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Estimation of Sugar Beet Yield and its Dry Matter Partitioning Under Different Irrigation and Nitrogen Levels

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Abstract

In this study, a simple logistic model was developed for estimating total dry matter of sugar beet under different irrigation and nitrogen levels. The experiment was conducted using line source sprinkler irrigation in 2013 and furrow irrigation in 2014. Irrigation treatments were from 44% to 130% of full irrigation and applied nitrogen treatments ranged from 0 to 240 kg N ha^{-1}. Results showed that the model was more accurate in predicting total dry matter at harvest date with the Normalized Root Mean Square Error (NRMSE) amounting to almost 10 percent. After total dry matter estimation, a model was needed for dry matter partitioning between different organs of sugar beet. To achieve this goal, another logistic model was developed and was compared with three revised models. Finally, white sugar content of root dry matter was estimated using a quadratic equation as a function of applied water and nitrogen. Validation results indicated that total and root dry matters, and white sugar yield were estimated fairly well. Results showed that excessive water had negative effects on total dry matter and root dry matter. Also, excessive nitrogen affected root dry matter negatively too, but even the excess had positive effects on total dry matter. In contrast to common belief, our results showed that drought stress reduced both ratios of root to leaf, and root to shoot dry matter.

Keywords: sugar beet, modelling, logistic model, dry matter partitioning

1. Introduction

Sugar beet (Beta vulgaris L.) is a biennial plant and is an economically important crop for its profound use in the production of sugar. It is harvested in the growing season of the first year of growth if it is to be used for sugar production, but will be kept in the ground until the second year if to be used for seed production. The plant has a large storage root that contains 14% to 20% sucrose in its fresh mass (Steduto, 2012). Its water management is of prime importance because of its high water requirement, especially in arid and semi-arid countries like Iran. Its water requirements depend on several factors such as the climate conditions, irrigation method, sowing date, water quality and soil properties.

The anatomy of sugar beet is divided into several parts such as: tap root (storage root), fibrous roots, blades and petioles. Total dry matter is considered to be comprised of these parts (Lukaszewska & Sliwinska, 2007). The partitioning of dry matter between the crop components is important in crop modeling. The patterns that are used for allocating the dry matter to the crop components have always been regarded as one of the most important challenges in crop modeling, since it plays an important role in the estimation of yield. Some models have been proposed to describe the term "assimilate partitioning" within the sugar beet plant (Webb et al., 1997). There have been descriptions of a dynamic model, specifically for partitioning the occurring assimilates between the shoot, storage root and fibrous roots. These were derived from observations dealing with the effect of soil nitrogen on crop growth. Werker et al. (1999) proposed allometric and logarithmic models which examine simple relationships between the sugar yield, total dry matter and soil nitrogen in rain-fed and irrigated sugar beet

Dry matter partitioning is significantly affected by several environmental variables, i.e. soil water, soil nitrogen, weather conditions and genotype. In many cases, nitrogen is a limiting factor, because few soils contain sufficient amounts of nitrogen in a form available for the crop to absorb (Draycott, 2008). Water is vital for sugar beet growth, especially in arid regions such as Iran (Hassanli et al., 2010). It can be construed that the most important elements for sugar beet growth are water and nitrogen.

It is obvious that achieving efficient models for dry matter partitioning depends on the accurate estimation of total dry matter. Several models are proposed for sugar beet that can estimate the total dry matter. These models include AquaCrop (Stricevic et al., 2011), CERES (Baey et al., 2014; Jones et al., 1986; leviel, 2000), Greenlab (De Reffye & Hu, 2003), SUBEMOpo (Vandendriessche, 2000a; Vandendriessche, 2000b), the Broom's Barn sugar beet growth model (Qi et al., 2005) and a model for water and salt stress condition (Sepaskhah et al., 2006). Of all these mentioned, few consider different scenarios for irrigation and nitrogen conditions. On the other hand, mechanistic models need various ranges of inputs (Baey et al., 2014; Mahbod et al., 2015). This gives rise to some researchers becoming interested in empirical models. One of the practical approaches is the logistic model. Stagnari et al. (2014) proposed a logistic model for the estimation of red beet dry matter, its root diameter and leaf dry weight under water stress conditions. Another logistic model has been proposed by Sepaskhah et al. (2011), which can be applied to predict the yield of maize under specific managements of water and nitrogen.

The objectives of this study are (i) to develop a logistic model for predicting the total dry matter of sugar beet by considering the affected of water and nitrogen application, (ii) to validate the developed model along with another four selected models for the estimation of dry matter partitioning and sugar yield under different conditions of water supply and nitrogen availability.

2. Methods

2.1 Field and Climate Description

This study was conducted during the growing seasons in 2013 and 2014 at the Experimental Station of Agricultural College, Shiraz University, at 29°56´_N, 52°02´_E and at 1810 m above sea level, in the southwest of Iran, where the climate is semi-arid, with an annually average air temperature of 13.4 °C, a relative humidity of 52.2%, and a precipitation value of 387 mm. The typical soil at the experimental site is silt-clay loam, which is consistent down to 1.2 m beneath the ground surface (Table 1). The chemical properties of the irrigation water are shown in Table 2. Meteorological data were obtained from the weather station at the Agricultural College, located near the experimental field. Figure 1 shows the maximum and minimum of daily air temperatures (Tmax and Tmin), the mean daily relative humidity (RHavg) and the daily reference evapotranspiration (ETo) during the growing seasons in 2013 and 2014. The reference evapotranspiration (ETo) was calculated by using a modified FAO-Penman–Monteith method (Razzaghi & Sepaskhah, 2012).

Table 1. Physical and chemical properties of soil at the experimental site

Depth (cm)	0-30	30-60	60-90	90-120
Texture*	SL**	CL	SCL	SCL
Clay (%)*	21.2	27.2	33.2	32.7
Silt (%)*	48.8	48.8	48.8	54.8
Sand (%)*	29.9	23.9	17.9	12.4
Bulk density (kg m^{-3})*	1290	1460	1540	1570
Field capacity (m^3 m^{-3})*	0.32	0.35	0.35	0.36
Wilting point (m^3 m^{-3})*	0.17	0.20	0.21	0.22
Organic matter (%)	1.06	1.15	-	-
pH	7.75	7.70	-	-
EC (dS m^{-1})	0.36	0.37	-	-
NO3-N (mg kg^{-1})	0.72	1.39	2.39	1.89
Available P (mg kg^{-1})	19.34	13.45	-	-
Available K (mg kg^{-1})	417.95	426.30	-	-

**Data from Ahmadi et al. (2014)*

*** SL: silt-loam, CL: clay loam, SCL: silt-clay loam*

Table 2. Chemical properties of irrigation water in the experimental site (Azizian & Sepaskhah, 2014)

EC dS m^{-1}	pH	Cl^{-1} meq L^{-1}	Na^{+} meq L^{-1}	Ca^{2+} meq L^{-1}	Mg^{2+} meq L^{-1}	HCO_3^{-1} meq L^{-1}
0.6	7.8	1.81	1.74	2.15	2	1.97

2.2 Treatments and Experimental Designs

The experiment in the first year (2013) was designed to have irrigation treatments as the main plot and the nitrogen fertilizer as the subplot. The Irrigation treatments were 130% (I1), 100% (I2), 85% (I3), 75% (I4), 66 % (I5) and 44% (I6) of full irrigation.

