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Prediction of Plant Height by Allometric Relationships in Field-grown Wheat

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Crop simulation models use allometric relationships to predict plant height from vegetative characteristics. The objective of this study was to find relationships between plant height (PH) and number of leaves on main stem (NLMS), stem dry weight (SDW) (g plant^{-1}) and total vegetative components (leaves and stems) dry weight (TVDW) (g plant^{-1}) in wheat (*Triticum aestivum* L.). For this purpose, an experiment was conducted using seven wheat cultivars including two durum wheat cultivars (Arya and Taro) and five bread wheat cultivars (Darya, Kuhdasht, Shiroudi, Tajan and Zagros) under irrigated and rainfed conditions during 2008–2009 at Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran. The experimental design was a randomized complete block design with four replications. Sampling was started from beginning of tillering and continued until maturity. A segmented nonlinear regression model was used to describe allometric relationships between PH and the vegetative characteristics. The results showed that there was no significant difference between cultivars and the two conditions for allometric relationships, so one equation was usable for all cultivars under both irrigated and rainfed conditions. Significant relationships were found between PH and NLMS (R^2 = 0.94), SDW (R^2 = 0.95) and TVDW (R^2 = 0.95). These equations can be used for estimation of PH in simulation models of wheat.

Keywords: allometric relationships, plant height, vegetative characteristics, wheat

Abbreviations: NLMS: number of leaves on main stem; PH: plant height; SDW: stem dry weight; TVDW: total vegetative components dry weight

Introduction

Allometry has been defined as relationships between growth rate of single components in an organism (Gardner et al. 1985). Allometric relationships in plants uncover size-correlated variation in form and development and characterize the relative growth of a part of a plant in comparison with the whole and or other of plant parts. These relationships in intraspecific comparisons are often based on data from mature plants (Niklas 1994). Generalized allometric relationships have been influential in the establishment of principles governing variability and constraints in trait expression within and between plant (Niklas 2004; Bonser and Aarsseh 2009). Different studies suggest that the ability of plants in ad-

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aptation to an environment can affect allometric relationships, especially in annual plants (Marvel et al. 1992; Weiner and Thomas 1992).

Stable allometric relationships in ontogeny can be used as a component of crop simulation models and to estimate plant variables that are difficult to measure (Niklas 1995). In crop simulation models, allometric relationships are used to predict organ growth, such as PH, from the growth of the whole crop or other organs. Allometric relationships and information obtained from them can also be used for crop management, analysis and explanation of plant growth behaviors, and to increase efficiency of breeding programs because of the better realization from plant growth (Soltani 2009).

Reddy et al. (1998) indicated that allometric relationships were different among soybean cultivars grown under the same conditions and among crops of the same cultivar grown under different conditions. Similarly, it has been shown that genetic modifications in wheat (Lenton et al. 1987) and oat (Semchenko and Zobel 2005) lead to changes in ontogenetic allometry. On the other hand, many allometric equations have been reported and have been successfully applied for various crops such as peanut (Ma et al. 1992), soybean (Reddy et al. 1998), barley (Ramos et al. 1983), *Chenopodium alum* plants (Nagashima and Terashima 1995), pearl millet (Payne et al. 1991), cotton (Akram-Ghaderi and Soltani 2007), chickpea (Pourreza et al. 2007) and corn (Robertson 1994).

PH prediction has important practical considerations for many wheat producers and for plant breeders developing cultivars to meet their needs (Budak et al. 1995). From a modeling perspective, PH is necessary to calculate canopy conductances for use in determining canopy temperature (Confalonieri et al. 2010) in applications such as irrigation scheduling (Allen et al. 1998), in soil erosion modeling (Retta et al. 2000) and competition between crop and weed (Pourreza et al. 2007). Crop models use the distribution of leaf area index by PH to calculate attenuation of radiation fluxes within plant canopies. Leaf and stem mass relationships with height can help land managers to determine how much standing biomass can be removed while still protection against erosion be maintained (Retta et al. 2000). The amount of residue left is a function of the height of cut. Water erosion models, such as the Revised Universal Soil Loss Equation (Renard et al. 1991), also need height distribution to estimate the fall-height of rain drops from standing canopies. Thus, for these and other application, relationships need to be developed among PH and plant vegetative characteristics.

