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RESEARCH PAPER

Comparative study of some non-linear dry matter models in winter cereals

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Abstract

Approach to plant growth modeling, despite differences in patterns, is a valuable method to quantitative analysis. In the present study, several non-linear models have evaluated the growth pattern of winter cereals dry matter during two growing seasons. Therefore, Logistic, Gompertz, Richards, Weibull, Truncated-Expolinear, Symetrical-Expolinear and two Beta models used to evaluation wheat (bread wheat and durum), barley (six-rowed, two-rowed and hull less barley), triticale and oat dry matter variation. Result showed that dry matter of winter cereals have been described very well by all models. Considering R_{MSE} and R^2 among the models, Gompertz, Truncated-Expolinear, logistic, Symmetrical-Expolinear, Richards and $Beta_1$ can be introduced as most suitable models for describing winter cereals dry matter pattern in growing season.

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Introduction

Above ground biomass is known as dry matter (DM) that is an important key variable for crop growth monitoring and yield prediction. The most simple and strong move toward to estimate crop yield is using modeling techniques based on direct correlation between vegetation parameter and yield (Gerighausen *et al.*, 2015). In order to evaluation plant growth based on physiological data properly, it is mandatory to select a fit growth model and its parameters should be able to be interpreted and described the pattern logically (Karadavut *et al.*, 2010).

Some non-linear theoretical models like logistic, Gompertz, Bertalanffy-Richards and Schnute models and empirical models such as polynomial model are used in order to describe plants dry matter accumulation pattern and prediction during growth season (Prasad *et al.*, 2008).

Logistic and Gompertz models have been recommended in a modeling study on *Solanum sisymbriifolium* L. for predicting germination under various temperatures treatments and water regimes (Immermans *et al.*, 2007).

In a study for describing the best equation of six wheat genotypes, corn accumulation total dry matter for individual plant and total dry matter pattern in wheat and chickpea, several models including logistic, Richards, Gompertz and Weibull growth equations, and two expo linear equations have been compared with Beta1 model. Despite differences in parameter estimation, all models well illustrated the variation of crop production and biomass development. Results showed that Beta$_1$ describes reasonably the dynamics of quantity and duration of a growth process in aforementioned plants (Yin *et al.*, 2003).

The objective of this study mentioned to compare the fitting several non-linear models for winter cereals dry matter data, and to select the best model fitting on several selection parameters.

Materials and methods

Site and location

This research was carried out in 2013-2014 and 2014-2015 growing season in Gonbad Kavous region, Iran (37° 15´ N and 45° 46´ E).

Seven winter cereals including bread wheat (*Triticum aestivum* L.), durum wheat (*Triticum turgidum* L.), barley (*Hordeum vulgare* L.) include two-rowed barley, six-rowed and hull less barley, oat (*Avena sativa* L.) and triticale (*Triticum wittmak* L.) were investigated at two nitrogen fertilizer application rates, zero and optimum in a factorial completely randomized block design with four replications.

Each plot was 1.5 m × 5.0 m, with 0.20 m distance between rows. Plant population was considered 350 plants per m^2 for triticale and wheat and 270 plants per m^2 for barley and oat beads on regional plant population.

At planting time P_2O_5 was applied at 80 kg ha^{-1}. Optimum nitrogen amount was applied 150 kg ha^{-1} for bread wheat and hull less barley, 120 kg ha^{-1} for durum wheat and two rowed barley, 210 kg ha^{-1} for six rowed barley, 240 kg ha^{-1} for triticale and 90 kg ha^{-1} for oat based on the result of soil analysis and the average of recent 10 years yield of each cereals in urea form at three stages: at planting time, tillering and stem elongation.

During the growing season twenty plants from each plot were selected by random, intervals of 10–15 days at winter time and 7 - 10 days at spring season (from tillers emergence stage to physiological maturity stage).

The plants divided into leaves, stems and heads. In order to evaluate dry matter accumulation each part of plants dried in oven at 70° C for 48 hours and then dry weight recorded.

