

Article

Estimation of Yield Response Factor for Each Growth Stage under Local Conditions Using AquaCrop-OS

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Abstract: We propose a methodology to estimate the yield response factor (i.e., the slope of the water-yield function) under local conditions for a given crop, weather, sowing date, and management at each growth stage using AquaCrop-OS. The methodology was applied to three crops (maize, sugar beet, and wheat) and four soil types (clay loam, loam, silty clay loam, and silty loam), considering three levels of bulk density: low, medium, and high. Yields are estimated for different weather and management scenarios using a problem-specific algorithm for optimal irrigation scheduling with limited water supply (GET-OPTIS). Our results show a good agreement between benchmarking (mathematical approach) and benchmark (estimated by AquaCrop-OS) using the Normalised Root Mean Square Error (NRMSE), allowing us to estimate reliable yield response factors (K_y) under local conditions and to dispose of the typical simple mathematical approach, which estimates the yield reduction as a result of water scarcity at each growth stage.

Keywords: AquaCrop-OS; crop yield function; yield response factor; growth stages

1. Introduction

Water is the main factor for crop development. Globally, irrigation in agriculture uses about 70% of the available fresh water resources [1] and so, improving irrigation management will increase the water use efficiency (WUE), which is defined as the amount of water necessary to achieve a given yield [2]. According to Saccon [3], the effective planning and management of water for crop production requires a deep knowledge of the system, as experimental results are generally site-specific and are not applicable to different weather, soil, crop, and management conditions. Furthermore, carrying out field experiments is expensive, laborious [4], and time-consuming.

To address the above concerns, the Food and Agriculture Organization (FAO) of the United Nations has developed the AquaCrop model [5]. This model simulates attainable yields of crops as a function of water consumption under rain-fed, supplemental, deficit, and full irrigation conditions, and has been used to accurately determine crop yields in maize [6–8], wheat [9–11], sugar beet [4,12,13], potatoes [14,15], barley [16], quinoa [17], and rice [18]. AquaCrop has also been linked to crop production functions [19–27] which relate yield reduction as a result of the relative loss in evapotranspiration [28].

For yield reduction due to water stress, Doorenbos and Kassam [20] proposed:

$$1 - \frac{Y}{Y_m} = K_y \left(1 - \frac{ET_a}{ET_c} \right), \quad (1)$$

where Y and Y_m are the actual and maximum crop yields, respectively; ET_a and ET_c correspond to actual and maximum evapotranspiration, respectively; and the coefficient K_y denotes the yield response factor, which relates the yield reduction ($1 - Y/Y_m$) to the water stress ($1 - ET_a/ET_c$) for a given environment [23].

In the literature, researchers have developed a multiplicative approach to the equation proposed by Doorenbos and Kassam [20,23,27,29]. This approach relates the crop yield reduction as a function of the water stress at specific growth stages. According to Shrestha et al. [30], with the rise in average yields and an increase in crop sensitivities to water stress, the K_y coefficients need to be updated. In the literature, K_y values have been estimated for maize, wheat, and sugar beet. For maize, Kresović et al. [31] have assessed the effects of different irrigation amounts, estimating grain yield functions depending on seasonal irrigation and water consumption. The latter depends seasonally on K_y . Djaman et al. [32] have measured and evaluated crop response to several variables under different levels of irrigation, quantifying seasonal values of K_y . With respect to sugar beet, Kiymaz and Ertek [33] have determined the effect of different irrigation and nitrogen levels on yield and other components, obtaining K_y for two growing seasons. Tarkalson et al. [34] have quantified the yield response to water input and actual evapotranspiration; they also obtained K_y for two growing seasons. Regarding wheat, Bandyopadhyay et al. [35] have analysed the effect of different combinations of sprinkler and surface flooding on crop production functions, obtaining K_y for each irrigation treatment and Liu et al. [36] have evaluated the performance of winter wheat under different irrigation amounts, estimating K_y for four growing seasons.

Foster et al. [37] developed the AquaCrop-OS model, an open-source code written in MATLAB, providing the opportunity to link it with other concepts to assess farming scenarios. Considering the importance of the sub-seasonal application of water in food production, we defined the following research question: Is it possible to incorporate the multiplicative approach of Doorenbos and Kassam [20] into AquaCrop-OS, in order to estimate K_y at each growth stage? Therefore, the main objective of our research was to develop and test a methodology to estimate K_y under local conditions for a given crop, soil, weather, sowing date, and management at each growth stage using AquaCrop-OS. Reliable K_y values under local conditions for each growth stage allow farmers to decrease uncertainty and improve risk management due to intraseasonal changes.

2. Methodology

Our proposed methodology aims to include the AquaCrop-OS model into the multiplicative approach of Doorenbos and Kassam [20], with the objective of determining K_y under local conditions (i.e., for a given crop, soil, weather, sowing date, and management) at each growth stage.

2.1. Crop Yield Equation

The multiplicative approach of the equation proposed by Doorenbos and Kassam [20] (Equation (1)) is:

$$\frac{Y}{Y_m} = \prod_{n=1}^N \left[1 - K_{y_n} \left(1 - \frac{ET_{a_n}}{ET_{c_n}} \right) \right], \quad (2)$$

where n is an index representing each growth stage and N corresponds to the number of functions between the square brackets [23].

2.2. Estimation of K_y Using AquaCrop-OS

This section was developed in MATLAB and is split into two parts: A benchmark definition and a benchmarking (Figure 1).

