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Water- and nitrogen-saving potentials in tomato production: A meta-analysis

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ABSTRACT

Tomato cultivation is primarily limited by availability of water and nitrogen (N). Water and N have highly variable effects on tomato yield, water-use efficiency (WUE) and N-use efficiency (NUE), which may be due to the effect of cultivar, growing season and water and N inputs. Despite these strong effects, no systematic investigation had been conducted into the effects of N and water on yield, WUE, and NUE in tomatoes. The water-saving potential (WSP) and N-saving potential (NSP) have also not been systematically estimated. In this study, we use meta-analysis of 49 studies with 733 individual observations across 10 countries to determine the effect on yield, WUE, and NUE. The global average yield was 16.43–37.02 t ha^{-1}, while the median yields ranged from 41.75 to 130.59 t ha^{-1}. Median values for WUE and NUE were 7.09 to 34.63 kg m^{-3} and 208.1 to 2050 kg kg^{-1}, respectively. Yield was correlated with temperature, water input and N input. Optimizing inputs of both water and N must consider their interaction to ensure consistency between high yield, WUE and NUE. Our results indicated that decreasing a supra-optimal water input to an optimal input would increase yield by 9.8%, WUE by 19.6% and NUE by 3.7% and that decreasing a supra-optimal N input to an optimal input would increase yield by 5.6%, WUE by 6.3% and NUE by 50.5%. WSP and NSP could be decreased by 41% (240 mm) and 37% (138 kg N ha^{-1}), respectively, without decreasing yield. The present study is important for guiding the optimal use of water and N in tomato cultivation and can help to greatly save water and N resources.

1. Introduction

Tomato (*Solanum lycopersicum*), is one of themost commonly consumed vegetables globally, in part due to its high nutritive content of vitamin C, minerals, antioxidants, and others (Du et al., 2017; Wang et al., 2015; Toor et al., 2006; Erba et al., 2013). Global tomato production increased from 27.6 million t in 1960 to 177 million t in 2016, with corresponding increases in production areas of 1.68 million ha in 1960 to 4.78 million ha in 2016, due to the high nutritional value of tomatoes and the development of the tomato-processing industry (FAO, 2016; Fig. 1). Greenhouse cultivation accounts for most vegetable cultivation due to its high controllability. Tomatoes are commonly grown in the Northern Hemisphere in three growing seasons, spring-summer (about March-July), autumn-winter (about August-December) and over winter (about November-March) (Wang et al., 2015; Biswas et al., 2015; Vázquez et al., 2006). Tomato crops have high demands for water and fertilizer because of the long growing seasons and the high greenhouse temperatures.

Nitrogen (N) plays a major role in the growth and development of plants (Ren et al., 2010; Elia and Conversa, 2012). It is also a key factor affecting crop yield and quality but is not easy to control. An adequate supply of N fertilizer during plant growth can guarantee maximum yield and economic benefits. The amount of N applied to tomato cultivation reported in various studies ranges from 50 to 1200 kg ha^{-1} along with no N applied as a control treatment (Elia and Conversa, 2012; Wang et al., 2015; Li et al., 2017a; Soto et al., 2015; Tei et al., 2002; Rinaldi et al., 2007), while N uptake by plants can vary from 150 to 470 kg ha^{-1}, (Elia and Conversa, 2012; Rinaldi et al., 2007; Soto et al., 2015; Tei et al., 2002), and the total N required varies from 100 to 574.35 kg ha^{-1} (Warner et al., 2004; Doorenbos and Kassam, 1986; Elia and Conversa, 2012; Wang et al., 2015; Li et al., 2017a,b; Soto et al., 2015; Tei et al., 2002; Rinaldi et al., 2007). These ranges have large gaps, perhaps due to different environmental and management factors. Ersahin and Rustu Karaman (2001) indicted that excessive N application greatly increased nitrate leaching, causing the pollution of the groundwater and surface watering system. Higher N rate application may also shift the balance between vegetative and reproductive plant growth towards to the excessive vegetative development, thereby

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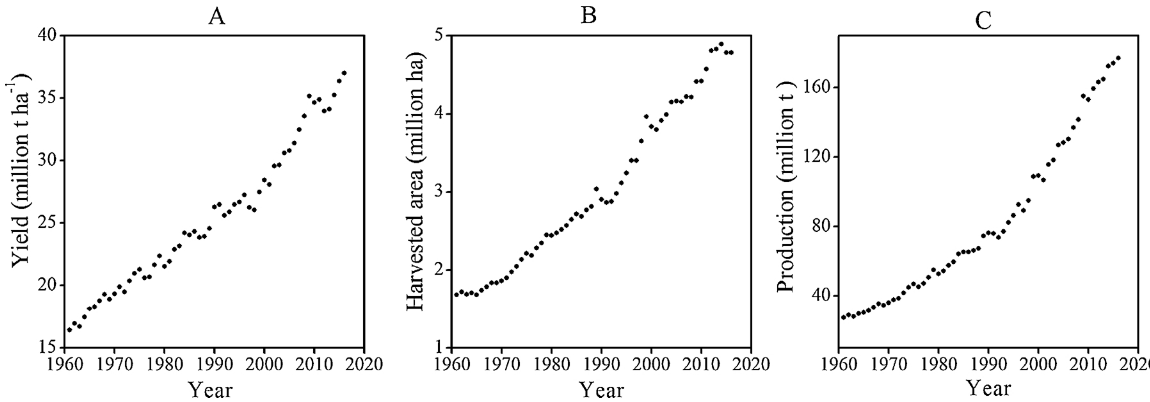

Fig. 1. Historical trends of global tomato yield (A), harvested area (B) and production (C) from 1961 to 2016.

delaying plant maturation and reducing crop yields (Hamzei, 2011). Furthermore, surplus N use combined with low N use efficiency can have negative consequences to the environment and can decrease soil microbial activity (Ramirez et al., 2012). Improving NUE by sound N management is thus crucial.