The objective of this study was, therefore, to develop relationships between PH and plant vegetative characteristics in wheat cultivars grown under rainfed and irrigated conditions in a temperate sub-humid environment.

Materials and Methods

Field experiment

A field experiment was conducted during growing season of 2008–2009 at Research Farm of Gorgan University of Agricultural Science and Natural Resource located at 37° 45’ N, 54° 30' E, and 13 masl, Grogan, Iran. The soil was silty clay loam and the climate was temperate sub-humid.

The experiment was conducted using seven wheat cultivars, including two durum wheat cultivars (Arya and Taro) and five bread wheat cultivars (Darya, Kuhdasht, Shiroudi, Tajan and Zagros) under two conditions, irrigated and rainfed. Experimental design under each condition was a randomized complete block design with four replications. Plot sizes were 5 m long with row spacing of 20 cm and included 10 rows.

Plant population density was approximately 300 plants per m^{-2}. Sowing was carried out on 20^{th} of December 2008 by hand at the soil depth of 3 cm. Based on a soil test results (depth of 0–30 cm) 150 kg ha^{-1} of triple super phosphate and 50 kg ha^{-1} of potassium sulfate was used at sowing time and 150 kg ha^{-1} urea was top-dressed in three times as sowing time, beginning of tillering and beginning of stem elongation. Under irrigated conditions, irrigation was performed when necessary. Weeds were hand-controlled and if necessary appropriate chemicals were applied against pests and diseases, so the effect of diseases, pests and weeds were minimal.

From emergence to maturity, phenological stages were recorded based on Zadox et al. (1974) scale every 3 days. In this study the number of leaves on main stem (NLMS), stem dry weight (SDW) g $plant^{-1}$, total vegetative components dry weight (TVDW) (leaves and stems) g $plant^{-1}$ and plant height (PH) cm were measured. Measurements started from beginning of tillering and continued until maturity every 7 to 10 days (depending on weather conditions). Han scale (Han 1973) was used for counting the number of leaves on main stem. To measure dry weight of leaves and stems, samples, were oven-dried at 70°C until a constant weight. PH measured from soil surface to uppermost part of plant by a ruler.

Data analysis

Traditionally a power equation was used to describe allometric relationship plants.

The form of the equation is:

$$y = aX^b \tag{1}$$

where, y is for example plant height, x is vegetative characteristics of plant, a is amount y when $x = 1$, b is coefficient allometric.

Equation (2) is simplified to a one-parameter model assuming $a = 1$:

$$y = X^b \tag{2}$$

Equation (1) can also be linearized for easy fitting by usual softwares as:

$$ln\, y = ln\, a + b \times ln\, x \tag{3}$$

However, in this study a segmented equation was used (4) for allometric relationship as purposed by Soltani et al. (2006). This new equation is easier to understand and its parameters are easier to interpret:

$$y = b_1 x \quad \text{if} \quad x \le x_0$$
$$y = b_1 x_0 + b_2 (x - x_0) \quad \text{if} \quad x > x_0 \qquad (4)$$

where y is plant height, x is vegetative characteristics of plant, x_0 turning point between the two phases, b_1 the rate of increase in plant height in phase 1 and b_2 the same as b_1 for phase 2 of plant height.

In this study, the regression functions fitted to anthesis date in four levels: (1) each cultivar in each condition, separately (2) each cultivar (combined conditions), (3) each condition (include all cultivars), and (4) one equation was fitted to all data of experiment (include all cultivars and conditions). The parameters were estimated by the least squares method using the non-linear (NLIN) regression procedure of the Statistical Analysis System software (SAS Institute 1989). Coefficient of determination (R^2) and root mean square of error (RMSE) were used to evaluate adequacy of the fitted regression models. These statistics were also used to determine whether or not pooling the data of cultivars and water conditions is warranted. Pooling was done if R^2 and RMSE did not decrease considerably.