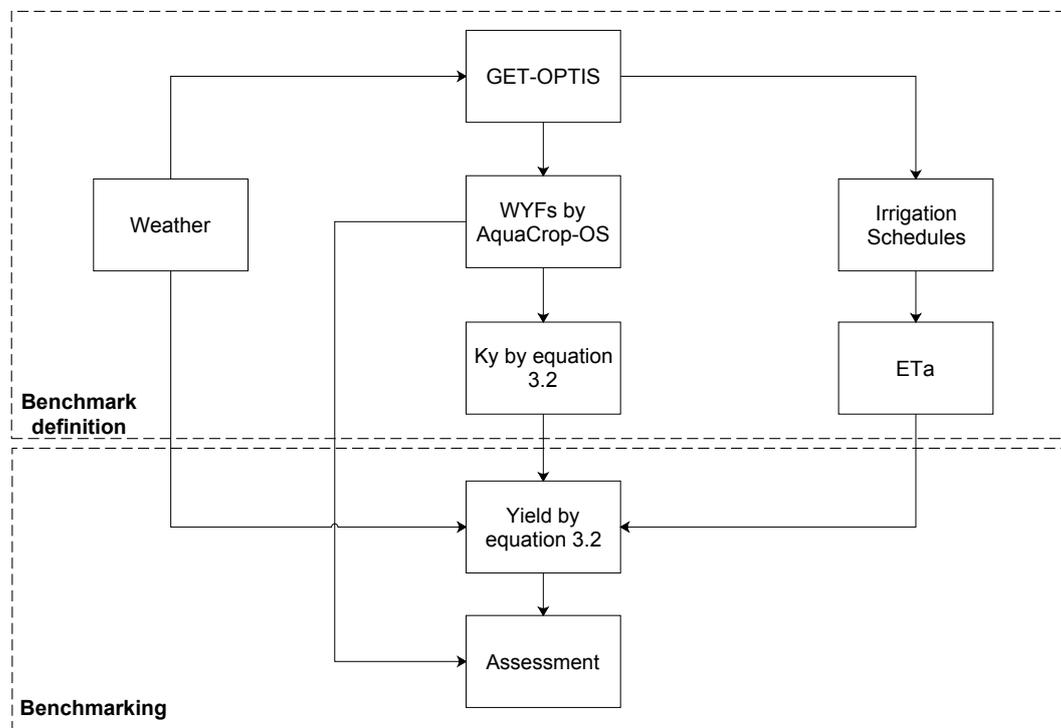


Figure 1. The methodology used for this research to estimate the K_y value at each growth stage under local conditions (i.e., for a given crop, soil, weather, sowing date, and management) using AquaCrop-OS.

As a benchmark definition, we started with a database of historical weather scenarios for a given area in which, for each year, the water-yield functions (WYF) have been determined using AquaCrop-OS [37] and a problem-specific algorithm for optimal irrigation scheduling with limited water supply. This is named the Global Evolutionary Technique for OPTimal Irrigation Scheduling (GET-OPTIS) [24]. The main objective of GET-OPTIS is to maximise the crop yield (Y) by finding an optimal irrigation schedule (S) composed of a date (d_i) and an irrigation depth (v_i) (Figure 2):

$$\begin{aligned}
 Y^* &= \max Y(S) : S = \{s_i\}_{i=1\dots n} \\
 &= \{(d_1, v_1), \dots, (d_i, v_i), \dots, (d_n, v_n)\} \quad n, d_i \in \mathbb{N}; v_i \in \mathbb{R}.
 \end{aligned}
 \tag{3}$$

This process required high computational effort, as building 34,020 scenarios (21 points for 45 years, 3 crops, and 12 soil types) was required. So, we used the parallel run mode in MATLAB R2017a [38]. Parallel computing allows us to carry out many calculations simultaneously, accelerating the computing speed. Once the WYFs were built, the K_y values (i.e., the slopes of the WYFs) were estimated, by considering Equation (2), through the least square method at each growth stage: (1) emergency or transplant recovery, (2) vegetative stage, (3) flowering stage, and (4) yield formation and ripening [39]. Finally, we considered discrete mean values of K_y every 5 years. It should be noted that there were no measured data used in this case, and the simulation results from AquaCrop-OS were used as the comparison benchmark for evaluation.

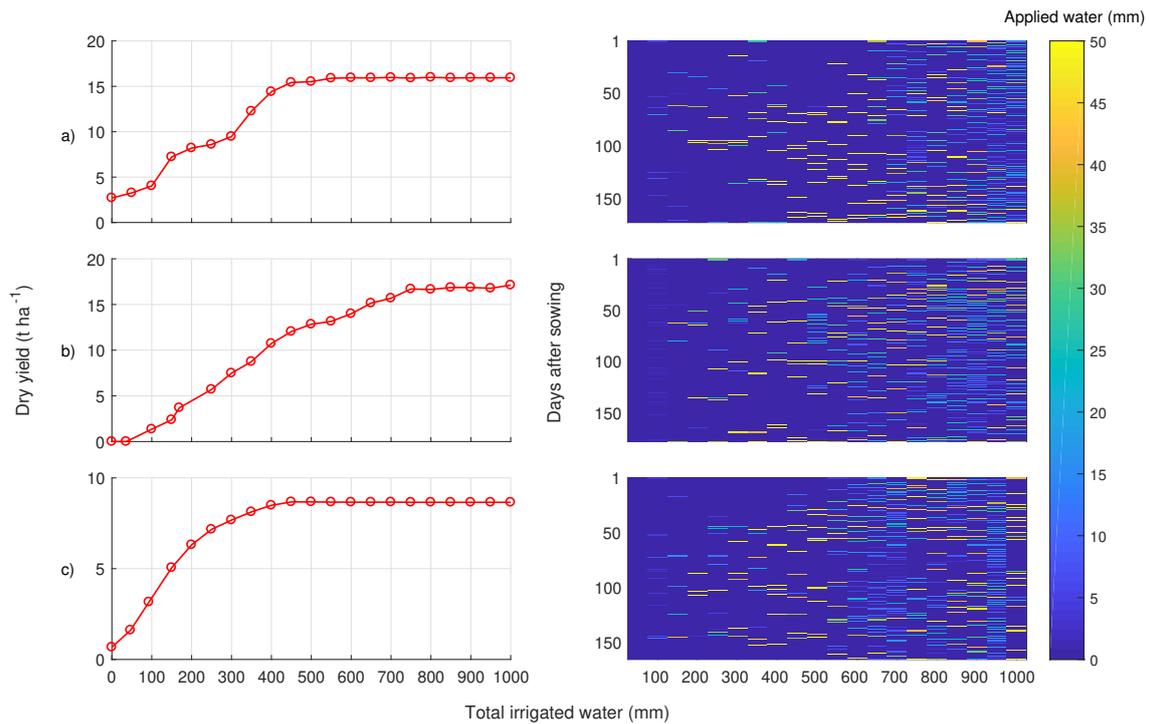


Figure 2. Water-yield functions (**left side**) and optimal irrigation schedules (**right side**) for maize (a), sugar beet (b), and wheat (c) under clay loam soil conditions.

