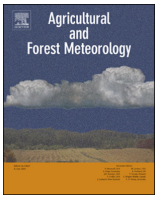
Agricultural and Forest Meteorology 259 (2018) 364–373

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Water productivity of rainfed maize and wheat: A local to global perspective

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ARTICLE INFO

Keywords:
Water productivity
Yield
Wheat
Maize
Management
Spatial framework

ABSTRACT

Water productivity (WP) is a robust benchmark for crop production in relation to available water supply across spatial scales. Quantifying water-limited potential (WPw) and actual on-farm (WPa) WP to estimate WP gaps is an essential first step to identify the most sensitive factors influencing production capacity with limited water supply. This study combines local weather, soil, and agronomic data, and crop modeling in a spatial framework to determine WPw and WPa at local and regional levels for rainfed cropping systems in 17 (maize) and 18 (wheat) major grain-producing countries representing a wide range of cropping systems, from intensive, high-yield maize in north America and wheat in west Europe to low-input, low-yield maize systems in sub-Saharan Africa and south Asia. WP was calculated as the quotient of either water-limited yield potential or actual yield, and simulated crop evapotranspiration. Estimated WPw upper limits compared well with maximum WP reported for field-grown crops. However, there was large WPw variation across regions with different climate and soil (CV = 29% for maize and 27% for wheat), which cautions against the use of generic WPw benchmarks and highlights the need for region-specific WPw. Differences in simulated evaporative demand, crop evapotranspiration after flowering, soil evaporation, and intensity of water stress around flowering collectively explained two thirds of the variation in WPw. Average WP gaps were 13 (maize) and 10 (wheat) kg ha^{-1} mm^{-1}, equivalent to about half of their respective WPw. We found that non-water related factors (*i.e.*, management deficiencies, biotic and abiotic stresses, and their interactions) constrained yield more than water supply in *ca.* half of the regions. These findings highlight the opportunity to produce more food with same amount of water, provided limiting factors other than water supply can be identified and alleviated with improved management practices. Our study provides a consistent protocol for estimating WP at local to regional scale, which can be used to understand WP gaps and their mitigation.

1. Introduction

Rising demand for food, livestock feed, and biofuels will increase competition for water resources and put pressure to improve water productivity (WP), broadly defined as the amount of agricultural output per unit of water depleted by the crop (Global Water Partnership, 2000; Rosegrant et al., 2009). Working definitions of WP require an explicit description of the numerator and denominator and the time scale (Sinclair et al., 1984; Tanner and Sinclair, 1983). From an agronomic perspective, we favor a seasonal time scale. For each definition of yield, namely potential[1] (Yp), water-limited[2] (Yw), and actual on-farm (Ya) yield there is a corresponding WP (WPp, WPw, and WPa). For rainfed

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Abbreviations: CZ(s), climate zone(s); Es:ETw, proportion of ETw evaporated from the soil during the crop cycle; ETw, seasonal water-limited potential crop evapotranspiration (mm); ETw_{POSTF}ETw, proportion of ETw after flowering; ETo, reference grass-based evapotranspiration during the crop cycle (mm); VPD, daytime vapor pressure deficit (kPa); WP, water productivity (kg ha^{-1} mm^{-1}); WPa, actual on-farm water productivity (kg ha^{-1} mm^{-1}); WPg, water productivity gap (kg ha^{-1} mm^{-1}); WPw, water-limited potential water productivity for rainfed crops (kg ha^{-1} mm^{-1}); Ya, actual on-farm yield (Mg ha^{-1}); Yw, water-limited yield potential (Mg ha^{-1})

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[1] Yield potential (Yp) is the yield of a crop cultivar when grown in an environment to which it is adapted, with non-limiting water and nutrient supplies, and with insect, pests, weeds, and diseases effectively controlled (Evans, 1993, van Ittersum and Rabbinge, 1997)

[2] In rainfed systems where water supply from stored soil water at sowing and in-season rainfall is not enough to meet crop water requirement, water-limited yield potential (Yw) is determined by water supply amount and its distribution during the growing season, and by soil properties influencing the crop water balance, such as rootable soil depth, available-water holding capacity, and terrain slope (van Ittersum et al., 2013).

