Journal of Agrometeorology 17 (2) : 223-226 (December 2015)

Development of agro-climatic wheat yield model for Surat district, India using dimensional analysis

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ABSTRACT

In this study attempt is made to develop agro-climatic wheat yield model using dimensional analysis approach in which it is tried to include most significant parameters from the climate, soil and agricultural domain. Developed agro-climatic wheat yield model is different from the existing models due to consideration of above predominant parameters collectively which made it more sensitive towards climate change. Estimated wheat yield using developed model is compared with the actual yield for its validation which shows adequate conformity. Also the statistical performance of the model confirms its fitness, as discrepancy ratio is 1.095 and mean percentage error is 7.30E-05. Developed model while compared with the established models demonstrate better performance with ease in handling and hence recommended for wheat yield predictions.

Keywords: Climate change, climatological parameters, Agricultural parameters, wheat yield, Dimensional analysis.

Mathematically crop yield is dependent on many factors like weather, soil type and its nutrient status, management practices and other inputs available. Weather plays an important role, probably more in India where irregular and uneven weather such as drought, flood, etc., is a rule rather than an exception. Efficient crop planning, therefore, requires proper understanding of agro-climatic correlations. Monitoring of crop production is important for the economic development of any nation. Crop yield prediction before harvesting is important for food security planning decisions and development of reliable crop yield models with significant parameters is necessary in agricultural research (Mohammed *et al.,* 2010).

Purely technical considerations have to be counterbalanced for the conception of new irrigation schemes in areas of little or no experience irrigable cropping pattern (Verheye 1995). Current low yields are not reduced by adjustment of cropping patterns under average climate change conditions (Sonneveld *et al.,* 2012).

Based on the literature review it is revealed that there are many models available in the literature for prediction of crop yield which include few parameters in its construction. Popularly used crop yield models found in the literature are Thornthwaite memorial model (Lieth *et al.,* 1972), Miami model (Lieth 1972, 1975), Chikugo model (Uchijima, 1985) etc. Comparing the results of these models with each other and with actual yield it was found that out of these models Thornthwaite memorial model gave comparatively better result (Ming-can,2001). Although Thornthwaite memorial model over predicted the yield values up to 25 %. This over prediction may be because of the consideration of limited parameters in the model which may be unable to express the entire process properly. Therefore, it is tried to develop agro-climatic wheat yield model with due considerations of climatological, agricultural and soil parameters together for the study area under consideration. It is also tried to develop such a model which may be used in the decision making processes based on the predicted yield from the developed model for the condition of known input values.

MATERIALS AND METHODS

Study area and data

Study area is taken as Surat district which is in the southern part of Gujarat State, India. It is located at 20° 552' N, 73°032' E.

In the development of agro-climatic wheat yield model various parameters considered were temperature, precipitation, relative humidity, cropping pattern, actual yield, evapotranspiration, sunshine hours, base period, duty and fertilizer consumption. The climatic data from 1998-2010 were collected from Indian Meteorological Department (IMD), Pune, State Water Data Center (SWDC), Gandhinagar, Gujarat and Surat Irrigation Circle (SIC), Surat. Base period of crop refers to the whole period of cultivation from the time when irrigation water is first issued for preparation of the ground for planting the crop, to its last watering before harvesting. Cropping pattern was considered in terms of cropping area sown in hectares. Evapotranspiration was calculated by using CROPWAT 8.0. Cropping pattern, actual yield and fertilizer consumption were collected from Department of Agriculture and Cooperation, Gandhinagar, Gujarat. The entire data were collected for the period of 1998 to 2010. The collected data were analyzed for its trend detection using M-K test. A result of M-K (Mann-Kendall) test shows no trends.

Before developing agro-climatic crop yield model, few established models were studied. For this study Thornthwaite memorial model and Miami models were chosen due to their popularity found in the literature. The Thornthwaite memorial model (Lieth *et al.,* 1972) is as follows:

$$P = 30000\left(1 - \exp\left(-0.0009695(v - 20)\right)\right) \tag{1}$$

$$V = 1.05\ R/\left(\mathrm{SQRT}\left(1 + (1.05R/L)^2\right)\right) \tag{2}$$

$$L = 300 + 25T + 0.05T^3 \tag{3}$$

Where P is the crop productivity (kg ha^{-1}), 30000 is the highest dry-matter output (kg) of natural plant per year and per unit area (Lieth *et al.,* 1972) ; V is the average annual evapotranspiration (mm), L is the average annual evaporation (mm) , T is the average annual temperature (^{o}C) and R is the average annual precipitation (mm). When R<0.316L, V=P; otherwise, Equ. (3) will be used in computation.