In the first year, sugar beet seeds were sown in 40 rows with spacing of 0.6 m on May 20, 2013. The field was thinned on June 15, so much so that the population of plants reached 67000 plants ha^{-1}. The field was irrigated via sprinklers set in line sources (Hanks et al., 1976). The sprinkler spacing on the line measured 6 m and the area of each plot was 2×6 m^2 (Figure 2). Phosphorus was applied in the form of triple superphosphate by 90 kg P ha^{-1}. Nitrogen was applied at 0 (N_0), 60 (N_1), 120 (N_2) and 180 (N_3) kg N ha^{-1} in the form of urea fertilizer. In order to minimize the marginal effects of N in different treatments, the set up of plots was designed as shown in Figure 2.

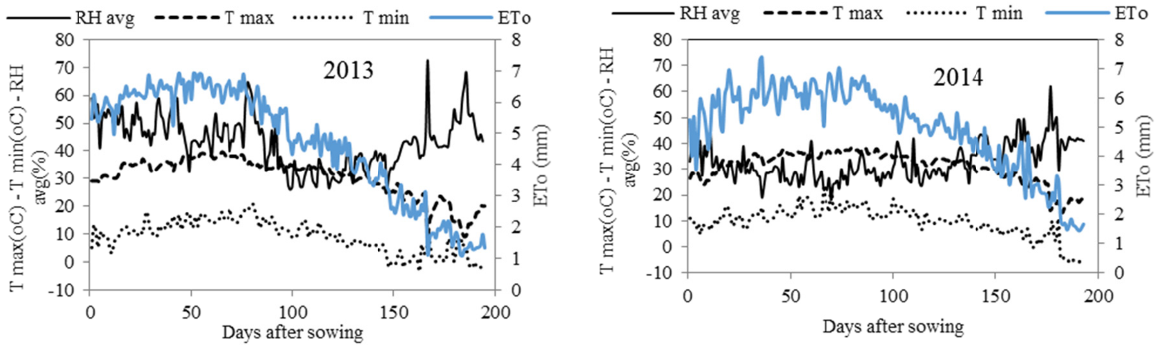


Figure 1. Daily maximum air temperature (T_{max}), minimum air temperature (T_{min}), relative humidity (RH_{avg}) and reference evapotranspiration (ET_o) during growing seasons in 2013 and 2014, beginning from May 21, 2013 and May 13, 2014

The amount of irrigated water at each treatment was measured with several cans (Figure 2). The Catchment cans were installed across the field in four rows, perpendicular to the line source, at a spacing of 2 m (Figure 2). Six irrigation treatments were used at each side of line source. Water was irrigated by an interval of seven days via sprinklers until September 14. For the first, second and third implementation of irrigation, the fields were irrigated by the furrow irrigation method, whereby water was irrigated by approximate amounts of 0.11, 0.05 and 0.04 m respectively.

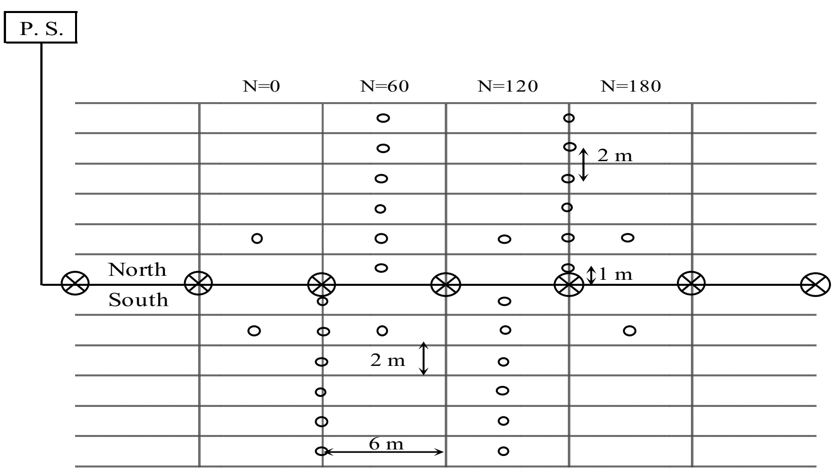


Figure 2. Schematic description of experimental field in the first year (2013)

In the second year (2014), the experimental design was a split plot arrangement in randomized complete block design, with irrigation treatment as the main plot and N fertilizer as the subplot, with three replications. The irrigation treatments were 120% (I_1), 100% (I_2), 80% (I_3), 80% (I_4) and 60% (I_5) of full irrigation. The experimental plots were irrigated by the furrow irrigation method. In the I_4 treatment, the degree of water deficit changed continually during the growing season, but its seasonal value remained equal to that of I_3 nonetheless. Therefore, the irrigation treatment of I_4 was deemed 100% of ET in the first growing stage. It became 90% in the second growing stage (after the establishment) and 35% in the last growing stage (after the mature growth of vegetation). Comparing the two treatments, I_3 and I_4, can provide useful information regarding the sugar beet susceptibility to drought during the growing season. The nitrogen treatments in the second year included 0 (N_0), 60 (N_1), 120 (N_2), 180 (N_3) and 240 (N_4) kg N ha^{-1} in the form of urea**.** The area of each plot was 3.6×4.5 m^2 and for the prevention of seepage from one plot to another, the distance between any of two adjacent plots was 1.0 m. Seeds were sown in five rows of 0.6 m spacing and 0.25 m between the plants in each row. The average population was 67000 plants ha^{-1}. Triple superphosphate at 90 kg P ha^{-1} was mixed with the soil before sowing the seeds at a soil depth of 0 − 0.3 m.

Nitrogen fertilizer was applied in three equal dosages in the both years. The first dosage was applied before planting, and the second and third dosages were applied when plants had 4-5 and 8-9 leaves, respectively. Harvesting was done at area of 5 m^2 after 193 and 195 days after planting in 2013 and 2014, respectively. Before each instance of irrigation, the soil water content was measured by the gravimetric method at different depths: 0.0, 0.3, 0.6, 0.9 and 1.2 m. The soil water content in the root zone was considered to determine the amount of irrigation water as calculated by the following equation:

$$d_n = \sum_{i=1}^{n}(\theta_{FCi} - \theta_i) \times \Delta z_i \quad (1)$$

Where d_n is the irrigation depth (m), θ_{FCi} and θ_i are the volumetric soil water contents in layer i at field capacity and before irrigation, respectively (m^3 m^{-3}), Δz is the soil layer thickness (0.3 m in this study), and n is the number of soil layers.

The root depth was estimated using the following equation (Borg & Grimes, 1986),

$$R_d = R_{d\ min} + R_{d\ max}\,(0.5 + 0.5\,sin(3.03\frac{D_{ag}}{D_{tm}} - 1.47)) \quad (2)$$

Where R_d is the root depth (m), $R_{d\ min}$ is the sowing depth (0.03m for sugar beet), $R_{d\ max}$ is the maximum root depth (1.1 m for sugar beet), D_{ag} is the number of days after the first irrigation, D_{tm} is the number of days needed for the plant to reach maximum root depth.

In order to ensure that the majority of seeds germinate almost altogether, three initial irrigations were applied to all treatments uniformly. Figure 3 illustrates the cumulative amounts of water for each irrigation as regards the different irrigation treatments and rainfalls during 2013 and 2014.

