Agriculture, Ecosystems and Environment 222 (2016) 103–111

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Water and nitrogen use efficiencies in citrus production: A meta-analysis

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ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form 18 December 2015
Accepted 31 January 2016
Available online 13 February 2016

Keywords:
Citrus
Efficiency
Fertilizer
Irrigation
Meta-analysis
Nitrogen
Oranges
Water

ABSTRACT

Water and nitrogen (N) are two key limiting factors for citrus production. Reported effects of water and N inputs on citrus yield, water use efficiency (WUE) and N use efficiency (NUE) vary greatly, mainly due to differences in cultivars, tree age, climate, soil types, and water and N input levels. So far, no systematic analysis has been performed, and as a result, the interactive effects of water and N inputs on yield, WUE and NUE of citrus orchards are unknown. Also, gaps between attainable and actual yields, WUE and NUE have not been established yet. Here, we report on a global meta-analysis of yields, WUE and NUE of citrus production systems, using 1009 observations from 55 studies, conducted in 11 countries. Median citrus yields ranged from 30 to 60 t ha^{-1}, which were in between average global yields (range 10–30 t ha^{-1}) and attainable yields (range 60–90 t ha^{-1}). Median WUE ranged from 2.5 to 5 kg m^{-3} and median NUE from 150 to 350 kg kg^{-1}. Citrus yields were related to water and N inputs and tree age. Relationships between water and N inputs and yield, WUE and NUE were also analysed for sub-datasets and quantiles, to examine the relationships near the extremes. There were statistical significant interactions between water and N inputs in yield and NUE, but not in WUE. This indicates that studies aiming at the optimization of water and N inputs must consider interactions and optimize water and N inputs simultaneously. Based on our analyses, we estimated that reducing over-optimal irrigation to optimal irrigation may increase citrus yield by 20%, WUE by 30% and NUE by 15%. Similarly, reducing over-optimal N fertilization to optimal N fertilization may increase yield by 10%, WUE by 15% and NUE by 40%. We concluded that there is room for a significant increase in yield, WUE and NUE through the simultaneous optimization of water and fertilizer N inputs via precision fertigation.

1. Introduction

Citrus is one of the most important fruits in the global market. Global citrus production has quadrupled from 16 million tons in the early 1960s to 68 million tons in 2012 (FAO, 2014). This increase was the combined result of the increase in the area of citrus orchards and the increase in fruit yield per unit area of land (Fig. 1). The rapid development in citrus production has been driven by the increasing demand for nutritious and healthy food (citrus fruits have a high vitamin C content), and is facilitated by significant improvements in crop husbandry, logistics and processing (notably frozen concentrated citrus juice).

Citrus trees are mainly grown in subtropical and tropical regions because of their sensitivity to low temperatures. Main cultivars are Valencia, Washington Navel, Salustiana and Shamouti. The trees produce citrus annually and continue to do so for many decades, when the trees are well-maintained. In the Northern Hemisphere, the main vegetative growth occurs in February and March. Most cultivars produce flowers in spring, and fruits may take 6–8 months to ripen, depending on the climatic conditions (Steduto et al., 2012). Because of the long growing season and warm climate, citrus trees require relatively large amounts of water and nutrients.

Evapotranspiration (ETc) by citrus orchards ranges from 800–1500 mm yr^{-1}, depending on region and climate (Steduto et al., 2012). For important citrus production regions, such as Spain, Brazil and Florida (USA), there is need for irrigation to supplement the deficit between ETc and the supply via rainwater. The amount of irrigation typically ranges between 200 and 800 mm yr^{-1} (Ballester et al., 2011, 2013; Morgan et al., 2010; Romero et al., 2009). Soil evaporation may contribute significantly to ETc, especially when the canopy of the orchard is small, the climate is hot and the whole field is irrigated. Because of shrinking freshwater resources, there is a pressing need to optimize the

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http://dx.doi.org/10.1016/j.agee.2016.01.052
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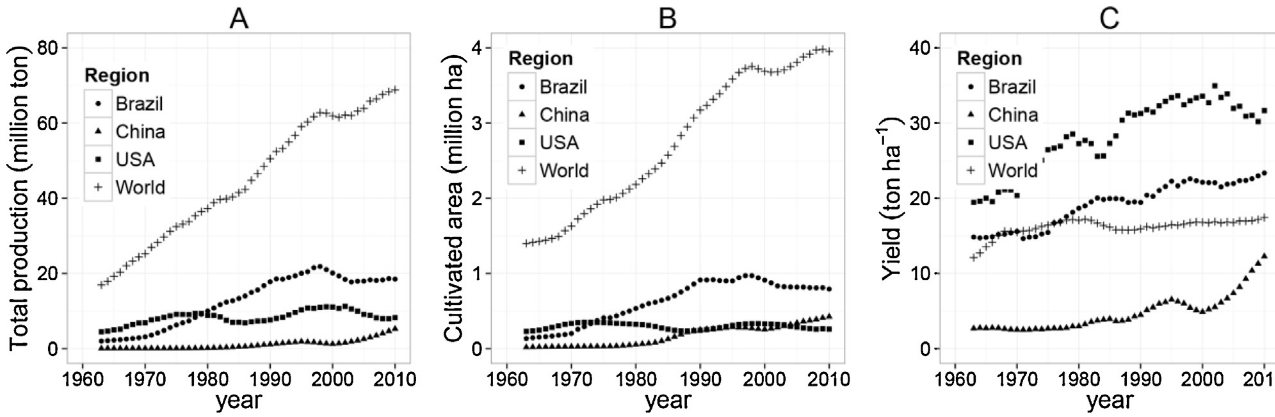