Water resources are extremely scarce in many areas of the world, which has become an increasingly serious problem due to the dramatic increase in population, global climate change and marginalization of agriculture toward arid and semi-arid areas (Solomon and Cramer, 1993; FAO, 2012). Saving more water and improving WUE are therefore urgently needed, especially for tomatoes, which have the highest planted areas of all vegetables worldwide (Ho, 1996). Tomato evapotranspiration (ET) ranges from 284 to 735 mm (Ozbahce and Tari, 2010; Soto et al., 2015; Patanè et al., 2011; Topcu et al., 2007; Vázquez et al., 2006), and water input during the growing season ranges between 0 mm (greenhouse) and 168 mm (Wang et al., 2015; Patanè et al., 2011; Ngouajio et al., 2007; Mukherjee et al., 2012; Vázquez et al., 2006; Farnesellia et al., 2015). Irrigation is necessary for tomatoes due to the large gap between rainfall and ET and is needed in important areas of tomato cultivation such as the United States, China and Italy. The amount of supplemental irrigation water varies from 100 to 500 mm (Farnesellia et al., 2015; Ngouajio et al., 2007; Patanè et al., 2011; Wang et al., 2015). Agricultural irrigation is responsible for 85% of global freshwater consumption (Van Schilfgaarde, 1994), and even a small amount of water saved can be used for other purposes. Optimizing irrigation management and decreasing the use of irrigation water as much as possible are thus necessary.

Cossani et al. (2012) reported that water deficits will reduce crop yield and N absorption. Good crop nutritional status, though, can increase the tolerance of crops to drought and increase crop WUE. The production of biomass is dependent on the co-limitation relationship between the availability of water and fertilizer (Sadras, 2004). Co-limitation implies that crop growth responds more to water and fertilizer than to either single factor, indicating that the strategies to optimize crop growth should ensure that both resources are equally available. Water deficit has been shown to remarkably decrease the N translocation ratio from the soil and to adversely affect the contribution of N in various organs (Hamzei, 2011). Sun et al. (2013) showed that the best management practices under furrow irrigation for tomato cultivation are irrigation with 300 mm and N application rate of 150 kg ha^{-1} in the autumn-winter season, or irrigation with 300 mm and N application rate of 250 kg ha^{-1} in the spring-summer season. However, Kuscu et al. (2014) indicated that the irrigation regime of 75 percent of the pan evaporation and N supply at 120 kg ha^{-1} or 180 kg ha^{-1} could be considered optimal under drip irrigation. Although previous studies have examined the potential to use water and N fertilizer more efficiently for tomato production, most only examined the role of one or the other factor. Optimizing the supply of water and N simultaneously depends on many factors, e.g. irrigation and fertilization techniques, crop varieties and soil types (Chen et al., 2014; Li et al., 2017a, b). Zhang et al. (2017) reported that the application of irrigation water at a rate of 80% ET did not decrease tomato yield compared with 100% ET. A decrease in water input to 60% ET, however, decreased tomato yield by 13.63%. Water deficits at different growth stages can also differentially affect tomato yield. A study by Chen et al. (2014) found that certain tomato life stages, such as the flowering and fruiting stages, were more susceptible to water stress than was the seedling stage. N requirements also vary among tomato cultivars. Yield increased with N input: 160 kg ha^{-1} resulted in a yield of 88.8 t ha^{-1}, while 300 kg ha^{-1} gave a maximum yield of 129.5 t ha^{-1} (Farnesellia et al., 2015; Erdal et al., 2006). The reported differences in water and N use between different studies is large, so it is not clear what the actual water and N saving potential is for tomato cultivation globally. There have not been systematic analyses of the impact of water- and N-saving on crops.

Potentially filling this gap, meta-analysis is a statistical model used to analyze datapoints from separate empirical studies (Stanley and Jarrell, 1989). Meta-analysis has the advantage of being able to systematically evaluate and summarize results from multiple independent research projects that have the same subject, allowing meta-analysis researchers to draw conclusions from concatenated datasets. Meta-analysis is widely used in agricultural research worldwide. Carrijo et al. (2017) applied a meta-analysis to examine the effect of alternate wetting and drying on rice yields and water use globally. Biederman and Harple (2013) applied a meta-analysis to examine the effect of biochar on plant productivity and nutrient cycling. Similar research was conducted by Adu et al. (2018) and Linquist et al. (2013) using meta-analysis methods. In the present study, a meta-analysis was also applied to systematically analyze the available information on the effect of water and N input on tomato yield, WUE, and NUE.

Such a quantitative analysis is necessary for improving the recommendations of water and N inputs in tomato cultivation. The specific objectives of the current study were to 1) collect and analyze the results of studies on water and N on yield, WUE, and NUE in tomato, and 2) to provide suggestions for improved yield with increased resource use efficiency. Our study uniquely examined the interactions of water and N input on yield, WUE, and NUE in tomato, which has been overlooked in many previous studies.

2. Materials and methods

2.1. Data collection

We used Google Scholar, Web of Science, and ScienceDirect search engines to search the literature for relevant citations, using the keywords 'tomato', 'water' and/or 'nitrogen', 'evapotranspiration' and 'irrigation' or 'fertilization'. We excluded non-English papers and conference proceedings and had a cut-off date of 31 January 2018. The