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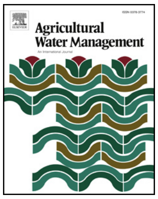

Calibration and validation of the AquaCrop model for repeatedly harvested leafy vegetables grown under different irrigation regimes

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ABSTRACT

Traditional leafy vegetables (TLVs’) are vegetables that were introduced in an area a long time ago, where they adapted to local conditions and became part of the local culture. In Sub-Saharan Africa, the use of TLVs’ as a nutrient dense alternative food source to combat micronutrient deficiency of rural resource-poor households (RRPHs), has gained attention in debates on food and nutrition security. However, TLVs’ are underutilised because of lack of information on their yield response to water and fertiliser. To better assess TLVs’ yield response to water stress, the AquaCrop model was calibrated (using 2013/14 data) and validated (using 2014/15 data) for three repeatedly harvested leafy vegetables [*Amaranthus cruentus* (Amaranth), *Cleome gynandra* (Spider flower), and *Beta vulgaris* (Swiss chard)] in Pretoria, South Africa. Experiments were conducted during two consecutive seasons, in which the selected leafy vegetables were subjected to two irrigation regimes; well-watered (I_{30}) and severe water stress (I_{80}). Measured parameters were canopy cover (CC), soil water content (SWC), aboveground biomass (AGB), actual evapotranspiration (ET_a), and water productivity (WP). Statistical indicators [root mean square error (RMSE), RMSE-standard deviation ratio (RSR), R^2, and relative deviation] showed good fit between measured and simulated ($0.60 < R^2 < 0.99$, $0.94 < \text{RMSE} < 5.44$, and $0.04 < \text{RSR} < 0.79$) values for the well-watered treatment. However, the fit was not as good for the water-stressed treatment for CC, SWC, ET_a and WP. Nevertheless, the model simulated the selected parameters satisfactorily. These results revealed that there was a clear difference between transpiration water productivity (WP_{Tr}) for C_4 crops (Amaranth and Spider flower) and a C_3 crop (Swiss chard); WP_{Tr} for the C_4 crops ranged from 4.61 to 6.86 kg m^{-3}, whereas for the C_3 crop, WP_{Tr} ranged from 3.11 to 4.43 kg m^{-3}. It is a challenge to simulate yield response of repeatedly harvested leafy vegetables because the model cannot run sequential harvests at one time; therefore, each harvest needs to be simulated separately, making it cumbersome. To design sustainable food production systems that are health-driven and inclusive of RRPHs, we recommend that more vegetables (including traditional vegetables) should be included in the model database, and that sequential harvesting be facilitated.

1. Introduction

Globally, the agricultural sector is utilising 70% of available fresh water. Projections indicate that the demand for water will increase due to population growth. By the year 2050, more water will be required to produce highly nutritious food for more than 9 billion people (IFPRI, 2016). Furthermore, climate change will increase temperature and carbon dioxide levels (Allan et al., 2013). An increase in carbon dioxide (from 380 to 550 ppm) at 25 °C has a benefit, depending on crop species. For C_3 crops, photosynthesis would increase by 38%, which in turn will increase yield; however, for C_4 crops, an increase in CO_2 level may not show an increase in photosynthetic activity, but an indirect increase in the efficiency of water use through reduction in stomatal conductance (Long et al., 2006). Several authors (Gido et al., 2017; Keatinge et al., 2011; Mabhaudhi et al., 2016; Uusiku et al., 2010) averred that the current food system focus is on enhancing food security through the production of mainstream crops [*Zea mays* (maize), *Triticum species* (wheat), *Sorghum bicolor* (sorghum), *Oryza sativa* (rice), *Hordeum vulgare* (barley), and *Pennisetum glaucum* (millet)] under water scarcity. These crops contribute significantly to dietary energy requirements; however, they are deficient in micronutrients (iron and zinc) and vitamin A. Globally, two to three billion people suffer from micronutrient deficiency, with Sub-Saharan Africa (SSA) accounting for approximately one billion (IFPRI, 2016; Keatinge et al., 2011). Focusing