The Miami model as proposed by Lieth (1972, 1975) expresses Net Primary Production (NPP) as a function of macro-climatic conditions. The NPP is expressed in g (DM) m^{-2} year^{-1}. The Miami model is as follows-

$$NPP = \min\left(NPP_T, NPP_P\right) \tag{4}$$

$$NPP_T = \frac{3000}{1+e^{(1.315-0.119T)}} \tag{5}$$

$$NPP_P = 3000\left(1 - e^{-0.000664P}\right) \tag{6}$$

Where T is average annual temperature in ^{o}C and P is annual precipitation in mm. According to whether T or P is limiting, the lowest value of NPP_T (NPP based on temperature) and NPP_P (NPP based on precipitation) is retained.

The agro-climatic wheat yield model was developed with due consideration of climatological, agricultural and soil parameters together using dimensional analysis approach.

Model development

Crop yield (C_Y; kg ha^{-1}) is dependent on many parameters viz. climatological parameters, soil parameters and agricultural parameters. Climatological parameters considered were precipitation (P; mm), temperature (q; ^{0}C), sunshine's hours (S_H; hours), relative humidity (R_H; %) & evapotranspiration rate (E_T; mm/day). Soil parameter considered in the model was in terms of water holding capacity of the soil based on soil type (S_T) viz. deep black soil for Surat district. It was measured as depth of available water in cm per meter depth of soil. Agricultural parameters like base period (B_P; days), which refers to the whole period of cultivation from the time when irrigation water is first issued for preparation of the ground for planting the crop, to its last watering before harvesting. Duty (D; ha/cumec) represents the irrigating capacity of unit of water. It is the relation between the area of crop irrigated and the quantity of irrigation water required during the entire period of the growth of that crop. Fertilizer consumption (F; kg ha^{-1}), was taken as fertilizers like Nitrogen(N),Phosphorus(P) and Potassium(K), which is given to the crop. Data for fertilizer consumptions was collected from FAO manual. Cropping pattern (C_P; ha) was considered as area sown in hectare & crop yield (C_Y; kg ha^{-1}) was considered in model development. Data for cropping pattern and crop yield is collected from Krushi bhawan, Gandhinagar. It was tried to cover up most significant parameters in the model which represents the entire phenomenon of the crop yield.

Therefore functionally crop yield is given as

$$C_Y = f(P, \theta, S_H, R_H, C_P, S_T, F, B_P, E_T, D) \tag{7}$$

By applying dimensional analysis approach (Buckingham,1914) and using Buckingham p theorem (Buckingham,1914), obtaining various pair of variables in the dimensionless form the regression analysis was carried out for combination of dimensionless pair of variables. The best performing combination of pair of variables was finally selected based on the coefficient of determination (R^2) giving the value greater than 0.9. To check the significance of the correlation T test and P test were carried out and obtained the value as 14.51 and 1.10443E-13 respectively. To select final form of the model various combinations were tried and regression analysis were carried out for all combinations.

Statistical performance

To check the statistical fitness of the developed model, it has been tested with four different statistical

Table 1: Results of regression analysis

Sr. No.	Combination	Coefficient (K)	Exponent (n)	Coefficient of determination (R^2)
1	C_Y/F v/s B_P/S_H	6.2512	-0.133	0.0464
2	C_Y/F v/s $S_H.E_T/P$	0.0072	0.1499	0.0277
3	C_Y/F v/s P.D	1E+08	0.2008	0.2115
4	C_Y/F v/s $C_P/P^2 * S_H.E_T/P$	5E-10	-0.919	0.8556
5	C_Y/F v/s $C_P/P^2*S_T/P$	7E-12	-1.27	0.6453
6	C_Y/F v/s $S_T/P * B_P/S_H$	0.0006	-0.334	0.1123
7	C_Y/F v/s $C_P/P^2*B_P*S_H*E_T*$ D	1.350	-0.94	0.9353

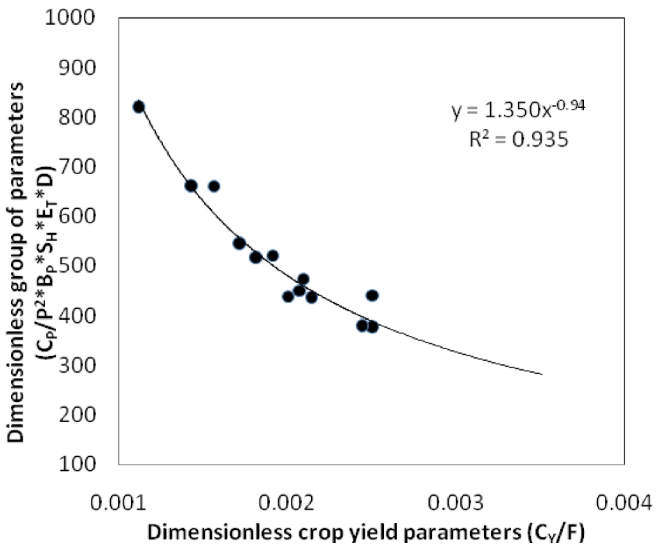

Fig. 1: Regression analysis between dimensionless crop yield parameter and dimensionless group of parameters