Benchmarking was carried out by determining crop yield using Equation (2), considering the K_y values for each combination of crop, soil type, and weather scenario for each year. Different statistical indices were used, such as Normalised Root Mean Square Error (NRMSE) and linear regression, for comparison of the results obtained from AquaCrop-OS and those estimated using the proposed methodology. The NRMSE (in %) was calculated according to Loague and Green [40]:

$$\text{NRMSE} = \left[\sqrt{\frac{\sum_{s=1}^S (Y_{AOS,k} - Y_{Prop,k})^2}{S}} \right] \times \frac{100}{\bar{Y}_{AOS,k}}, \quad (4)$$

where $Y_{AOS,k}$ and $Y_{Prop,k}$ correspond respectively to the crop yield estimated by AquaCrop-OS and the proposed methodology for the year k and $\bar{Y}_{AOS,k}$ represents the mean value of the crop yields estimated by AquaCrop-OS for the year k . A simulation is considered excellent if its NRMSE is less than 10%, good if its NRMSE is greater than 10% and less than 20%, fair if its NRMSE is greater than 20% and less than 30%, and poor if its NRMSE is greater than 30% [41].

2.3. Case Study

Our proposed model was applied to conditions characteristic of the Central Valley of Chile (see Figure 3). The annual mean precipitation in this area is about 1025 mm, and the average maximum and minimum temperatures are 20.6 and 7.6 °C, respectively [42]. This region contains about 28% of the national cropping area. Some of the most-produced crops are wheat (34.3%), maize (11.6%), and sugar beet (6%), which contribute to 27.9%, 22.5%, and 60% of the national planted surface, respectively [43]. The soils are formed from volcanic ashes (Andisols) deposited over an unrelated substrate of andesitic tuff and fluvio-glacial materials. The texture is predominately silty clay loam, silty loam, and loam, and the bulk density ranges from 0.71 to 1.35 Mg m⁻³ [44–46].

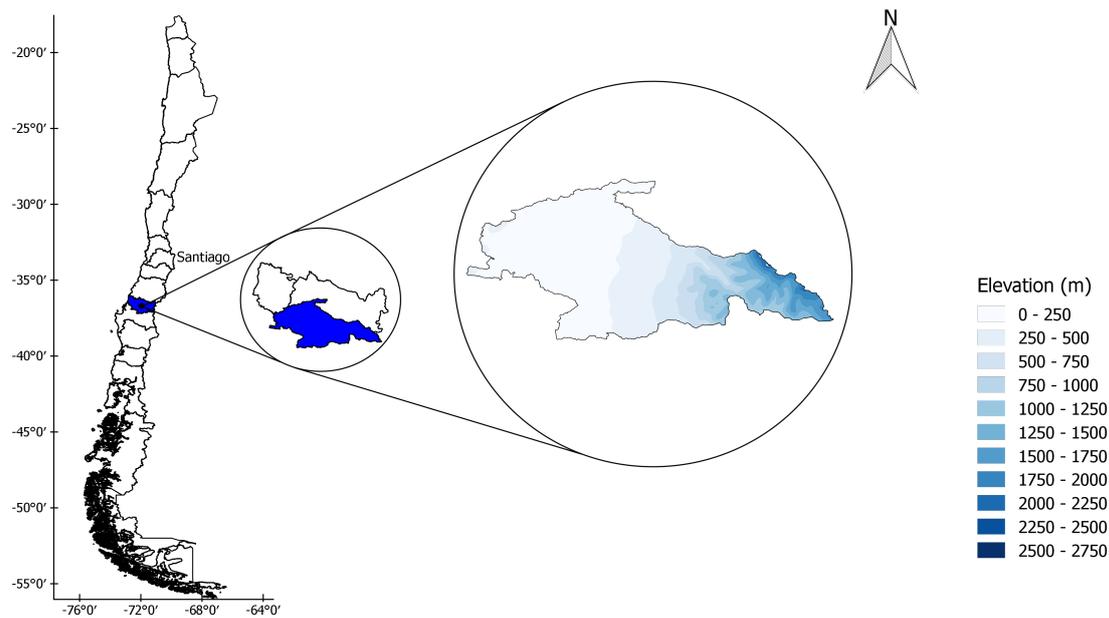


Figure 3. Study area location.

2.4. Model Inputs

Sowing dates for maize, wheat, and sugar beet for each year correspond to the first day of November, September, and August, respectively [47]. A weather database from 1970 to 2014 (Figure 4) was extracted from the Explorador Climático website (<http://explorador.cr2.cl/>). Reference evapotranspiration was estimated according to Allen et al. [48]. Crop parameters from the AquaCrop-OS [37] database were considered (see Table 1). On the other hand, soil hydraulic parameters (Table 2) were extracted from Granda et al. [45] and saturated hydraulic conductivity (Ks) was estimated using the RETC model [49]. Soils in the area of study are mainly derived from volcanic ashes, with strong vertical and horizontal variability. The data in Table 2 are based on field studies (see Granda et al. [45] and Kuschel-Otárola [50]), such that the Ks values lie in the range of variation and provide realistic values for representative soils. However, we draw attention to the fact that andesitic soils are less-studied soils and show high variability in hydraulic parameters, despite having similar texture. Moreover, agricultural operations have effects on changes in bulk density which are not always accounted by pedotransfer functions. For soils, the numbers 1, 2, and 3 correspond to low, medium, and high bulk density, respectively. Each growing season started with 50% of the total available water. Regarding fertilisation, there was no differentiated management to not alter the water management conditions.