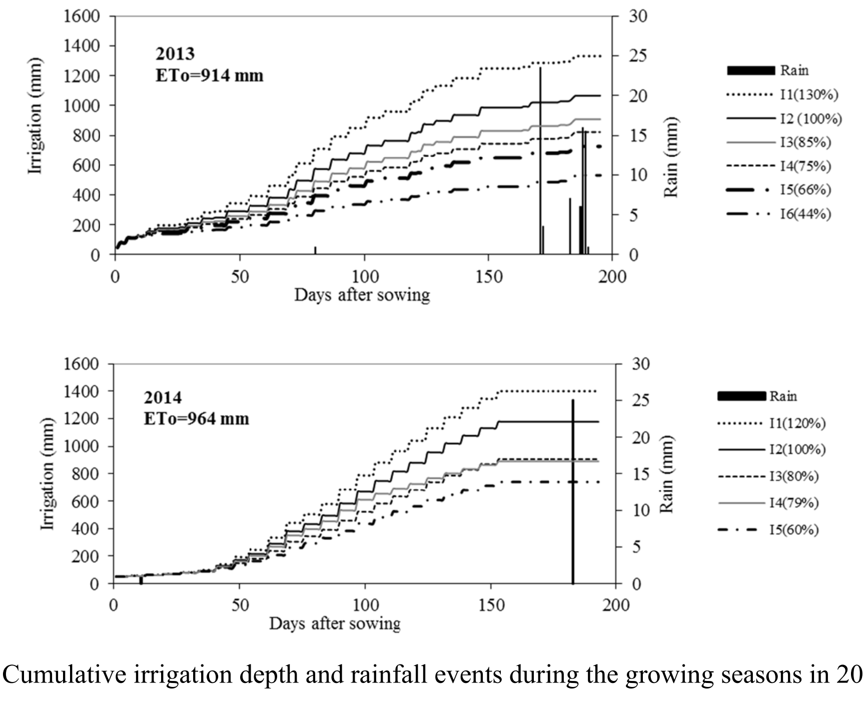


Figure 3. Cumulative irrigation depth and rainfall events during the growing seasons in 2013 and 2014

2.3 Description of the Logistic Model

A logistic model was fitted against GDD for the estimation of total dry matter as follows:

$$W = \frac{W_m}{(1+A*exp(-B\times GDD))} \quad (3)$$

where W is the total dry matter (Mg ha^{-1}), W_m is the maximum total dry matter (Mg ha^{-1}), A is the values corresponding to the maximum total dry weight, B is a parameter describing the rate of the increases in growth and GDD is the accumulative growing degree days that stands for elapse time.

The values of W_m, A and B pertained to the applied water and nitrogen as:

$$W_m = W_1 + W_2(IR^*) + W_3(N^*) + W_4(IR^*)^2 + W_5(N^*)^2 + W_6(IR^* \times N^*) \quad (4)$$

$$\boldsymbol{A = A_1 + A_2(IR^*) + A_3(N^*) + A_4(IR^*)^2 + A_5(N^*)^2 + A_6(IR^* \times N^*)} \quad (5)$$

$$\boldsymbol{B = B_1 + B_2(IR^*) + B_3(N^*) + B_4(IR^*)^2 + B_5(N^*)^2 + B_6(IR^* \times N^*)} \quad (6)$$

where $IR^* = \frac{IR}{ET_o}$, $N^* = \frac{N}{N_r}$, IR is the amount of water being irrigated, ET_o is the reference evapotranspiration, N is the amount of applied and soil residual nitrogen and N_r is the soil residual and fertilizer nitrogen for no deficiency (kg ha^{-1}). The optimal values of W_1 to W_6, A_1 to A_6 and B_1 to B_6 were estimated using the multiple linear regression method.

It is better to consider the amount of total nitrogen as the amount of residual soil nitrogen plus the amount of nitrogen fertilizer. In the present study, we consider this point of view accordingly:

$$N = N_s + N_f \quad , \quad N_r = N_s + N_{fr} \quad (7)$$

Where N_s is the residual soil nitrogen (kg ha^{-1}), N_f is the amount of applied nitrogen (kg ha^{-1}) and N_{fr} is the nitrogen fertilizer amount for no deficiency (kg ha^{-1}).

After estimating the total dry matter, a dry matter partitioning model is needed to estimate the dry matter weights of the root and shoot. Therefore, another logistic model is developed in the present study in order to estimate the root dry matter. Root dry matter is calculated when the total dry matter is multiplied by the dry matter partition coefficient (P_r):

$$\boldsymbol{R = P_r \times W, S = W - R} \quad (8)$$

$$\boldsymbol{P_r = \frac{P_m}{(1+a*exp(-b\times GDD))}} \quad (9)$$

$$\boldsymbol{P_m = P_1 + P_2(IR^*) + P_3(N^*) + P_4(IR^*)^2 + P_5(N^*)^2 + P_6(IR^* \times N^*)} \quad (10)$$

$$\boldsymbol{a = a_1 + a_2(IR^*) + a_3(N^*) + a_4(IR^*)^2 + a_5(N^*)^2 + a_6(IR^* \times N^*)} \quad (11)$$

$$\boldsymbol{b = b_1 + b_2(IR^*) + b_3(N^*) + b_4(IR^*)^2 + b_5(N^*)^2 + b_6(IR^* \times N^*)} \quad (12)$$

where R is the root dry matter, S is the shoot dry matter, P_r is the fraction of the total dry matter which is considered to be the storage root, P_m is the maximum fraction of root dry matter, a is the values corresponding to the maximum fraction of root dry matter and b is a parameter which describes the increase in growth. Optimal values of P_1 to P_6, α_1 to α_6 and b_1 to b_6 were estimated using the multiple linear regression method.

2.4 Models that Describe the Dry Matter Partitioning

In this study, three models were used to compare the validity of the logistic model for dry matter partitioning. The first models were proposed by Webb et al. (1997), while the second and third were proposed by Werker et al. (1999). Meanwhile, (Webb et al., 1997) described a *quadratic* model for the partitioning of assimilates between the shoot, storage root and fibrous roots, which was estimated based on observations regarding the effect of soil nitrogen on crop growth as follows:

$$Q_s = P^2, Q_k = (1-P), Q_r = P(1-P) \quad (13)$$

Where Q_s, Q_k and Q_r are the partitioning of assimilates to the shoot, storage root and fibrous root, respectively; P is a partitioning variable being described by using the following logistic function:

$$\boldsymbol{P = \alpha + \frac{\beta}{1+e^{\sigma(t-\mu)}}} \quad (14)$$

Where t is time (days from January 1); α, σ and μ are constant parameters, while β illustrates the nitrogen content in the soil. The optimal values of α, σ, μ and β were obtained using the solver menu of Excel as α = 0.48, σ = 0.364 (d^{-1}), μ = 209.52 (d) and β = 0.15, 0.18, 0.22, 0.23, 0.24, 0.26 and 0.27 for different nitrogen applications of 0, 30, 60, 90, 120, 150 and 180 (kg N ha^{-1}), respectively.