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on cereal production as a solution to combat hunger will not abate the widespread occurrence of micronutrient deficiency-related diseases, including stunted growth and impeded cognitive development. There is a need to increase the consumption of vegetables as a strategic intervention for addressing micronutrient (iron and zinc) and vitamin A deficiency. This can be done by constructing sustainable food systems that are inclusive of both rich and poor, and that are highly nutritious, climate-smart, and health-focused (Bello and Walker, 2017; IFPRI, 2016; Mabhaudhi et al., 2016; Tata-Ngome et al., 2017).

Research funding has focused on the production of vegetables with low β-carotene, iron, and zinc, such as cabbage and tomato, supported by large established consumer markets. This has undervalued the nutritional component of some vegetables (Keatinge et al., 2011). Consuming nutrient-dense vegetables is a first step in alleviating micronutrient deficiency. The World Health Organisation recommends a vegetable intake of at least 400 g person^{-1} day^{-1} for a healthy and nutritious life; a requirement that is not met by half of the countries in SSA (Tata-Ngome et al., 2017). Sub-Saharan Africa has a wide variety of traditional leafy vegetables (TLVs') that are rich in vitamins, carotenoids, and other micronutrients (iron, zinc, magnesium) (Chivenge et al., 2015; Gido et al., 2017; Mabhaudhi et al., 2016; Tata-Ngome et al., 2017; Nyathi et al., 2016). However, TLVs' are underutilised because of lack of information on their yield response to water and fertiliser, the threat of becoming extinct when collected from the wild or as "weeds" next to cropped land, and limited insight into the factors affecting their nutritional content (Mavengahama et al., 2013). These factors undermine the potential of TLVs' to contribute to nutritional food security. Traditional leafy vegetables present advantages over alien vegetables; their abundance in the "wild" or next to cereal crops, their high nutrient concentration (iron, zinc, β-carotene, magnesium), their drought tolerance, their resistance to pests and diseases, and the low need to apply water and fertiliser (Keatinge et al., 2011; Mavengahama et al., 2013; Tata-Ngome et al., 2017; Uusiku et al., 2010). These characteristics make TLVs' ideal crops for RRPHs.

In this paper, we do not wish to undermine the essential role played by modern cereal crops in combating the energy-deficiency of the food security quest. Following Smith (2013), we advocate for a sustainable intensification of food production as "*the process of delivering safer, nutritious food, (e.g. tonnes of cereals, grams of protein, and grams of micronutrients) per unit of resource (land area, water, fertiliser, and agrochemicals)*". There are approximately 500 million RRPHs in SSA and Asia, who provide 80% of the food produced there (IFPRI, 2016). However, they are vulnerable to nutritional food insecurity because of low productivity and over-reliance on a few selected vegetables that require high inputs such as water for irrigation and fertiliser. Introducing TLVs' to RRPHs as cultivated leafy vegetables have the potential of contributing significantly to the dietary diversification (Bello and Walker, 2017) under resource (water and fertiliser) constrained conditions. Experiments aimed at assessing the effect of two water stress levels on nutritional water productivity of *Amaranthus cruentus* (Amaranth), *Cleome gynandra* (Spider flower), and *Beta vulgaris* (Swiss chard var. *Ford hook Giant*) were conducted in South Africa during the 2013/14 and 2014/15 seasons. We chose Amaranth and Spider flower because they are underutilised in southern Africa, but have a high potential of being cultivated as leafy vegetables, whereas Swiss chard was included as a reference crop, because it is a widely accepted leafy vegetable that has been commercialised worldwide. The challenge with field experiments is that they yield location specific results that may not be applicable to other locations with different climate and soils. Conducting experiments for evaluating the yield response of crops to different deficit irrigation strategies is time-consuming, laborious, expensive, and complicated. Therefore, a combination of field experimentation and analysis based on crop water productivity models can be helpful to develop and assess different deficit irrigation strategies, identify various environmental and management strategies, separate evaporation and transpiration from evapotranspiration (to assess beneficial use of water by crops), and to aid decision-making for improved irrigation and cultivation management (Mustafa et al., 2017).