Dry matter models and formulas

All models were fitted to the dry matter and LAI data of winter cereals through 2013-2014 and 2014- 2015 field data collections as given below:

$$Y=DM_{max}/(1+exp(-k*(x-tm))) \qquad (Eq. 1)$$

(logestic model)

$$Y=(c_m/r_m)*log(1+exp(r_m*(x-t_o)) \qquad (Eq. 2)$$

(truncated-expolinear model)

$$Y=(c_m/r_m)*(\log(1+\exp(r_m*(x-t_o)/ \quad 1+\exp(r_m*(x-t_o-w_{max}/c_m)) \qquad \text{(Eq.3)}$$

(symmetrical-expolinear model)

$$Y=W_{max}/(1+v*\exp(-k*(x-t_m**(1/v)) \qquad \text{(Eq.4)}$$

(Richards)

$$Y=W_{max}*\exp(-\exp(-k*(x-t_m)) \qquad \text{(Eq.5)}$$

(Gompertz)

$$Y=W_{max}*(1-\exp(=-a*x**b)) \qquad \text{(Eq.6)}$$

(Weibull)

$$Y=W_{max}*1+(t_e-x)/(t_e-t_m)*(x/t_e)**(t_e/(t_e-t_m)) \qquad \text{(Eq.7)}$$

($Beta_1$)

$$Y=W_{base}+(w_{max}-w_{base})*1+(t_e-x)/(t_e-t_m)*((x-t_b)/(t_e-t_b))**((t_e-t_b)/(t_e-t_m)) \qquad \text{(Eq.8)}$$

($Beta_2$).

Where y id depended variable, DM_{max} is, a, b and c are coefficients, X is days after planting, c_m is the maximum crop growth rate in log phase, r_m is the maximum crop growth rate in exponential phase, t_o is the time till starting growth lag phase, w_{max} is the maximum of dry matter simulation, k is coefficient of dry matter increasing, v, is a stable coefficient, t_m is the time a crop reaches to maximum of crop growth rate, t_e is the time that crop growth period will be terminated , w_{base} is the initial of crop dry matter, t_b time of growth beginning.

Results and discussion

In order to model evaluation and fitness value of winter cereals field data, two parameters including RMSE and R^2 have been considered in this study.

$$RMSE=\sqrt{\sum \frac{(p-o)2}{n-1}} \qquad \text{(Eq.9)}$$

Where P stands for predictable quantity, O is for real observation and n is define as number of observation.

$$R^2= 1-SSE/SSG \qquad \text{(Eq.10)}$$

Where SSE is sum square of error and SSG is total sum square of observation.

All models Parameters have been shown in Table 1. Coefficients, R^2 and RMSE value show that all models are significantly fitted to dry matter variation of winter cereals during growing season. All models proved high R^2 value that is evidence for dry matter of winter cereals have been described very well by these models. Total dry matter in different winter cereals was varied by fitting different model equations.

According to results (table 1) maximum of total dry matter was observed in triticale by Gomperzt model (3016.8± 772.7).

Minimum dry matter was observed in oat and durum wheat while the quantity differed in different models (Table 1).

Table 1. Parameters estimation of total dry matter models of winter cereals.

Model	Cereal	Oat	Durum	Bread wheat	Two rowed barley	Hull less barley	Six rowed barley	Triticale
Logestic	TD_{max}± SE	1730.0± 161.9	1816.7± 277.5	2268.1± 294.9	1859.2± 111.4	1916.6 ±276.4	2127.8± 262.2	2677± 394.8
	k± SE	0.0818± 0.0156	0.0977±0.0423	0.0886± 0.0275	0.0899± 0.0130	0.0836± 0.0284	0.0768± 0.0184	0.0863± 0.0293
	t_m± SE	122.7±3.5276	117.1± 5.7296	120.1± 4.8709	116.4± 2.4115	118± 5.7230	121.8± 4.8633	120.3±5.5837
	R^2	0.98	0.91	0.95	0.98	0.94	0.97	0.94
	R_{MSE}	130.72	343.54	293.03	134.36	282.15	205.67	378.02
Truncated-Expolinear	w_{max}± SE	1597.7± 101.5	1598.9± 185.8	2181.4± 220.3	1820.3± 108.1	1888.2± 211.7	2003.9± 214.5	2619.3± 276.2
	c_m± SE	32.3411± 8.2059	72.8875± 180.6	40.8425± 13.1950	33.247± 5.3252	32.2756± 12.5948	35.2856± 8.7068	45.348± 14.9078
	r_m± SE	0.1087±0.0694	0.0479± 0.0420	0.1341± 0.1672	0.1379± 0.0910	0.1128± 0.1473	0.10±0.0737	0.1460± 0.2212
	T_o± SE	97.1830± 9.6536	122.1± 98.8648	93.1747± 12.3368	89.633± 6.3271	89.7982± 16.3504	93.2087±11.0319	91.283± 12.6298
	R^2	0.98	0.93	0.95	0.98	0.94	0.97	0.94
	R_{MSE}	143.54	321.81	311.6	152.94	299.36	214.5	390.65
Symmetrical-Expolinear	w_{max}± SE	1629.7± 308.3	1525.7± 586.6	1575.6± 864.8	1640.1± 492.1	1629± 735.7	1746± 807.5	1986.6± 2397.4
	c_m± SE	730.5± 1075638	373.5± 396324	1121.2± 8987613	817.9± 2875784	535.7± 1288444	770± 2962509	520± 2009350
	r_m± SE	0.0682± 0.0781	0.0724± 0.2327	0.0681± 0.2093	0.0604± 0.1025	0.0609± 0.1700	0.0599± 0.1395	0.0501± 0.2219
	T_o± SE	123.6± 1641.8	118.3± 2168.8	123.4± 6280.9	120.8± 3523.2	120.8± 3654.8	124± 4357.2	124.9± 7353.6

