows a similar approach as the proposed heat shock module and also resembles much of the frost stress index calculations by STICS (see, Brisson et al., 2003, 2008).

- Rezaei et al. (2015) suggested to study in more detail the impact of short episodes of extreme heat around flowering – which have been reported to have likely large negative effects on cereal grain yields (see, Porter and Gawith 1999 for wheat); that phenomenon had already been studied in some detail for rice in the 1970s – and empirical data had been used to modify temperature response functions to account for spikelet sterility in rice from short episodes of extreme heat (see, e.g. Horie et al., 1995); however, Jagadish et al. (2011) observed different responses under combined heat and drought stress conditions compared to independent exposure of both.

- It has also been suggested to more closely consider the combined effects of different abiotic stresses, such as heat and drought (see, e.g. Barnabas et al., 2008; Trnka et al., 2014). Combined effects cannot be explained or directly extrapolated from plant response to individual stresses (e.g. Mittler, 2006; Hlavacova et al., 2017; Hláváčová et al., 2018; Urban et al., 2018).

- Rezaei et al. (2015) proposed consideration of canopy temperature as a driver of crop models (instead of just air temperature, as is usually done) as a promising innovation for simultaneously accounting for heat and drought (see, Webber et al., 2017).