To make the results of our field experiments more generic and applicable, we selected the model AquaCrop (http://www.fao.org/aquacrop), which was developed by the Food and Agriculture Organisation to simulate yield responses of crops to water, especially where water is limiting for crop production. AquaCrop has been utilised in many studies (e.g. Abedinpour et al., 2012; Araya et al., 2016; Battisti et al., 2017; Bello and Walker, 2016; Greaves and Wang, 2017; Katerji et al., 2013; Mirsafi et al., 2016; Montoya et al., 2016; Mustafa et al., 2017; Paredes et al., 2014, 2015; Pawar et al., 2017; Razzaghi et al., 2017; Tavakoli et al., 2015; Yuan et al., 2013) to assess yield response of crops [(*Beta vulgaris* (sugar beet), *Glycine max* (soya beans), wheat (*Triticum spp.), Hordeum vulgare* (barley), *Pennisetum glaucum* (pearl millet), potato (*Solanum tuberosum*), maize (*Zea mays*), sunflower (*Helianthus annuus*), oats (*Avena sativa*), cabbage (*Brassica oleracea*), *Sorghum bicolor* (sorghum), *Crocus sativus* (saffron), and Solanum lycopersicum (tomato)] to water stress. Bello and Walker (2017) calibrated the model for Amaranth. However, it was not clear how they accounted for repeatedly harvested leaves of Amaranth. To our knowledge, the AquaCrop model has not been calibrated and validated for Spider flower and Swiss chard. Therefore, our main objective was to calibrate and validate the model for Amaranth, Spider flower, and Swiss chard. In this study we: (1) parameterised AquaCrop for selected leafy vegetables under two water stress levels; (2) compared TLVs' yield response with that of Swiss chard; and, (3) considered the practice of harvesting these selected leafy vegetables repeatedly throughout the growing period, which is currently absent as a management practice in AquaCrop Version 4.0.

2. Materials and methods

2.1. Study site, experimental setup, irrigation water management, and agronomic practices

Experiments were conducted under a rain-shelter at the Agricultural Research Council, Vegetable and Ornamental Plants (ARC-VOP), Roodeplaat, Pretoria (25° 60′ S; 28° 35′ E; 1168 m a.s.l.), in the Gauteng Province of South Africa, during the 2013/14 and 2014/15 summer seasons. The rain-shelter has a rain sensor that triggers an electric motor during a rainfall event and the shelter automatically covers the experimental field. Therefore, the experiment experiences normal field conditions, except when it is raining (Mabhaudhi et al., 2014). Long-term climate data (1990–2015) shows a rainfall of approximately 650 mm per year on average, concentrated in the summer (October–March). January is the month with the highest average maximum temperature (30 °C). The experiment was a 3 × 2 factorial design; with three crops (Amaranth, Spider flower, and Swiss chard) and two irrigation water regimes (I_{30} – well-watered and I_{80} – severe water stress). Irrigation water regimes mean that crops were irrigated back to field capacity after 30% and 80% depletion of plant available water. The maximum effective rooting depth (0.6 m) for the selected leafy vegetables was determined using neutron probe readings. We executed the experiment as a randomised complete block design and it was replicated three times. Three water samples were sent to the ARC-Institute for Soil, Climate, and Water, to determine the quality (salinity, ds m^{-1}) of irrigation water. Irrigation scheduling was based on irrigation water regimes, using readings of the calibrated neutron water meter (CPN, 503 DR Hydroprobe). Aluminium access tubes were installed in the middle of each plot to a depth of 1 m. Soil water content (SWC) was measured twice a week at fixed depth increments of 0.2 m. Actual evapotranspiration (ET_a, mm) was calculated using the soil water balance equation (Eq. 1).

$$ET_a = I + \Delta W \tag{1}$$