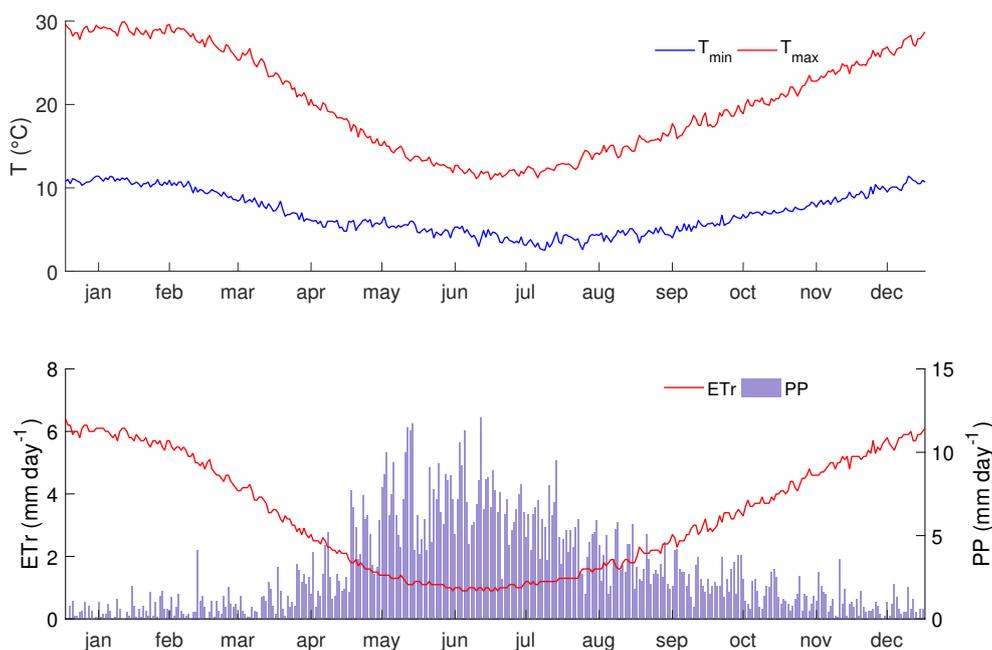


Figure 4. Minimum and maximum temperature (T_{min} and T_{max}), reference evapotranspiration (ETr), and precipitation (PP) for the study area, presented as mean values from 1970 to 2014.

Table 1. Conservative (constant) and generally applicable parameters for maize, sugar beet, and wheat in the Central Valley of Chile.

Parameter	Crop		
	Maize	Sugar Beet	Wheat
Conservative (generally applicable)			
Base temperature ($^{\circ}\text{C}$)	8.00	5.00	0.00
Cut-off temperature ($^{\circ}\text{C}$)	30.00	30.00	26.00
Canopy cover per seedling at 90% emergence (CC_0)	6.50	1.00	1.50
Canopy growth coefficient (CGC)	1.25	1.05	0.50
Maximum canopy cover (CC_x)	96.00	98.00	96.00
Crop coefficient for transpiration at $CC = 100\%$	1.05	1.10	1.10
Decline in crop coef. after reaching CC_x	0.30	0.15	0.15
Canopy decline coefficient (CDC) at senescence	1.00	0.39	0.40
Water productivity, normalised to the year 2000 (WP^*)	33.70	17.00	15.00
Leaf growth threshold (P_{upper})	0.14	0.20	0.20
Leaf growth threshold (P_{lower})	0.72	0.60	0.65
Leaf growth stress coefficient curve shape	2.90	3.00	5.00
Stomatal conductance threshold (P_{upper})	0.69	0.65	0.65
Stomata stress coefficient curve shape	6.00	3.00	2.50
Senescence stress coefficient (P_{upper})	0.69	0.75	0.70
Senescence stress coefficient curve shape	2.70	3.00	2.50
Considered to be conservative but can or may be cultivar-specific			
Reference harvest index (HI_0)	48	70	48
GDD from 90% emergence to start of anthesis	800	842	1100
Duration of anthesis, in GDD	180	0	200
Coefficient, inhibition of leaf growth on HI	7	4	10
Coefficient, inhibition of stomata on HI	3	-	7
Maximum yield (t ha^{-1}) (more details in Kuschel-Otárola et al. [27])	15	100	7

Table 2. Bulk density (ρ_a), saturation (θ_s), field capacity (θ_{fc}), permanent wilt water content (θ_{pwp}), and saturated hydraulic conductivity (K_s) representative of the Central Valley of Chile. A constant soil depth of 2.3 m was considered and there was no influence from the water table.