Werker et al. (1999) proposed simple relationships between sugar yield, total dry matter and soil nitrogen under rain-fed and irrigated conditions. They proposed two models for the dry matter partitioning, the first of which was named the *allometric* growth function and the second was named a *logarithmic* model. The first function is based on the assumption that the relative growth rates of plant components are proportional to each other and remain constant. After solving some equations, the allometric growth function was proposed as follows:

$$Y = Y_0\left(\frac{W}{W_0}\right)^{\alpha_0 \frac{W_0}{Y_0}} \tag{15}$$

where W is the total dry matter (W=Y+G), Y is the storage dry matter (sugar), G is the structural dry matter, W_0 is the initial total dry matter, Y_0 is the initial storage dry matter (sugar), and α_0 is the initial partitioning fraction of total dry matter set against Y.

Another model proposed by *Werker et al.* (1999) is a logarithmic model. They simplified the model with some assumptions, and finally presented the model as follows:

$$\boldsymbol{G = \frac{1}{k} log(1 + kW)} \tag{16}$$

$$\boldsymbol{Y = W - \frac{1}{k} log(1 + kW)} \tag{17}$$

Where k is a constant parameter that shows the speed of the partitioning function (g^{-1} m^2). The effects of drought and nitrogen deficiency were estimated by two separate equations. The effect of drought was estimated for the purpose of harvesting the dry matter and evaluating the effect of nitrogen on the partitioning. These were analyzed by allowing the parameter k to vary with respect to the nitrogen supply.

As it was expected, these three models for dry matter partitioning could not reasonably estimate the dry matter partitioning under different water and nitrogen conditions. Therefore, they were modified in the present study so as to consider the water and nitrogen being used therein.

2.4.1 The Revised Quadratic Model

As mentioned earlier, in the alternative model constructed by Webb et al. (1997), the amount of water for irrigation was not to be considered in the dry matter partitioning and α was a fixed parameter, while β showed the effect of nitrogen content in the soil. But in this study, we had α and β as being related to the nitrogen added to the soil and the irrigated water in dimensionless formulas as follows:

$$R = (1 - P)W, S = W - R$$

$$P = \alpha + \frac{\beta}{1 + e^{\sigma(GDD - \mu)}}$$

$$\alpha = \alpha_1 + \alpha_2(IR^*) + \alpha_3(N^*) + \alpha_4(IR^*)^2 + \alpha_5(N^*)^2 + \alpha_6(IR^* \times N^*)$$

$$\beta = \beta_1 + \beta_2(IR^*) + \beta_3(N^*) + \beta_4(IR^*)^2 + \beta_5(N^*)^2 + \beta_6(IR^* \times N^*) \tag{18}$$

Where σ and μ are constant parameters, while α and β show the effects of water and nitrogen. Optimal values of σ, μ, α_1 to α_6 and β_1 to β_6 were estimated using a multiple linear regression method.

2.4.2 The Revised Allometric Model

The second model was extracted from the allometric growth function previously described according to Equation 15. In this model, R represents the storage root dry matter, S is the shoot dry matter, λ is the initial partitioning fraction of total dry matter to the storage root (R) as follows:

$$R = R_0\left(\frac{W}{W_0}\right)^{\lambda \frac{W_0}{R_0}}, \; S = W - R$$

$$\lambda = \lambda_1 + \lambda_2(IR^*) + \lambda_3(N^*) + \lambda_4(IR^*)^2 + \lambda_5(N^*)^2 + \lambda_6(IR^* \times N^*) \tag{19}$$

Optimal values of λ_1 to λ_6 were estimated using the multiple linear regression method.

2.4.3 The Revised Logarithmic Model

The third model is derived from Equation 16. In this model, K is considered to indicate the effects of drought and nitrogen on dry matter partitioning — the dry matter that is divided between the root and shoot. The equation is as follows:

$$R = \frac{1}{k}\log(1 + kW) \quad , S = W - R$$

$$k = k_1 + k_2(IR^*) + k_3(N^*) + k_4(IR^*)^2 + k_5(N^*)^2 + k_6(IR^* \times N^*) \quad (20)$$

The optimal values of k_1 to k_6 were estimated using the multiple linear regression method.

2.5 Sugar Yield Estimation

White sugar yield is estimated when the root dry matter is multiplied by the sugar content (Sc) as a function of IR^* and N^* as follows:

$$\boldsymbol{SY = Sc \times RDM} \quad (21)$$

$$\boldsymbol{Sc = Sc_1 + Sc_2\,(IR^*) + Sc_3\,(IR^*)^2 + Sc_4\,(N^*)^2 + Sc_5\,(IR^* \times N^*)} \quad (22)$$

Where SY is sugar yield, Sc_1 to Sc_5 are constant coefficient and their values are estimated using the multiple linear regression method. All the equations were calibrated via experimental data of the second year and were validated via experimental data of the first year.

2.6 Criteria for Evaluating the Models

Part of the assessments included a process to evaluate the results of the models in order to predict the fractions of dry matter allocation to the root and shoot. Accordingly, three statistical parameters were defined. These are the coefficient of determination (R^2), the Normalized Root Mean Square Error (NRMSE) *(*Loague & Green, 1991) and the index of agreement Willmott (1982). The parameters comprise the following equations:

$$NRMSE = \frac{100}{\bar{O}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (23)$$

$$\boldsymbol{d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=0}^{n}(|P'_i| + |O'_i|)^2}\right], 0 \le d \le 1} \quad (24)$$

Where P_i and O_i are the i^{th} estimated and measured values, respectively, $\overline{O}$ represents the mean measured values, $P'_i = P_i - \overline{O}$, $O'_i = O_i - \overline{O}$, and n is the total number of observations. The normalized root mean square error (*NRMSE*) gives information on the relative error based on the comparison between the measured and predicted values. The simulation is considered excellent, good, fair and poor if the values of NRMSE are, respectively, less than 0.1, greater than 0.1 but less than 0.2, greater than 0.2 but less than 0.3, and greater than 0.3 (Jamieson et al., 1991).

According to the d-index, values that are closer to one indicate a better agreement between the two variables that are being compared. The index (d) is intended to be a descriptive measure, and it is both a relative and a bounded measure which can be widely applied in order to make cross-comparisons between models (*Willmott*, 1982).

3. Results and Conclusion

The precipitation during the growing periods in 2013 and 2014 were 75 mm and 26 mm, respectively, and the relative humidity was greater during the first growing season. The air temperature averaged nearly the same during the two years.

The root dry matter, relating to the different irrigation levels and nitrogen supplements of fertilizer, resulted in different values (Tables 3 & 4). The amount of yield was observed to increase parallelly to increasing irrigation; however, in some treatments, the excessive supply of water served to reduce the root dry matter due to nitrogen leaching.

In the second season, the static (I_3) and dynamic (I_4) treatments had no considerable difference in the root dry matter. In the dynamic treatment, a severe drought occurred in the late period of the growing season, hence, soil water content of the root zone declined and the root dry matter portion decreased in this period. Moreover, in the dynamic treatment, greater irrigation occurred in the early and middle periods of the growing season, as compared to the static treatment, hence, dry matter production was increased. In the static treatment, the occurrence of early drought caused the root system and canopy cover to shrink and reduced solar radiation interception and water uptake, compared to the occurrence of late drought (Brown et al., 1987).