https://doi.org/10.1016/j.agrformet.2018.05.019
Received 17 December 2017; Received in revised form 22 May 2018; Accepted 27 May 2018
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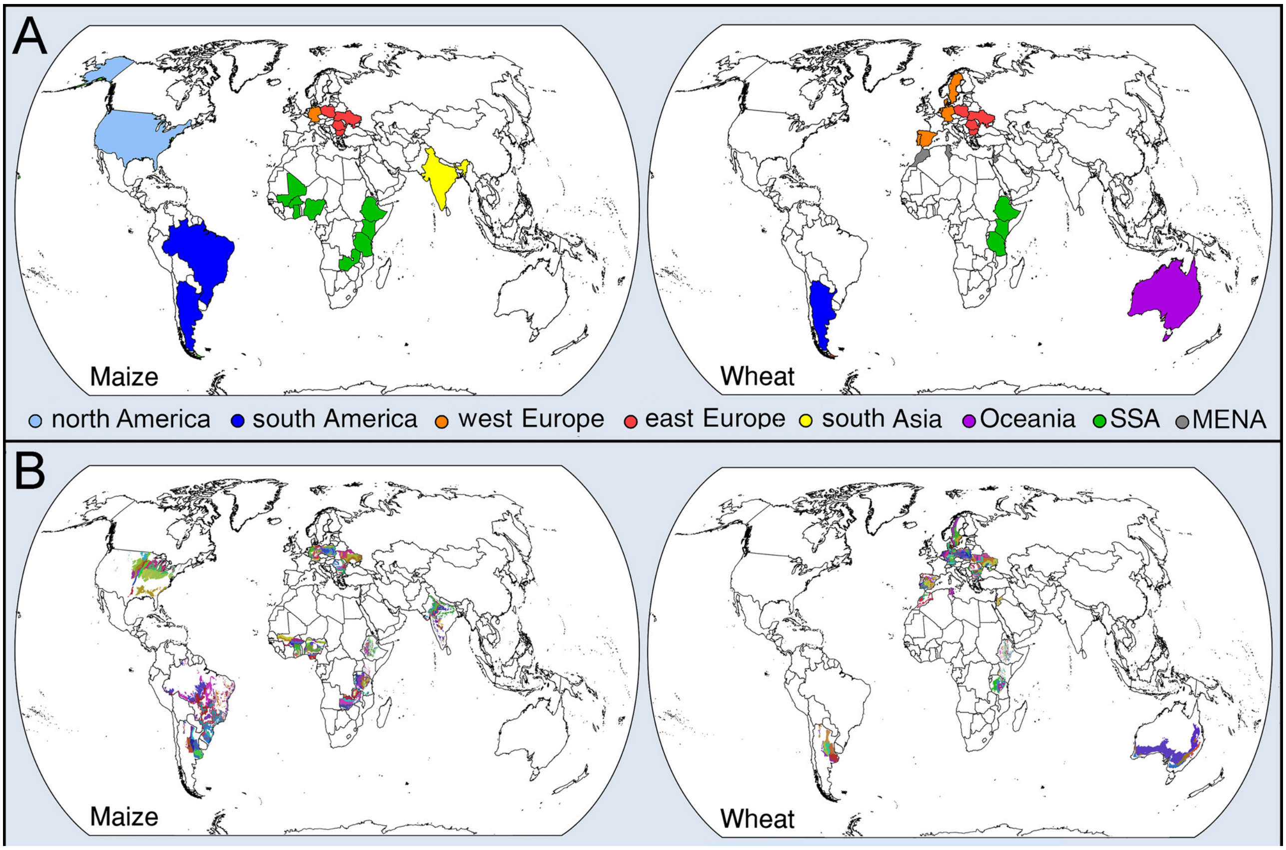