Soil	Sand	Silt (%)	Clay	ρ_a (g cm ⁻³)	θ_s	θ_{fc} (m ³ m ⁻³)	θ_{pwp}	K_s (mm day ⁻¹)
ClayLoam 1	22	48	30	0.72	0.73	0.45	0.30	3415.9
ClayLoam 2	35	38	27	0.97	0.64	0.57	0.33	269.1
ClayLoam 3	39	28	33	1.39	0.47	0.34	0.26	132.4
Loam 1	34	42	24	0.71	0.73	0.44	0.28	3517.8
Loam 2	31	46	23	1.07	0.60	0.59	0.40	69.5
Loam 3	41	37	22	1.13	0.57	0.55	0.34	110.3
SiltyClayLoam 1	10	52	38	0.78	0.70	0.46	0.32	2382.0
SiltyClayLoam 2	11	52	37	0.81	0.69	0.50	0.32	1903.3
SiltyClayLoam 3	15	49	36	0.86	0.68	0.50	0.36	1534.2
SiltyLoam 1	27	50	23	0.71	0.73	0.44	0.28	3571.7
SiltyLoam 2	22	51	27	0.98	0.63	0.59	0.38	183.9
SiltyLoam 3	24	51	25	1.03	0.61	0.59	0.44	76.3

3. Results and Discussions

3.1. Yield Response Factor for Each Growth Stage

The K_y values for each growth stage (emergency or transplant recovery, vegetative stage, flowering stage, and yield formation and ripening) are presented in form of box plots for maize, sugar beet, and wheat, in Figures 5–7, respectively. These figures represent K_y as a discrete mean value over 5 years for benchmarking (i.e., 1970–1974, 1975–1979, 1980–1984, 1985–1989, 1990–1994, 1995–1999, 2000–2004, 2005–2009, and 2010–2014) for different soil types in the study area with low (1), medium (2), and high (3) bulk densities (Table 2) considering optimal irrigation scheduling (GET-OPTIS). In each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered as outliers, and the outliers are plotted individually using the “+” symbol.

3.1.1. Yield Response Factor For Maize

Figure 5 shows the K_y values for maize at each growth stage and for soils with low (1), medium (2), and high (3) bulk densities. According to Steduto et al. [28], $K_y > 1$ implies that the crop is very sensitive to water deficits, $K_y < 1$ means that it is more tolerant to water deficits, and $K_y = 1$ corresponds to a direct proportion of yield reduction to reduced water use. The K_y value for the first growth stage was close to zero for all soil types. On the other hand, K_y always reached its maximum in the third growth stage (flowering). Its values ranged from 0.9 to 1.4, indicating that maize is very sensitive to water deficits in this stage. Thus, water stress during this stage incurs larger reductions than in other stages [20,28]. For clay loam soil, the higher the bulk density, the lower the value of K_y was in the third growth stage. With the exception of the fourth growth stage, the obtained values were lower than those proposed by the FAO [51].

3.1.2. Yield Response Factor for Sugar Beet

Figure 6 shows the K_y values for sugar beet at each growth stage and for each soil type. Similarly to the results obtained for maize (Figure 5), the K_y value in the first growth stage was close to zero for all soil types, indicating that yield is not affected when there is enough water in the soil profile. It reached its maximum value in the third growth stage for most soil types; except for clay loam soil with high bulk density, where this value was the lowest (compared with the other soil types).

Furthermore, this soil type presented the highest values for the second and fourth growth stage. The obtained values were lower than those proposed by the FAO [51], for each growth stage.

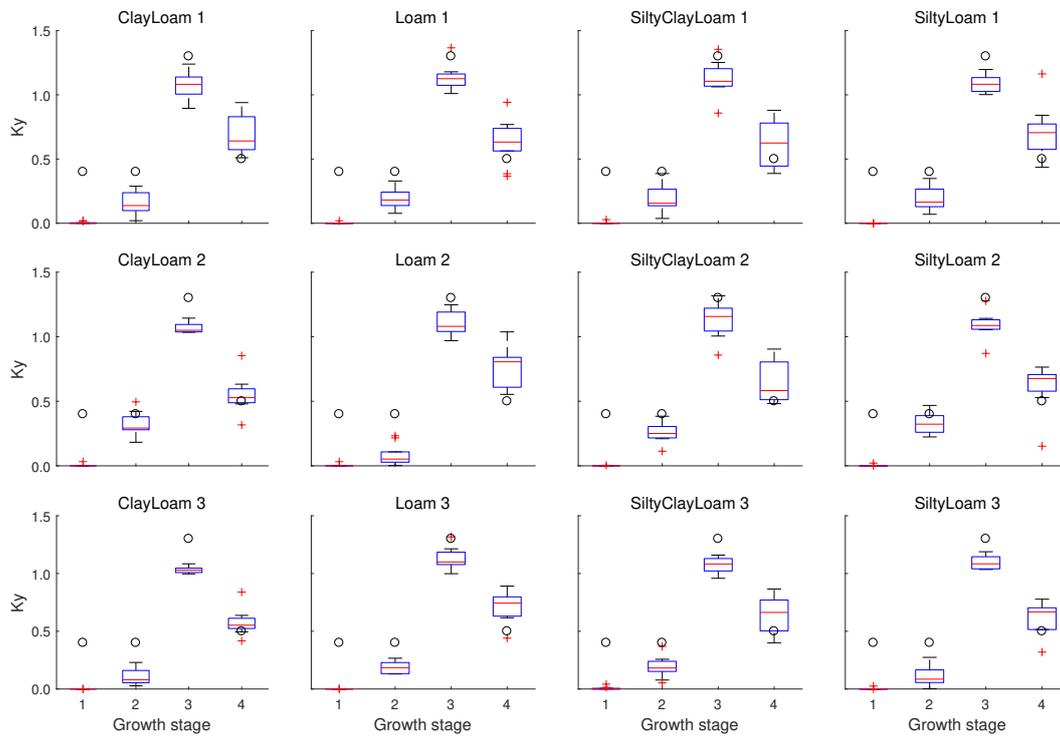


Figure 5. Yield response factor (K_y) obtained for maize for every soil type, considering the benchmark process. Circles represent K_y values proposed by the FAO [51].