	R^2	0.97	0.86	0.86	0.92	0.88	0.9	0.8
	R_{MSE}	179.69	453.81	518.16	920.36	416.16	378.39	742.64
Richards	w_{max}± SE	1646.2± 194	1451.2± 213.6	2010.9± 168.9	1804.8± 133.1	1828.1± 300.4	2027.3± 334.5	2415.3± 217.8
	v± SE	1.7397± 1.9504	79.3641± 2836346	169.7± 497629	1.6049± 1.4229	2.0264± 3.8981	1.6859± 2.4929	131.1± 337371
	k± SE	0.1126± 0.0837	3.9030± 139485	8.1342± 23857.1	0.1164± 0.0656	0.1240±0.1638	0.1031± 0.1008	6.0765± 15633.1
	T_m± SE	124.5± 5.2715	133.4± 30898.7	137.1± 1494.1	118.2± 4.3544	120.8± 10.0650	123.5± 7.0927	137.2± 1645.1
	R^2	0.98	0.8	0.56	0.98	0.94	0.97	0.95
	R_{MSE}	134.78	383.33	292.59	137.14	291.15	212.32	377.15
Gompertz	w_{max}± SE	2094.2± 405.7	1983.8± 513.8	2572.1± 599.2	2085.8± 226	2185± 564.8	2588.7± 653.3	3016.8± 772.7
	k± SE	0.0403± 0.0116	0.0528± 0.0295	0.0471± 0.0201	0.085± 0.00991	0.0448± 0.0209	0.0379± 0.0138	0.0468± 0.0217
	T_m± SE	119.4± 6.1039	111.3± 7.4301	115.2± 6.7772	111.4± 3.3411	113.1± 7.9437	118.4± 8.4009	115.1± 7.5007
	R^2	0.98	0.99	0.95	0.98	0.94	0.97	0.96
	R_{MSE}	137.17	356.22	301.58	144.23	289.42	67.59	386.52
Weibull	w_{max}± SE	1615.6± 60.3158	1360.2± 177.5	2133.3± 91.2843	1795.8± 50.784	1818.4± 79.2812	1993.5± 84.2357	2523.8± 973842
	a± SE	1.1E-16± 3.31E-16	1.83E-15±1.5E-14	6.7E-18± 3.02E-17	2.3E-1± 5E-15	5.85E-16±2.1E-15	2 E-15± 5.6E-17	2.8E-17± 1.0E-16
	b± SE	7.5735± 0.6098	6.9955± 1.7287	8.1933± 0.9356	7.0206± 0.4892	7.2874± 0.7848	6.9839± 0.5861	7.8938± 0.7656
	R^2	0.99	0.9	0.92	0.99	0.99	0.95	0.94
	R_{MSE}	186.28	472.66	360.15	196.77	297.59	758.12	104.98
Beta 1	w_{max}± SE	1619.3± 39.6851	1869.7± 70.2251	2213.1± 71.7694	1839.7± 37.4448	1861.0± 56.8241	1969.3± 47.6093	2632.9± 71.3094
	t_e± SE	152± 1.7644	145.8± 0.9204	148.6± 1.3077	149± 1.2371	149± 1.6453	151± 1.6333	147.7± 0.8229
	t_m± SE	130.9± 1.0517	126.8± 1.3270	129.1± 1.1972	126.1± 0.9050	127.3± 1.2799	129.6± 1.0382	129.3± 0.9280
	R^2	0.95	0.9	0.99	0.96	0.92	0.95	0.95
	R_{MSE}	189.48	343.25	359.59	200.184	297.46	238.82	345.86
Beta 2	w_{bas}± SE	46.3478± 84.5908	0.0710± 167.5	9.911E-9± 0	79.23± 99.0661	74.9113± 265.3	68.9956± 207.9	1.452E-8± 231.8
	w_{max}± SE	1564.7± 98.19	1619± 218.3	2002.6± 177.7	1550.9± 102.1	1467.2± 290.1	1584.1± 274.1	2378.5± 268.3
	t_b± SE	61.0 ± 71.3191	-1.97E16±3.12E31	-1.9214± 1.42E27	61± 74.2645	61± 164.5	61± 140.4	-6.2E16± 3.682
	te± SE	149.4± 8.6730	137.4± 5.1208	139.1± 7.9525	142.4± 10.1793	151.3± 32.4888	153.1± 25.3384	137.8± 5.4744
	t_m± SE	127± 6.8307	131.3± 4.4192	129.3± 4.9812	120.7±8.2831	122.8± 25.2317	126.2± 17.9536	132.1± 10.9347
	R^2	0.96	0.77	0.95	0.95	0.8	0.86	0.81
	R_{MSE}	142.64	417.39	315.58	179.59	382.4	320.45	510.86