Results

Preliminary analysis

Fig. 1 represents changes in PH *vs.* time in selected cultivars under both rainfed and irrigated conditions. Analysis of variance for data of anthesis sampling showed that differences between cultivars are significant (Pr < 0.0001), but differences between growing conditions (Pr > 0.7) and interactions between cultivar and growing conditions (Pr > 0.3) were not significant.

For describe ability segmented regression model, a sample fitting of the three allometric equations (1, 2 and 4) to data of PH *vs.* NLMS in *cv.* Arya under rainfed condi-

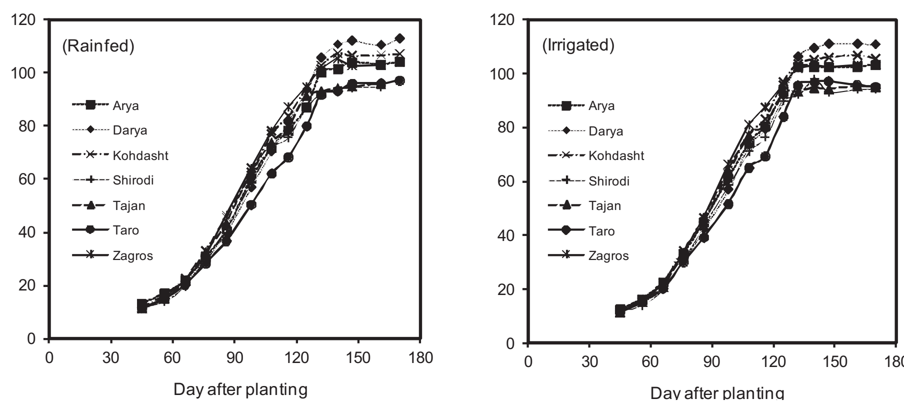

Figure 1. Plant height (cm) variations progress curves *vs.* day after planting represented for all cultivars in different environmental conditions

tions is presented in Fig. 2. Results indicated that both Eqs. (1) and (2) well-described the relationship between PH and NLMS. However, Eq. (3) did not give comparable fit to Eq. (1) and Eq. (2). It seems that segmented model (4) could be a good substitute for traditional power equation as the parameters of the segmented model are meaningful from physiological point of view. Therefore, the segmented model was used here to describe the allometric relationships between PH and plant vegetative characteristics.