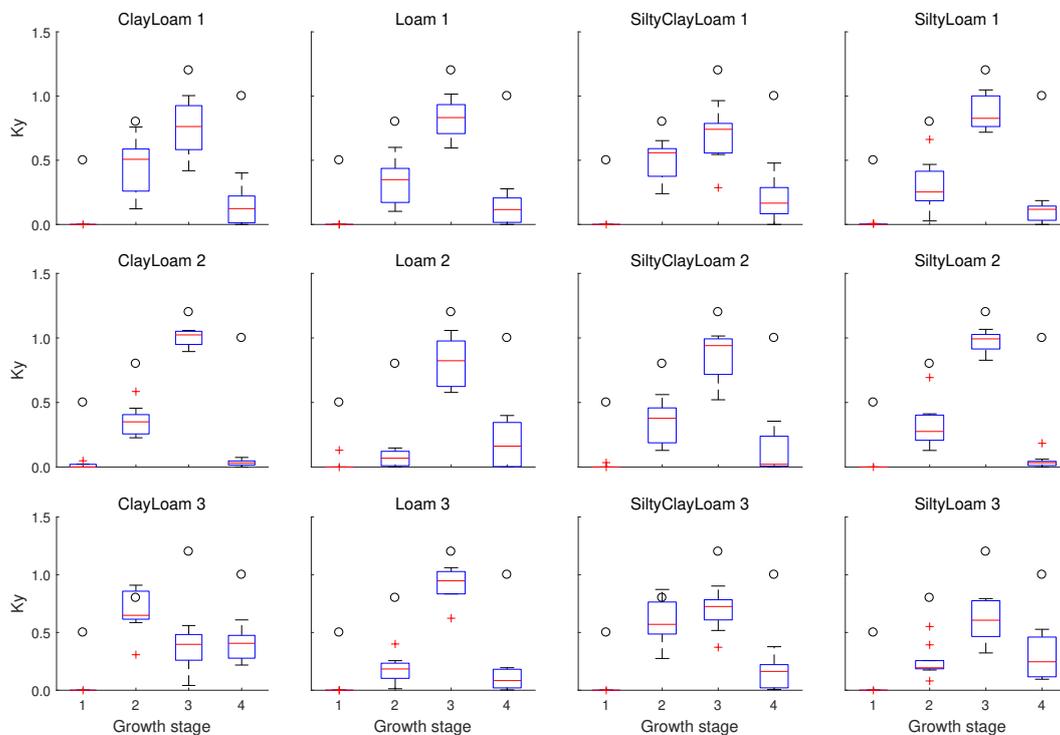


Figure 6. Yield response factor (K_y) obtained for sugar beet for every soil type, considering the benchmark process. Circles represent K_y values proposed by the FAO [51].

3.1.3. Yield Response Factor For Wheat

Figure 7 shows the K_y values for wheat for each growth stage and for each soil type. Similarly to the results obtained for maize (Figure 5) and sugar beet (Figure 6), the K_y value in the first growth stage was close to zero, except for loam soil with medium bulk density ($K_y = 0.15$). Regarding the value for the third growth stage, this value was relatively low when compared to maize and sugar beet. The lowest value for the third growth stage was presented in loam soil with medium bulk density ($K_y = 0.73$); this soil type also presented a value over the 70th percentile for the second growth stage ($K_y = 0.30$). With the exception of the third growth stage, the obtained values were lower than those proposed by the FAO [51]. Soils with high bulk density (index number 3) showed lower differences, with respect to the values proposed in the literature.

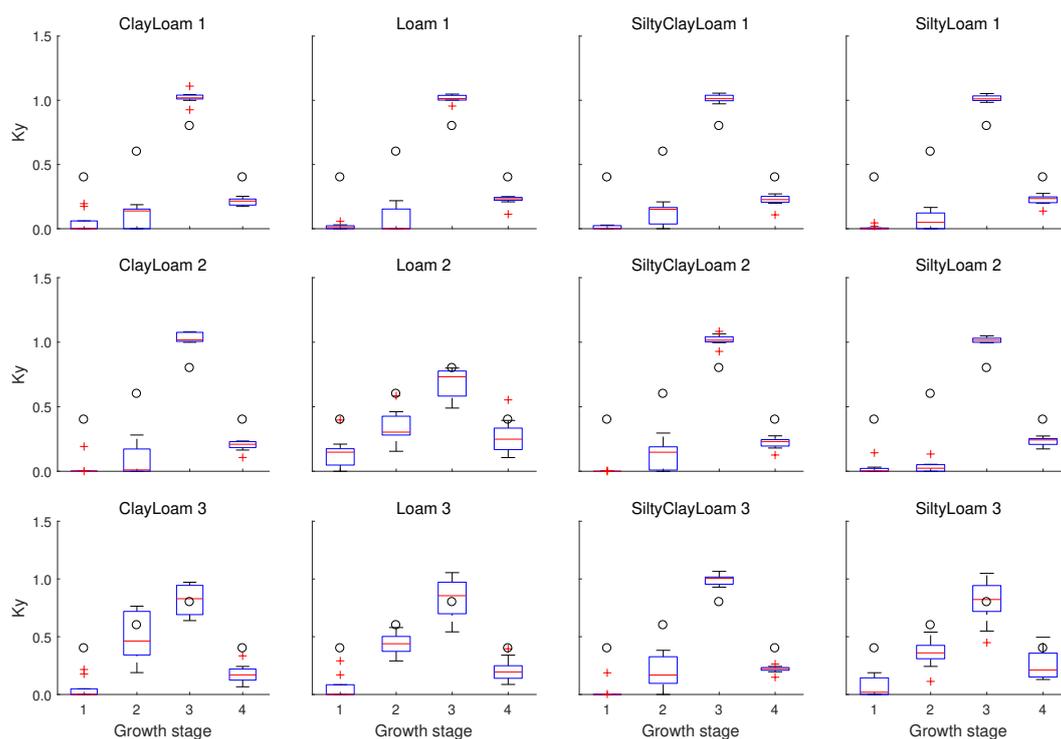


Figure 7. Yield response factor (K_y) obtained for wheat for every soil type considering the benchmark process. Circles represent K_y values proposed by the FAO [51].