According to Table 4, it can be concluded that the use of nitrogen fertilizer has significant effects on increasing the yield. However, when the amount of fertilizer exceeds 180 kg ha^{-1}, the fresh roots and thus their dry matter cease to increase significantly any further. Therefore, it is clear that the application of nitrogen fertilizer in an amount more than the actual need of the crop will not improve the root dry matter significantly. The available nitrogen in the soil increases slightly late in the season, partly because higher amounts of nitrogen are applied at the time, and as Malnou et al. (2008) mentioned, the late application of nitrogen can increase the foliage dry weight, but without positive effects on the sugar yield. Furthermore, excess nitrogen acts reversely to reduce the yield and quality of the root dry matter (Monreal et al., 2007). Nonetheless, the decrease was insignificant in some cases of this present study.

Table 3. Average values of the produced root dry matter under different supplies of water and nitrogen in 2013

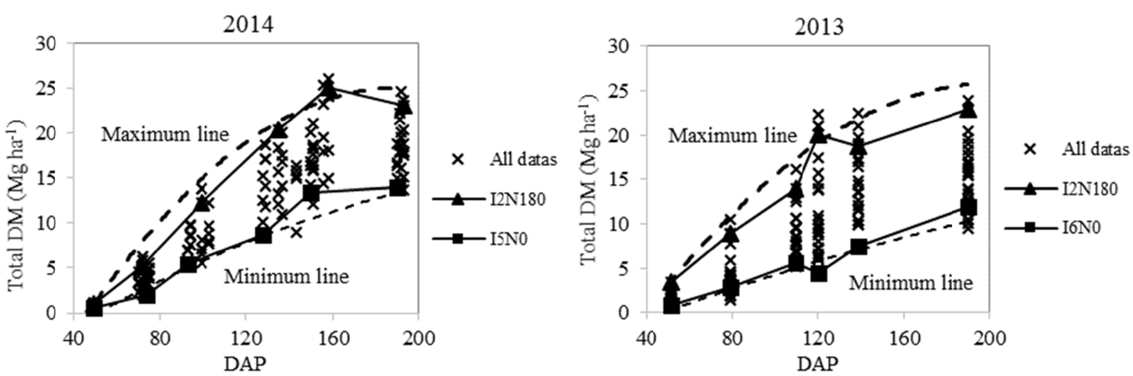
Root dry matter (Mg ha^{-1})						
N (kg ha^{-1})	I_1(1.3FI)	I_2(FI)	I_3(0.85FI)	I_4(0.75FI)	I_5(0.66FI)	I_6(0.44FI)
0	14.35	15.7	14.44	14.70	12.69	9.49
60	16.6	17.90	16.35	14.47	13.17	9.50
120	19.66	19.33	15.77	14.41	15.21	10.58
180	20.61	20.15	16.47	16.59	13.93	10.65

Table 4. Average values of the produced root dry matter under different applied water and nitrogen in 2014

Root dry matter (Mg ha^{-1})						
N (kg ha^{-1})	I_1(1.2FI)	I_2(FI)	I_3(0.8FI)	I_4(0.8FI)	I_5(0.6FI)	average
0	15.9fghi	15.4ghi	15.0ghi	15.2ghi	11.1j	14.6λ
60	16.2efghi	15.8fghi	15.4ghi	16.3efgh	12.2j	15.2λ
120	18.3bcd	18.5bc	16.5defg	17.5cdef	14.2i	17.1β
180	20.7a	20.8a	18.0bcde	19.2abc	15.8ghi	19.1α
240	19.5ab	19.3abc	18.8bc	19.5ab	14.4hi	18.4α
average	18.1A	18.0A	16.7B	17.5AB	13.3C	

Mean values followed by the same letter in each column and row are not significantly different at 5% level of probability by Duncan multiple range test.

The various forms of dry matter (Mg ha^{-1}) are shown as they correspond to the different days after the sowing of seeds in 2013 and 2014 (Figure 4). The best results were obtained via optimum nitrogen supply. The values of the produced dry matter rose sharply at the beginning of the growth season and then reached a plateau. However, green blade dry matter decreased sharply at the end of the growth season. Since sugar beet is a biennial plant and can tolerate cold weather, the green blade dry matter was not significantly affected as the weather became cold during the early days of September.



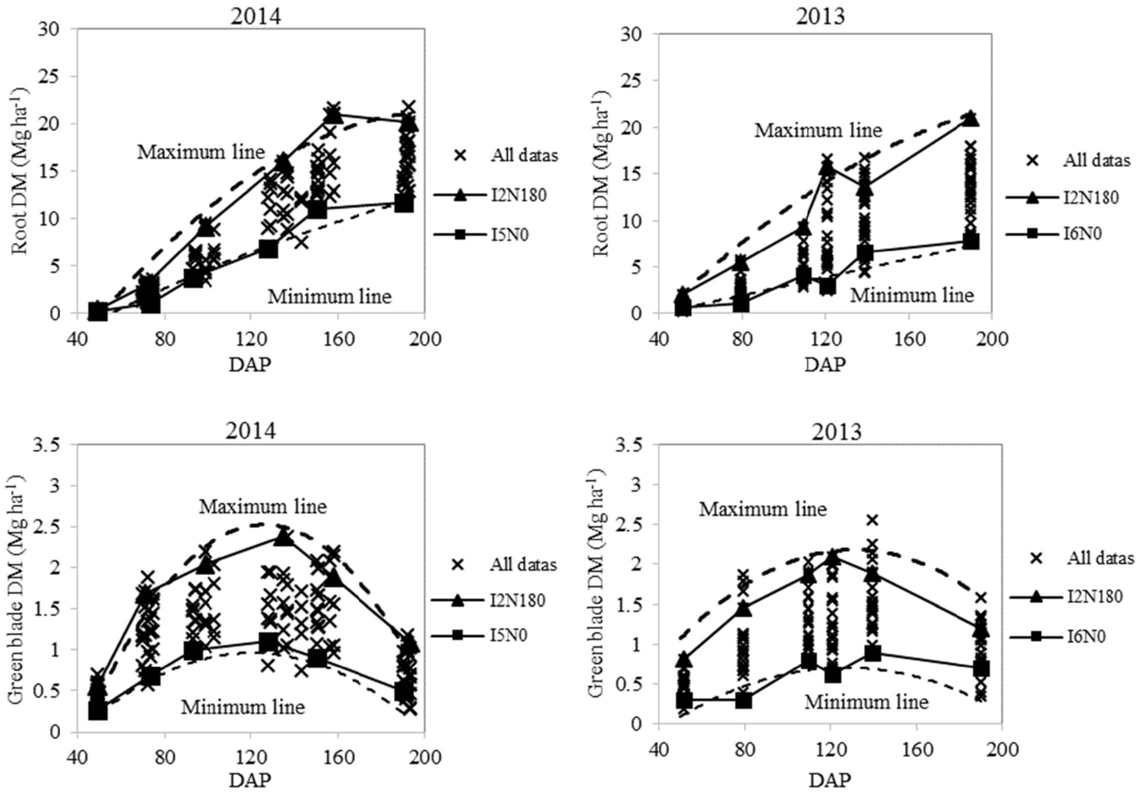


Figure 4. Total dry matter (DM), root and green blade DM of different irrigation and nitrogen treatments on different days after sowing (sowing date was in May 21, 2013 and May 13, 2014)