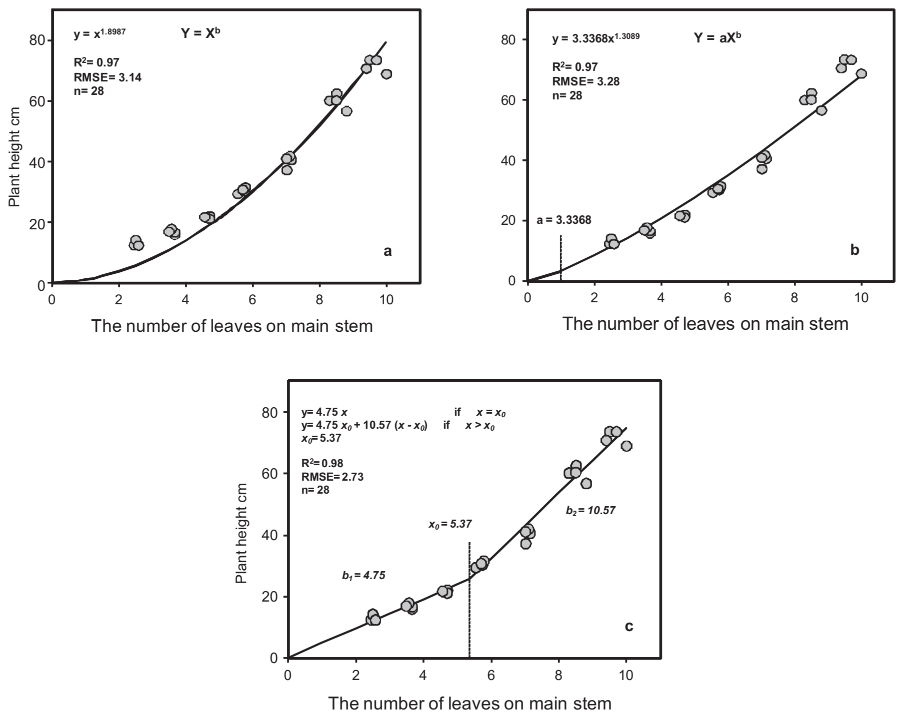

Figure 2a, b, c. Comparison of two allometric equations, Eq. (2) (*a*), Eq. (1) (*b*) and simplified of allometric equation, Eq. (4) (*c*) for describe the relationship between plant height and the number of leaves on main stem (Data are respective to *cv.* Arya, rainfed condition)

Relationship between plant height and number of leaves on main stem

Plant height ranged from 9.66 to 99.36 cm per plant across cultivars, corresponding to 2.28 to 10.00 leaves on main stem per plant. The segmented regression model described well relationship between PH and NLMS. The fitting Eq. (4) was done in each four levels. R^2 values were higher than 0.94 for all cultivars and conditions. RMSE values were between 2.54 and 6.00 cm for *cvs.* Taro and Tajan under rainfed conditions, which were 5.38% and 12.71% of their corresponding means of PH, respectively. There was no significant difference between cultivars and conditions based on confidence intervals for the co-

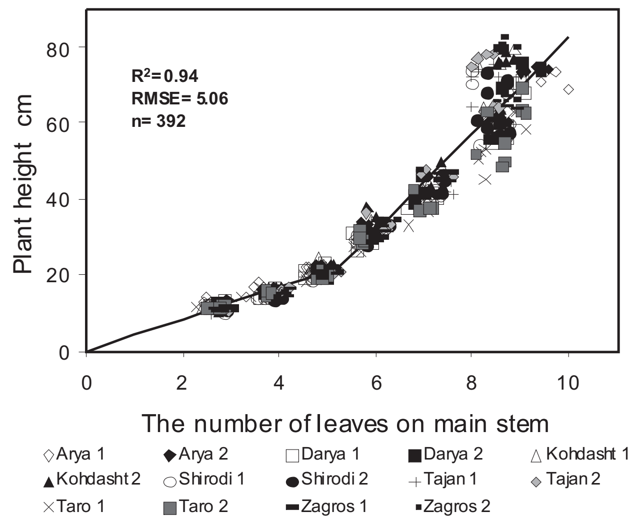

Figure 3. The relationship between plant height and the number of leaves on main stem. The fitted line is the segmented regression model (eqs. 4 and 5) fitted to all experimental data

efficients of the segmented model (Data not shown). Therefore, one general equation (5) can be used for all cultivars and both condition instead of individual equations (Fig. 3).

The form of the equation is:

$$\begin{aligned} y &= 4.21x && \text{if} \quad x \le 5.24 \\ y &= (4.21 \times 5.24) + 12.68(x - 5.24) && \text{if} \quad x > 5.24 \end{aligned} \qquad (5)$$

Generally, the results obtained in this study showed that PH rate in phase 1 was 4.21 cm per leaf production on main stem until the appearance of leaf 5.24 on main stem. In phase 2, PH increased 12.68 cm per leaf production on main stem until appearance of the flag leaf (Fig. 3). The increased rate of PH in phase 2 was related to the beginning of stem elongation in wheat.