3.2. Benchmarking of the Proposed Methodology

3.2.1. Benchmarking for a Specific Year

Figure 8 shows the comparison between the dry yield obtained by AquaCrop-OS (red line 1:1) and the estimates obtained by the proposed methodology (blue dots). There was generally a good agreement between the results obtained by AquaCrop-OS and the proposed methodology, with NRMSE values ranging from 1.62% (wheat in a silty loam soil) to 15.80% (sugar beet in a loam soil). The K_y values used in this case were extracted from the benchmark between 2010–2014 (see Table 3). According to Steduto et al. [28], sugar beet (*Beta vulgaris*) is a biennial plant which produces a large storage root as a part of its tap root, containing 14–20% sucrose on a fresh mass basis; thus, the crop yield values of sugar beet can reach 80–120 t ha⁻¹.

3.2.2. Benchmarking for All Years

The benchmarking for all years was carried out by determining the Normalised Root Mean Square Error (NRMSE) for every year. Figure 9 shows the NRMSE values for each year for maize (a), sugar beet

(b), and wheat (c), for all soil types, where the lowest and highest values are presented in blue and red, respectively. According to the classification suggested by Jamieson et al. [41], the values are ranged from 0% to $\geq 30\%$. It can be seen that wheat presented the best performance.

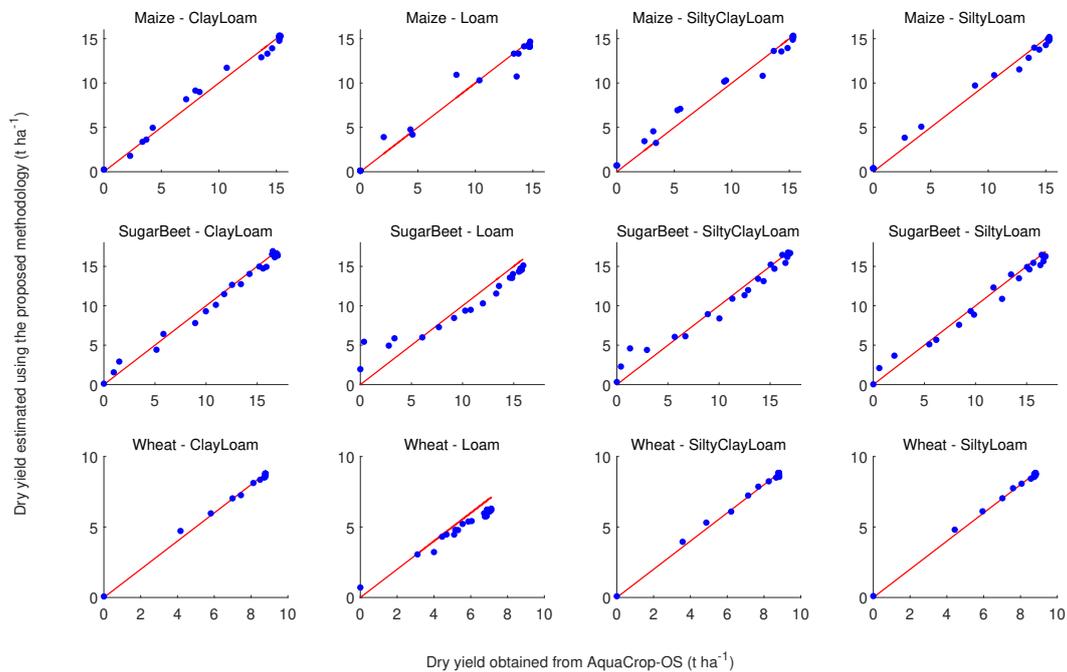


Figure 8. Crop yield (Y) obtained from the benchmarking for maize, sugar beet, and wheat in various soil types considering the mean value of bulk density in the year 2014. Red lines present the benchmark estimated by AquaCrop-OS, while each blue dot corresponds to the crop yield estimated by the proposed methodology.

Table 3. Yield response factor (K_y) obtained for maize, sugar beet, and wheat in various soil types considering the mean value of bulk density, valid for the years 2010–2014.

Crop	Soil	1st	2nd	3rd	4th	Total
Maize	ClayLoam	0.00	0.29	1.04	0.48	1.07
	Loam	0.00	0.05	0.97	0.73	1.01
	SiltyClayLoam	0.00	0.22	0.86	0.58	1.10
	SiltyLoam	0.00	0.47	1.05	0.15	1.10
Sugar beet	ClayLoam	0.00	0.59	1.02	0.00	1.16
	Loam	0.00	0.12	0.82	0.21	1.13
	SiltyClayLoam	0.00	0.51	0.96	0.00	1.15
	SiltyLoam	0.00	0.41	1.00	0.00	1.16
Wheat	ClayLoam	0.00	0.00	1.01	0.23	1.05
	Loam	0.16	0.40	0.73	0.26	1.09
	SiltyClayLoam	0.00	0.00	1.01	0.25	1.09
	SiltyLoam	0.00	0.00	1.02	0.25	1.04

On the other hand, Figure 10 shows a comparison of the frequency of NRMSE values, as suggested by Jamieson et al. [41]. Local estimation of the K_y values presented better performance, compared to the values reported in the literature [20,51], as they were not specific to a particular soil type or management. Local estimation increased the frequency of the best performance (excellent) in maize (from 0 to 67%), sugar beet (from 0 to 35%) and wheat (from 46 to 82%). Wheat, however, presented the best performance, considering the K_y values suggested by the FAO [51].