Preliminary analyses of individual field dry matter data showed that maximum plant dry matter was strongly observed in triticale while durum and oat showed the minimum total dry matter. Behavior the growth curves of different plants can change according to living organisms, the phenotype, genotype, morphological and agronomic (leaf shape, leaf area index, plant height, and so on.) and environment condition (radiation interception and efficiency, nutrient uptake and so on.), to which it is exposed. Various leaf area index and leaf expansion in different cereals caused to different radiation interception canopy and led to assimilates allocation to reproductive organs differences that is according to Ghadiryan *et al.*, (2011). Logistic, Gompertz, Richards, Weibull, Truncated Expolinear, Symetrical Expolinear and two kinds of Beta models have been evaluated by Ghadiryan *et al.* (2011) in order to describe the biomass accumulation of wheat cultivars in irrigated and rainfed conditions.

Results well documented that all models described well the pattern of variation dry matter versus day after planting. The best fitted model base on value of R^2 and RMSE could be introduced as Gompertz, logistic, Truncated-Expolinear, Symmetrical-Expolinear, Richards and Beta$_1$. Table 1 showed that Weibull and Beta$_2$ with no logical coefficients have lower R^2 value and more RMSE. Also, Symmetrical-Expolinear model showed logical coefficients but lower R^2. All these models with close determinant coefficient in describing winter cereals dry matter pattern during season should introduce the suitable models for cereal dry matter modeling subject. Model Beta$_2$ showed lower R^2 in comparison with other models.

Thus a $Beta_2$ model has not been suggested as suitable one base on field data of dry matter pattern variation in winter cereals.

According to Khamis *et al.* (2004) Gompertz, Stannard and Exponential logistic models were not suggested as suitable models for tobacco plant growth for the value of correlation coefficient. Because of morphological and growth habit variation in different cultivars, the proper model is slightly differed from one another (Ma *et al.*, 1992). The non-linear evaluation of the plant growth in mathematical relationship, estimate organs economic formation in plant growth mechanism as a basis of energy exchange (Jesus *et al.*, 2001).Crops growth curves can change according to environment condition, phenotype and different plant species (Yang *et al.*, 2005; Karadavut *et al.*, 2010).

In summary, mathematical models to describe winter cereals growth and accumulation dry matter are important part of cereal growth and development concept. In conclusion, Gompertz, Richards, logistic, Truncated-Expolinear and Symmetrical-Expolinear were found to be the most suitable models to fit with winter cereals dry matter pattern in this study.

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