Relationship between plant height and stem dry weight

Stem dry weight varied from 0.01 to 3.38 g plant^{-1} across cultivars. Fig. 4 shows PH plotted as a function of SDW. The variation of data around the regression line highly increased when SDW was greater than 1 g plant^{-1} or PH greater than 60 cm as a result of differences PH and SDW cultivars in anthesis date (Fig. 4). Results showed that Darya and Shiroudi were the tallest and the shortest cultivars with respect to PH, respectively. These cultivars also had the greatest and lowest SDW, respectively (data not shown). R^2 values were greater than 0.95 for all cultivars and conditions, and RMSE values ranged from 4.52 to 6.71 cm (9.57 to 14.21% of the means), indicating that the relationships are appropriate. There was no significant difference between cultivars and conditions for the coefficients of the segmented function (data not shown). As to the numbers of leaves on main stem relationship, therefore, one general equation was adequate for all the cultivars and conditions (6), which is valid up to anthesis date.

The form of the equation is:

$$\begin{aligned} y &= 286.3x & \text{if} \quad x \le 0.16 \\ y &= (286.3 \times 0.16) + 18.79(x - 0.16) & \text{if} \quad x > 0.16 \end{aligned} \qquad (6)$$

Results indicated that in phase 1 from sowing to achieve SDW to 0.16 g plant^{-1}, PH was increased with rate 286.3 cm g and afterwards height increasing 15 times slow initial rate (18.79 cm g) until anthesis date (Fig. 4). Lower rate of PH increase in phase 2 was related to tillering and beginning of stem elongation, because increase in SDW at this phase was faster than increase in stem elongation.

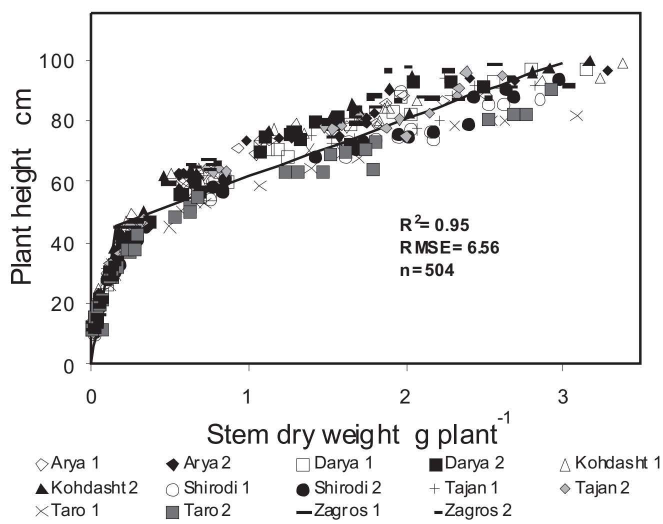

Figure 4. The relationship between plant height and stem dry weight. The fitted line is the segmented regression model (eqs. 4 and 6) fitted to all experimental data

Relationship between plant height and total vegetative components dry weight

Total vegetative components dry weight ranged from 0.02 to 4.23 g plant^{-1} across cultivars. The fitting Eq. (4) was done in each four levels, separately. The segmented model accounted well for the relationship between PH and TVDM from sowing to anthesis date with R^2 values all higher than 0.95 and RMSE values ranged from 3.55 to 6.15 cm (7.51 to 13.02% of the means), indicating that the relationships are appropriate (Data not shown). After investigation standard error estimated parameters values results indicated that cultivars and conditions had no significant effect on estimated parameters. So, one equation was adequate for all the cultivars and both conditions. Fig. 5 shows the fit of a segmented regression model to pooled data of experiment.