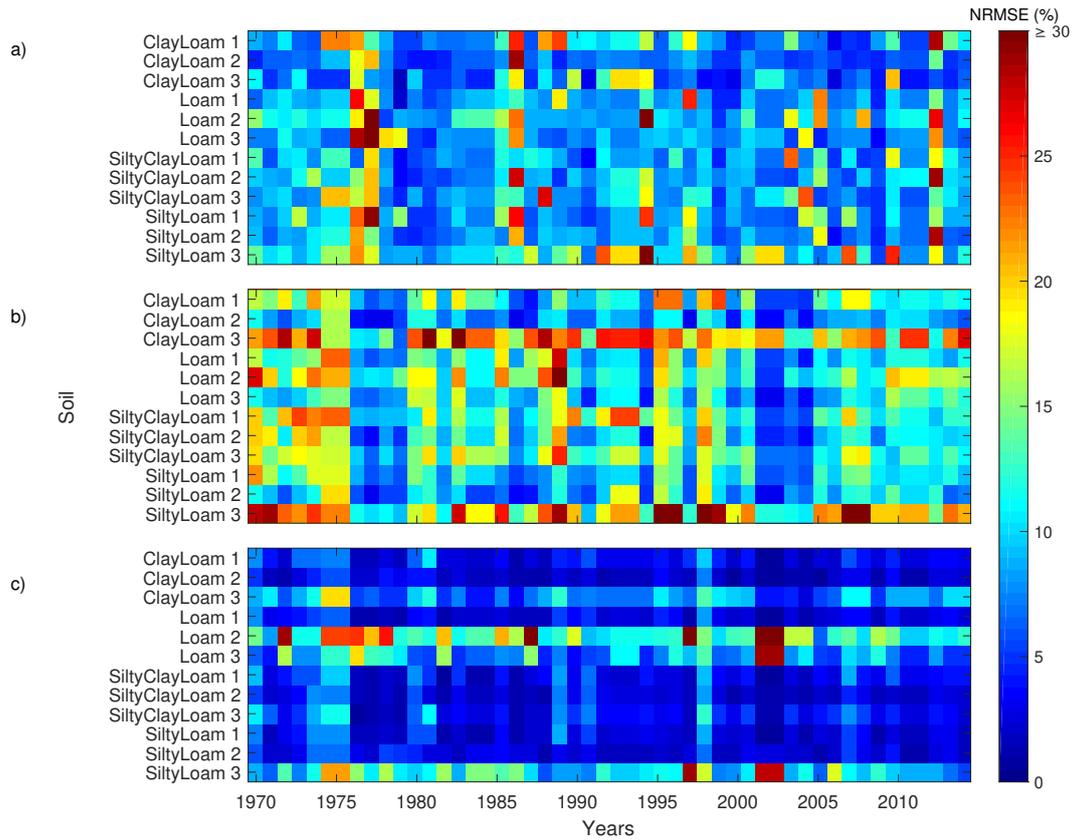


Figure 9. Normalised Root Mean Square Error (NRMSE) for maize (a), sugar beet (b), and wheat (c), for every soil type, from 1970 to 2014.

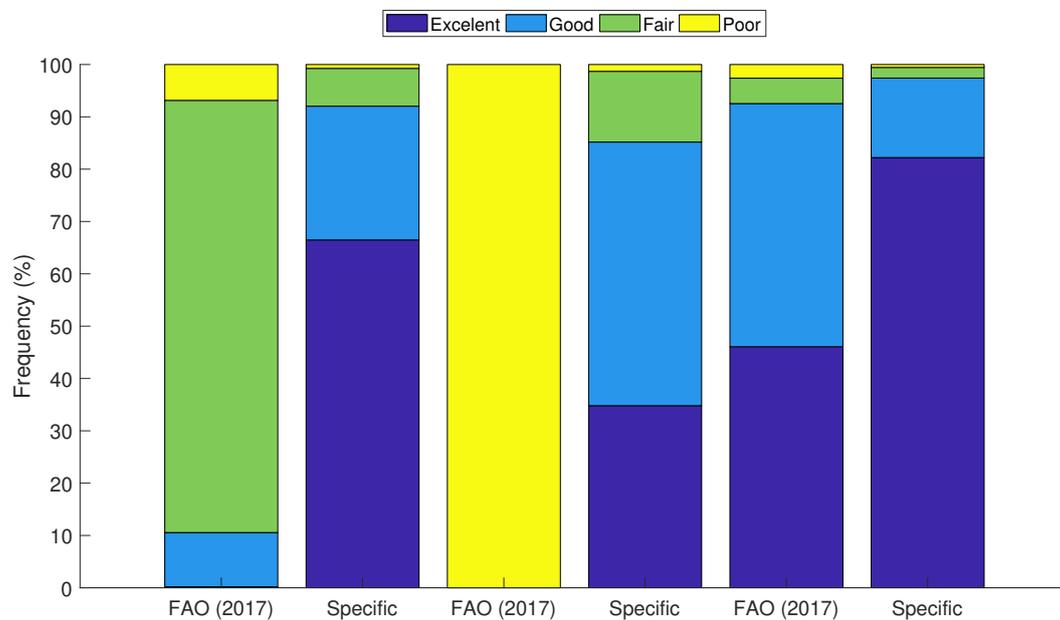


Figure 10. Comparison of the frequency of NRMSE values obtained by the proposed methodology and recommended by CROPWAT database [51].

4. Conclusions

We developed and assessed a methodology to estimate the K_y value under local conditions for a given crop, soil, weather, sowing date, and management, as well as for each growth stage,

using AquaCrop-OS under Chilean conditions. The proposed methodology presented a good agreement; excellent simulation of 67%, 35%, and 82% was observed for maize, sugar beet, and wheat, respectively (Figure 10), allowing us to estimate the K_y values under local conditions and to dispose of the typical simple mathematical approach in which yield reduction is estimated as a result of water scarcity at each growth stage.

Most irrigation managers consider resources to be available over the whole season. However, at sub-seasonal time scales—weekly, monthly, or even daily—irrigation managers and farmers must make decisions and take action based on new information regarding climate drivers and resource availability. Thus, the K_y value could be used to tailor water management strategies under changing conditions [27]. Future studies should focus on the estimation of K_y under a more diverse range of management scenarios.

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