3.1 Estimation of Total Dry Matter

The parameters W_m, A and B (Equations 4, 5 and 6.) were estimated using multiple linear regression method as follows:

$$W_m = 5.145 + 17.6\,(IR^*) - 0.254\,(N^*) - 6.666\,(IR^*)^2 + 0.910\,(N^*)^2 + 4.978\,(IR^* \times N^*)$$
$$R^2 = 0.98, n = 120$$
$$A = -261.1 + 494.3\,(IR^*) + 548.2\,(N^*) - 169.4\,(IR^*)^2 - 386.9\,(N^*)^2 + 11.6\,(IR^* \times N^*)$$
$$R^2 = 0.91, n = 120$$
$$B = 3.44 \times 10^{-4} + 1.61 \times 10^{-3}(IR^*) + 2.89 \times 10^{-3}(N^*) - 4.56 \times 10^{-4}(IR^*)^2$$
$$-1.81 \times 10^{-3}(N^*)^2 - 5.5 \times 10^{-7}(IR^* \times N^*)$$
$$R^2 = 0.92, n = 120 \qquad (25)$$

The results pertaining to the calibration and the validation of the logistic models for total dry matter are shown in Figure 5. It is apparent that the proposed logistic model can estimate total dry matter fairly well since the observed and the predicted total dry matter are in good correlation. On the other hand, because of the lower value of NRMSE, and the higher value of index of agreement (d), Figure 5 (ii) indicates that the model performs better in estimating the total dry matter at harvest time. Figure 5 (iii) presents the samples of the measured and estimated total dry matter with respect to the processes of validation and calibration for the two individual treatments during the growing season with good accordance.

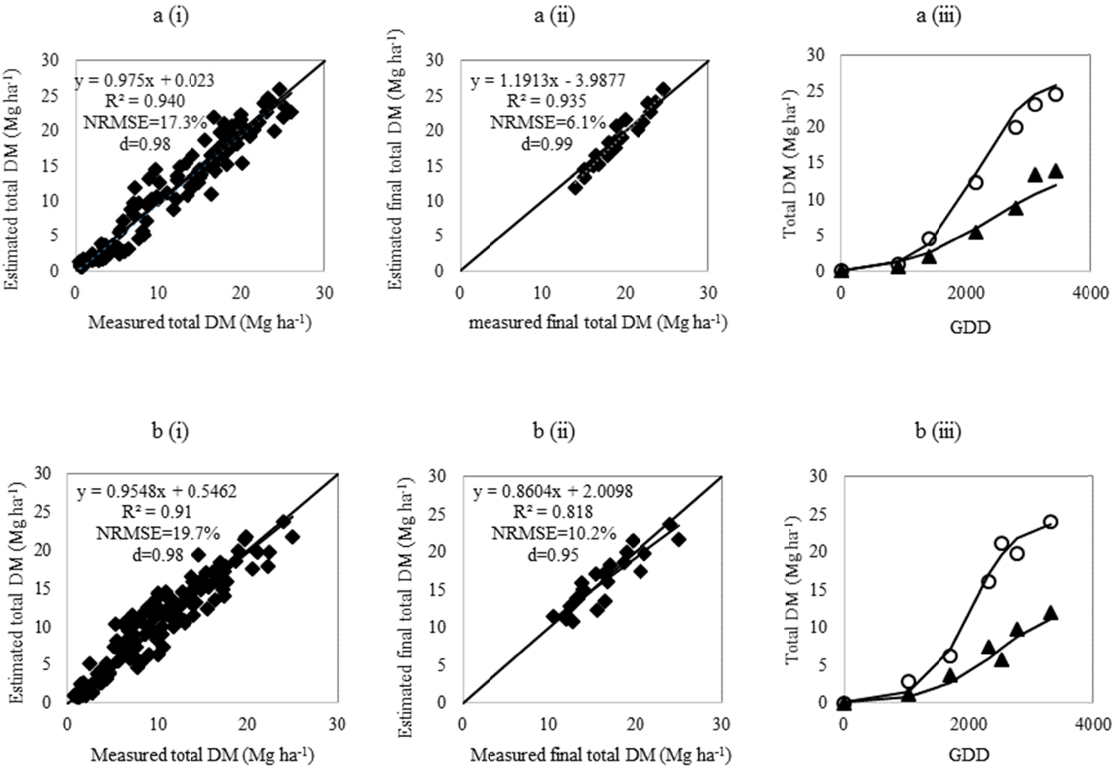
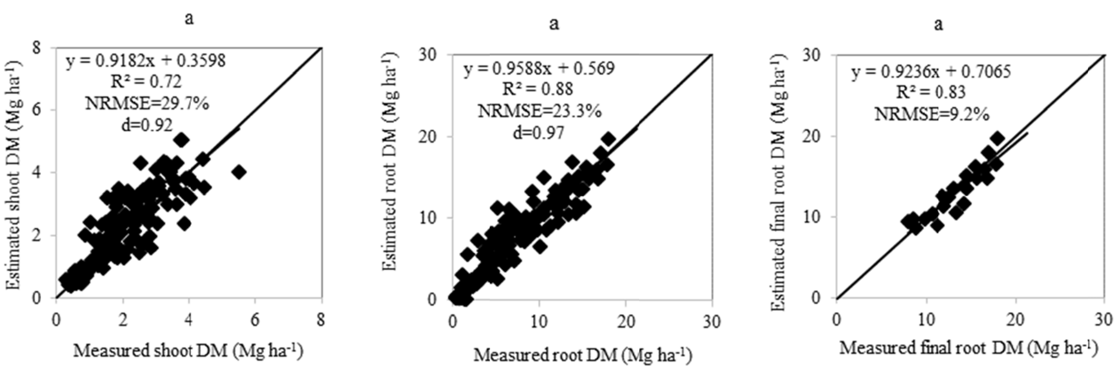


Figure 5. (a) Calibration and (b) validation of the logistic model in the estimation of (i) total dry matter (DM) during the growing season, (ii) harvested total DM and (iii) sample of results for the measured (○, ▲) and estimated total DM during the growing period

3.2 Models for Dry Matter Partitioning

For validating the proposed logistic model and comparison with the revised quadratic, revised allometric and revised logarithmic models, the measured field data of the first year of the experiment (2013) were used. The estimated shoot and root dry matter during the growing period, and root dry matter at harvest time were compared to their measured values in Figure 6. The calculated values of NRMSE and d-index (Figure 6) showed that there were good agreements between the measured and estimated values for the proposed logistic models for shoot and root dry matter during the growing period with acceptable accuracy and for root dry matter at harvest time with good accuracy. The highest values of the d-index and coefficient of determination (R^2) and the least normalized root mean square error (NRMSE) for the root dry matter occurs in the logistic model (Figure 6). However, for all revised models (quadratic, allometric and logarithmic), estimation of root dry matter at harvest time are good, and estimation of root and shoot dry matter during the growing period are acceptable except that shoot dry matter in revised allometric model (with poor accuracy).