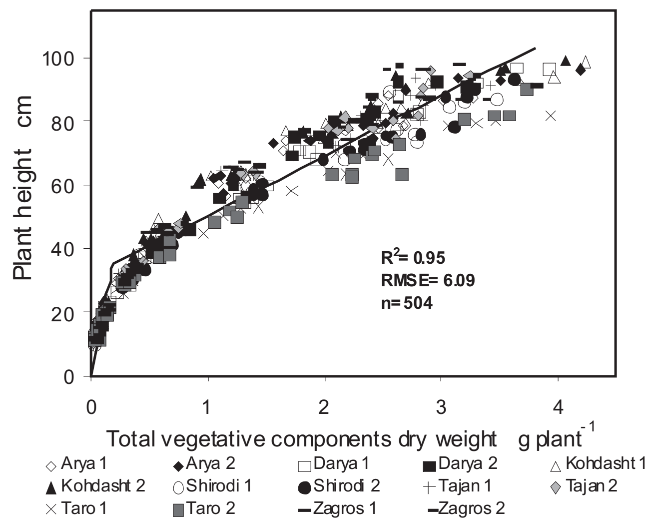

Figure 5. The relationship between plant height and total dry weight of vegetative components. The fitted line is the segmented regression model (eqs. 4 and 7) fitted to all experimental data

The form of the equation is:

$$\begin{aligned} y &= 185.5x && \text{if} \quad x \le 0.19 \\ y &= (185.5 \times 0.19) + 18.78(x - 0.19) && \text{if} \quad x > 0.19 \end{aligned} \quad (7)$$

Results indicated that equation 7 adequately described changes of PH and TVDM (Fig. 5). Average estimates parameters of x_0, b_1 and b_2 were 0.19, 185.5 and 18.78 for pooled data. The slowly increase rate of PH in phase 2 was related to the tillering and stem elongation stages, because of increase in total vegetative components dry weight at phase 2 was faster than increase in stem elongation.

Discussion

The close relationship between PH and NLMS found in this study is in agreement with those reported by Robertson (1994) and Hodges and Evans (1990) in corn and Pourreza et al. (2007) in chickpea. Robertson (1994) in corn showed that across all cultivars there was a consistent relationship between PH and leaf appearance, with height increasing at a slow initial rate until the appearance of leaf 7, afterwards height increased at 5 times the initial rate until appearance of the flag leaf. Pourreza et al. (2007) in chickpea used a traditional power equation to describe relationship between PH and NLMS, and reported that plant density had no effect on the allometric relationship. Hodges and Evans (1990) in maize proposed a strong relationship between leaf appearance and PH. In crop simulation models, NLMS is predicted based on phyllochron (thermal time elapsed between appearances of the two consecutive leaves in ºC d) concept from cumulative growth degree days

(Soltani 2009). Having NLMS, plant height can be simulated using Eq. (5) found here. It seems this equation can be applied for all the cultivars, selected for this study.

The relationship between SDW and PH found in this study is in line with the findings of Pourreza et al. (2007) in chickpea, Reddy et al. (1998) in soybean and Nagashima and Terashima (1995) in *Chenopodium album* who have used a traditional power equation to describe the relationship instead of the segmented function used in the present study.

Pourreza et al. (2007) in chickpea indicated that at earlier growth stages of the plant when SDW was lower, PH increased faster per each g increase in SDW. However, at later stages when SDW was greater, increase in PH per each g increase in SDW was lower. It was also, reported that PH can be successfully estimated from SDW using a power function.

Ramos et al. (1983) in barley and Pourreza et al. (2007) in chickpea have used linear and non-linear regression models, respectively to describe relationship between PH and TVDW. Our results confirmed the findings of these authors that during early season when leaf and stem biomass is lower, PH increases faster and the inverse is true at later stages.

Generally, our results indicated that there were strong allometric relationships between PH and NLMS ($R^2 = 0.94$), SDW ($R^2 = 0.95$) and TVDW ($R^2 = 0.95$). Also, one allometric relationship was sufficient for all selected cultivars under both irrigated and rainfed conditions. Allometric relationships and information reported here can be used to predict PH in crop simulation models of wheat crop. These allometric relationships contribute to better understanding of plant growth and development in wheat, which is necessary for optimal management of the crop and for genetic improvement.

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