Fig. 1. (A) Evaluated countries for rainfed maize ($n_{countries}$ = 17) and wheat (n = 18), which represent 57 and 23% of global harvested area during the 2010–2014 period, respectively. (B) Selected climate zones for maize in north America ($n_{climate\ zones}$ = 18), south America (20), sub-Saharan Africa (SSA, 54), west Europe (7), east Europe (24), and south Asia (17) and for wheat in south America (8), SSA (18), Middle East and North Africa (MENA, 10), west Europe (19), east Europe (31), and Oceania (7). Note that the color scheme to identify geographic regions in panel (A) is identical in all figures.

crops, Yw and WPw are the relevant benchmarks. The denominator of the WPw equation can be crop transpiration, evapotranspiration, or water supply. The latter includes crop available soil water at sowing and in-season rainfall. WPa is typically below WPw as reported for maize and soybean in USA (Grassini et al., 2009b, 2011, 2015a), maize in China (Zhang et al., 2014), wheat in Australia, USA, China, and the Mediterranean basin (Cornish and Murray, 1989; French and Schultz, 1984; Patrignani et al., 2014; Sadras and Angus, 2006), sunflower in Argentina (Grassini et al., 2009a), and millet in sub-Saharan Africa (Sadras et al., 2011). The difference between WPw and WPa is termed water productivity gap (WPg). Robust estimates of WPw and WPg can help farmers, researchers, and policy makers estimate realistic goals of agricultural production considering available water resources and assist to identify non-water related factors that constrain WPa (Passioura, 2006; Passioura and Angus, 2010).

Previous studies that estimated WPw and WPa can be roughly grouped into two categories. The first group includes local field observations, which typically include yield, some measure of crop water availability during the crop-growing season, and a generalized boundary function representing WPw (French and Schultz, 1984; Grassini et al., 2009b; Passioura, 2006; Sadras and Angus, 2006). Recognized limitations of the boundary function approach include lack of consideration of spatial and seasonal variation in daytime vapor pressure and rainfall, and variation in soil evaporation with soil type and rainfall pattern (Angus and Van Herwaarden, 2001; Connor et al., 1985); there are also inconsistent use of crop water availability indicators (*e.g.*, seasonal water supply *versus* in-season rainfall) among studies that constrains boundary function comparisons. The second group includes regional or global studies that follow a “top down” approach to estimate WPa based on soil water balance, crop modelling, and/or remote sensing (Bastiaanssen and Steduto, 2017; Fader et al., 2011; Liu et al., 2007; Mekonnen and Hoekstra, 2010; Zwart et al., 2010). Owing to large data requirements, this approach mostly relies on gridded weather data and coarse assumptions about the crop system context, including crop sequence, management practices (sowing time and crop length), and soil water content at sowing (Fader et al., 2011; Jägermeyr et al., 2016; Mekonnen and Hoekstra, 2010; Mekonnen and Hoekstra, 2014). Perhaps more importantly, the focus of these studies is on estimating WPa, without providing a measure of WPw that can be taken as a benchmark to assess WP in farmer fields and identify opportunities for improvement.

To our knowledge, there is no protocol for estimating WPw and WPa with local to global relevance that is applicable across biophysically and agronomically diverse cropping environments. We argue that such a protocol requires (i) an accurate description of the local cropping system context (*e.g.*, weather, soil, crop sequence, and sowing dates), (ii) a robust spatial framework to upscale WPw from local to regional level, and (iii) a tool to reliably estimate Yw and the water that is available for crop transpiration during the growing season. To fill this gap of knowledge, the present study describes the protocol developed by the Global Yield Gap Atlas (Grassini et al., 2015b; van Bussel et al., 2015; www.yieldgap.org) to estimate WPw and WPa. This method is based on a combination of (i) soil, weather, and crop management data, (ii) a bottom-up approach to upscale results from location to region, and (iii) robust crop simulation models that have been validated for their ability to estimate Yw and WPw. This protocol was used to estimate WPw and WPa of rainfed crops in 17 countries for maize and 18 countries for wheat (available at www.yieldgap.org). Estimates of WPw were evaluated against data from the literature and spatial variation in WPw and WPa was investigated. Specific objectives were to evaluate