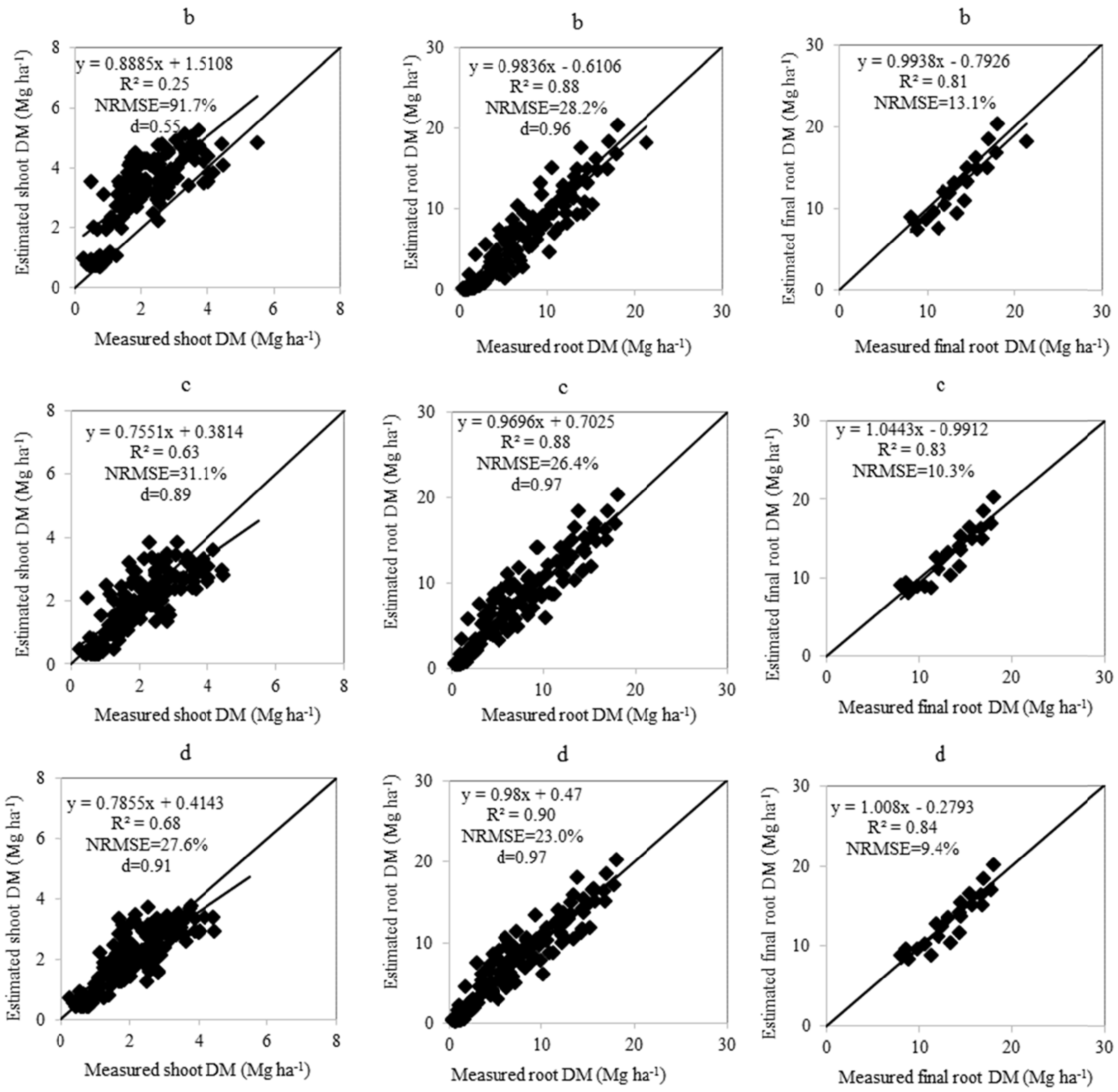


Figure 6. Validation of models and their results: a) revised quadratic model, b) revised allometric model, c) revised logarithmic model and d) logistic model. These are used for the estimation of shoot dry matter, root dry matter and the harvested root dry matter

The proposed equations fit well for the highest values of the conformed coefficients of determination (Table 5). The low amounts of *P-value* illustrate that the models have significant coefficients that differ from zero. Results reveal that in the revised quadratic model, α and β are more affected by water than by nitrogen, as water coefficients are greater than nitrogen coefficients, and excessive water and nitrogen have negative effects on β, due to the negative coefficients of $(N^*)^2$ and $(IR^*)^2$ (Table 5). Similar results were observed for coefficients of other models too. Water is more effective factor than nitrogen, but there is a difference in the revised allometric model. In the revised allometric model, the value of α_r is more influenced by nitrogen than water. This could be the reason behind the poor accuracy of this model.

The dry matter allocated to the root is highly dependent on water in the logistic model, because P_m is more affected by water than by nitrogen (Table 5). Furthermore, excess water has negative effects on P_m and W_m (Equation 25). Excessive nitrogen affects P_m negatively too, but even the excess can have positive effects on W_m. This means that more of nitrogen fertilizer can lead to a greater total dry matter production. Therefore, it can be concluded that the application of excess nitrogen acts to reduce the root dry matter production, but increases the shoot and total dry matter.

Table 5. Statistical analysis for proposed model functions (n=120)

Model		R^2	Variables					
			Intercept	++IR*	+++N*	++(IR*)^2	+++(N*)^2	++IR*×+++N*
Revised quadratic model	α	0.91	0.603	-0.509	0.093	0.201	-0.028	-0.021
			+(1.71E-08)	(1.85E-04)	(4.41E-02)	(9.16E-04)	(2.31E-01)	(4.28E-01)
	β	0.73	-0.828	3.611	0.140	-1.435	-0.034	0.160
			(2.65E-01)	(1.95E-02)	(8.10E-01)	(4.47E-02)	(9.11E-01)	(6.60E-01)
Revised allometric model	α_r	0.97	0.336	-0.0199	-0.0476	0.006	0.021	-0.0044
			(3.04E-16)	(2.09E-01)	(2.50E-06)	(4.10E-01)	(1.62E-05)	(2.82E-01)
Revised logarithmic model	K_r	0.91	-0.137	0.892	-0.223	-0.331	0.059	-0.036
			(3.37E-01)	(4.62E-03)	(6.27E-02)	(2.01E-02)	(3.58E-01)	(6.08E-01)
Logistic model	P_m	0.88	0.688	0.337	-0.021	-0.135	-0.018	0.006
			(2.38E-10)	(1.18E-03)	(5.56E-01)	(4.27E-03)	(3.32E-01)	(7.89E-01)
	a	0.99	2.16	-3.19	5.78	3.52	-2.95	0.596
			(7.43E-03)	(3.06E-02)	(5.13E-08)	(6.71E-05)	(7.02E-08)	(1.06E-01)
	b	0.97	3.73×10^{-4}	1.14×10^{-3}	1.02×10^{-3}	-2.15×10^{-4}	-4.48×10^{-4}	-1.67×10^{-4}
			(2.25E-02)	(1.11E-03)	(4.45E-07)	(1.28E-01)	(3.43E-06)	(3.74E-02)

+ Values in parenthesis indicate *P-values*

++ Irrigation variable

+++ Nitrogen variable

3.3 White Sugar Yield Estimation

The sugar yield is estimated using the multiplication of root dry matter and its sugar content (Sc) (Equations 21 and 22). The value of Sc is estimated as a function of IR^* and N^* as follows:

$$Sc = 0.361 + 0.301\,(IR^*) - 0.111\,(IR^*)^2 - 0.021\,(N^*)^2 - 0.005\,(IR^* \times N^*)$$
$$R^2 = 0.89, n = 20 \qquad (26)$$

The measured and predicted sugar yield at 2013 (calibration) and 2014 (validation) are compared with the measured values in Figure 7 with good accuracy. Although the measured data are scattered along the 1:1 line, the slope of regression line is very close to one and NRMSE is less than 0.1. However, using nitrogen causes decreasing root sugar content, but increasing root dry matter causes increasing in white sugar yield. Also excess applied water decrease *SP*.