Fig. 1. Historical trends of total production (A), total cultivated areas (B) and mean yields (C) of citrus for the world and for three main producers USA, China and Brazil during the period 1961 to 2010. Results are presented as five-years moving averages. Data. Source: (FAO, 2014).

irrigation management and to reduce the amount of irrigation water where possible (Ballester et al., 2013; Steduto et al., 2012).

Fertilizer nitrogen (N) inputs in mature citrus orchards typically range between 150 and 350 kg ha^{-1} yr^{-1}. Leaching losses of N can be high (50–150 kg ha^{-1} yr^{-1}), especially when N fertilizer supply is over-optimal (Alva et al., 2008, 2006a; Lidon et al., 2013; Quiñones et al., 2007). These N losses contribute to pollution of groundwater and surface water bodies and there is therefore a great need to reduce these losses (Sutton et al., 2013, 2011).

Several studies have explored options to save water and fertilizer N in citrus production systems, but these studies often focus on the optimization of the use of either water or N separately. The simultaneous optimization of water and N supply is complicated due to the many interacting factors, such as climate, crop variety, soil type and irrigation and fertilization technology, and also because of different disciplinary research interests (Alva et al., 2008; Srivastava, 2012; Steduto et al., 2012). Ballester et al. (2011) reported that deficit irrigation may save 20% of the irrigation water without yield reduction, compared to 100% ETc. However, a reduction with 44% relative to the 100% ETc level led to a yield reduction of 17% (Gonzalez-Altozano and Castel, 1999). The sensitivity to water stress also differs between growth stages (Steduto et al., 2012). For example, the flowering and fruit set period has been reported as the most sensitive to stress for small citrus, such as clementines and oranges (Gonzalez-Altozano and Castel, 1999; Perez-Perez et al., 2008a).

The optimal N input varies with variety and citrus yield. For a yield of 40 t ha^{-1}, the optimal N input is around 150–200 kg ha^{-1}. For a yield level of 80 t ha^{-1}, the optimal N input is around 250 kg ha^{-1} (Alva et al., 2006b; Quiñones et al., 2007).

The available information on the effects of water and N inputs and of their possible interactions on citrus yield, water use efficiency (WUE) and N use efficiency (NUE) have not been systematically analyzed and synthesized yet. Such integrative analyses may increase the quantitative understanding of the effects of water and N inputs on citrus yield, WUE and NUE, and may contribute to improved recommendations for irrigation and fertilization of citrus orchards. The objectives of this study were therefore (i) to review and summarize the information in literature on water and N use in citrus production systems, (ii) to quantify the relationships between water and N inputs on yield, WUE and NUE, and (iii) to explore the options for increasing yield, WUE and NUE in citrus production systems. In particular, we were interested in possible interactions between water and N inputs in yield, WUE and NUE, as the optimization of water and N inputs in separated studies will likely neglect such interactions.

2. Materials and methods

2.1. Data collection

We searched in peer-reviewed literature for publications that reported water and N use in citrus production, using Scopus (Elsevier; access date 01-May-2015). Search terms included 'citrus' and/or 'orange', 'water' and/or 'nitrogen', 'evapotranspiration', 'irrigation' or 'fertigation' in the article title, abstract, and keywords. Conference proceedings and non-English language publications were excluded. We screened the publications on the basis of the following criteria: (1) citrus yields; water and N inputs were documented; (2) experimental site and year were provided; and (3) age and cultivar of the citrus tree were indicated. The final analysis was based on 1009 yield observations from 55 studies conducted in 11 countries.

2.2. Definitions

Water use efficiency (WUE, in kg m^{-3}) was defined as:

$$WUE = \frac{Y}{W} \quad (1)$$

where Y is citrus yield (in t ha^{-1}), W is the sum of rain and irrigation water (in mm). We used W as denominator because W represents the actual water input to the system. W can be larger than ET because surface runoff and leaching (belowground drainage) may occur. Possible changes in soil moisture between growing seasons were neglected, mainly because citrus tree is a perennial crop.

Nitrogen (N) use efficiency (NUE, kg kg^{-1} or in %) was defined as:

$$NUE = \frac{Y}{N} \quad (2)$$

where N is the N fertilizer input (kg ha^{-1}). Possible N inputs from atmospheric deposition, bio-fixation and net mineralization of organically bound soil N were neglected, because these inputs were likely relatively small, difficult to manage, and because most studies did not report these inputs.

2.3. Data analysis

2.3.1. Estimating the mean effects of multiple independent variables

The effects of water and N inputs, tree age and mean temperature on citrus yield, WUE and NUE were analysed with a mixed-effects model via the R package "nlme" (Pinheiro et al.,