The relationship between root sugar content (*Sc*) with IR^* and N^* is shown in Figure 8 that shows with increasing in N^*, sugar content of the root is decreased. This Figure also shows that with increasing IR^*, the value of *SP* increases and.

The decreasing root sugar content with increasing nitrogen supply agrees with Milford and Watson (1971). Several experiments have been conducted to study the effect of water stress on sugar content, but still, skepticism persists among specialists. Although there is a common belief that water stress increase sugar content, results of some researches (Kiymaz & Ertek, 2015; Yonts et al., 2003) do not show significant effect of water stress on sugar content. In some other researches, the results show increasing root sugar content with increasing applied water (Cole, 1976; Woolley, 1956). It seems that the effect of water cannot be easily separated from the effect of nitrogen. Sugar content may be improved by applying less irrigation and reducing leached N, where excess water leaches N from the soil in the growing season (Hills, 1990).

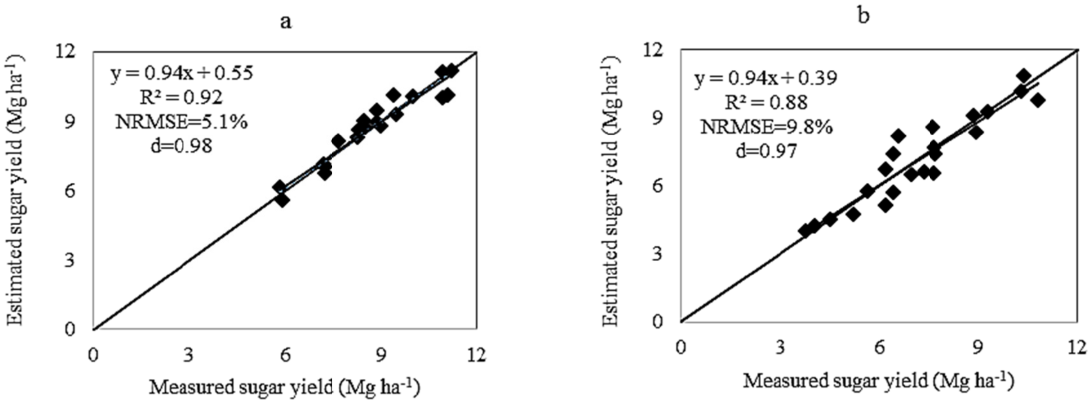


Figure 7. (a) Calibration and (b) validation of the model in the estimation of sugar yield

In commercial practice, the root sugar content is usually expressed as the ratio of sugar weight per root fresh weight. In the present study, the root sugar content is expressed as the ratio of root dry weight, and Since root water content in irrigated fields is higher than those prepared in fields with deficit irrigation (Choluj *et al.*, 2004), depends on sugar content terminology, water stress may produce conflicting effect on sugar content.

The results show that drought stress reduces both ratios of root to leaf, and root to shoot dry matter (Table 6). Several experiments have been conducted to study the effect of water scarcity on dry matter partitioning, but still, skepticism persists among specialists. There are common beliefs among scientists that the ratio of root to shoot is increased as a result of water deficit (Brown et al., 1987; Camposeo & Rubino, 2003; Shaw et al., 2002). But, this is not the case with sugar beet. *Hoffmann* (2010) noted that insufficient water supply can restrict the growth of both root and shoot, but root dry matter is more reduced than leaf dry matter under drought stress. Therefore, the ratio of root to leaf dry matter decreases considerably under drought stress.

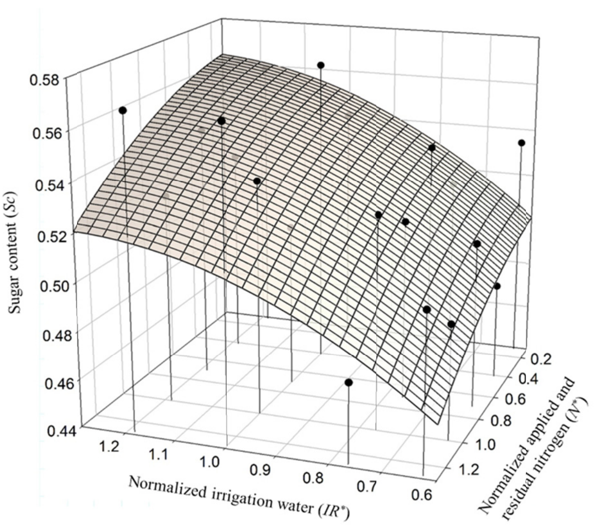


Figure 8. Three-dimensional relationship between root sugar content (*Sc*) as function of normalized irrigation and rainfall (IR^*) and normalized applied and residual nitrogen (N^*)

There appear to be marked discrepancies between research results due to the lack of consistency in the definition of root to shoot ratio. In some research, like the one by *Brown et al.* (1987), the definition embraced fibrous roots too, but, in some other research, like the one by *Hoffmann* (2010) and also this present study, the definition of root was confined to taproot. And yet, further studies are required to verify in more detail the effect of drought stress on the root to shoot ratio of dry matter.

Table 6. Effect of water scarcity on the root to shoot dry matter ratio and root to foliage dry matter ratio (Results pertain to the post-maturity stage of the plant)

Irrigation treatment	root/shoot		root/leaf	
	2013	2014	2013	2014
I1	5.09	4.05	9.42	11.26
I2	4.17	4.44	8.09	13.23
I3	3.28	4.03	5.82	9.64
I4	3.46	3.99	5.09	9.48
I5	3.16	3.33	5.9	9.12
I6	2.71	-	4.4	-

4. Discussion

On the one hand, the logistic model can be a good candidate if the production of root dry matter is of prime importance. On the other hand, when the objective turns to harvesting a more a more proliferative shoot dry matter, the logistic and revised quadratic models become more reasonable. The prediction of shoot dry matter can be useful in crop modeling, especially for estimating the leaf area index (LAI).

The results showed that fertilizers with excessive nitrogen caused increases in the shoot to root ratio as Milford et al. (1985) noted the general concept that nitrogen fertilizers encouraged the growth of shoot, possibly more than any other treatment. The effect of nitrogen on shoot growth was more prominent than the effect on root production, as Draycott (2008) indicated that crops growing on nitrogen–rich soils participate in the majority of their biomass to the growth of tops, in which case the root and sugar yield dwindled.

Moreover, the logistic model shows that excessive irrigation could reduce the total dry matter and root dry matter. This may happen due to the leaching of nitrate (Gholamhoseini et al., 2013; Jégo et al., 2008).

Results showed that drought stress made a negative effect on the ratio of root to shoot. This implied that when water is scarce, the crop tends not to send dry matter to the root, but tends to send it to the shoot.

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