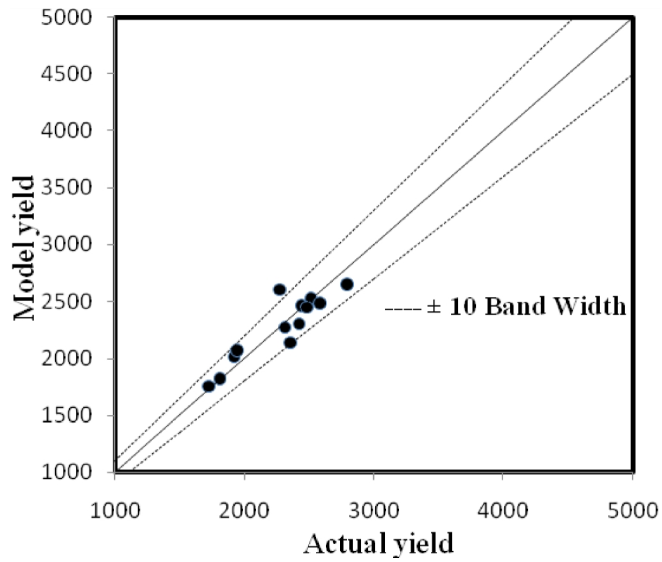

Fig. 2: Scatter plot of model and actual yield data points with ±10 % band width

parameters. Discrepancy ratio, r which was calculated as the ratio of calculated crop yield and actual crop yield. For all the data points of Surat district the discrepancy ratio was calculated for Thornthwaite memorial model, Miami model and developed agroclimatic wheat yield model. The model for which the value for r is 1 should be considered as best fit. Standard deviation of discrepancy ratio was calculated for all the data points of all the models. Also mean percentage error was calculated by taking the ratio of difference of calculated crop yield and actual crop yield divided by actual crop yield in percentage. Standard deviation of mean percentage error was also calculated.

RESULTS AND DISCUSSION

Regression analysis carried out for all combinations of dimensionless terms. Regression analysis between dimensionless crop yield parameter $\left(\frac{C_Y}{F}\right)$ and group of parameters $\left(\frac{C_P}{P^2} * B_P * S_H * E_T * D\right)$ is shown in Fig.1.

Results of regression analysis carried out for all other combinations in terms of coefficient k, exponent n and value of coefficient of determination (R^2) are shown in Table 1.

Out of several trials for the various combinations carried out the following form of combination shown in Equ. (8) gave better agreement for which coefficient of determination (R^2) obtained was 0.9353 and hence considered as final form of the model.

Here C_Y/F represents dimensionless crop yield parameter and $(C_P/P^2*B_P*S_H*E_T*D)$ represents dimensionless group of parameters.

Hence, the form of agro-climatic wheat yield model obtained from the regression analysis is considered as final model as given in Equ. (8)

$$\left(\frac{C_Y}{F}\right) = 1.350 \left(\frac{C_P}{P^2} * B_P * S_H * E_T * D\right)^{-0.94} \quad (8)$$

To check the adequecy of the developed model as

Table 2: Statistical performance of developed agro- climatic wheat yield (kg ha^{-1}) model (Equ.(8)) (Yield kg ha^{-1})

Year	Actual yield	Developed model yield	Thornthwaite memorial model	Miami model
1998-99	2360	2139	26156	26694
1999-00	1920	2013	25966	26667
2000-01	2440	2456	25418	26410
2001-02	1810	1810	25287	26113
2002-03	1730	1757	25151	26126
2003-04	2310	2277	25427	26169
2004-05	2420	2303	25602	26277
2005-06	2510	2516	25396	26114
2006-07	2490	2450	25674	26335
2007-08	1950	2061	25614	26303
2008-09	2280	2605	25515	26222
2009-10	2590	2476	25501	26264
2010-11	2800	2642	25380	26142
Discrepancy ratio		1.095	0.083	0.083
Standard deviation of discrepancy ratio		0.473	0.043	0.032
Mean percentage error		7.30E-05	-0.001	-0.001
Standard deviation of mean percentage error		0.0004	5.36E-05	4.04E-05

given in Equ.(8), yield is calculated by using developed wheat yield model and compared it with the actual yield. The results of actual yield, model yield and statistical performance of the developed model are shown in Table 2. Also the scatter plot between the actual yield and model yield shows the variation of the data points falls within the range of ± 10% band width as shown in Fig. 2.

Statistical performance test results show the statistical fitness of the developed model over other models. Hence developed form of the agro-climatic wheat yield model (Equ.(8)) is accepted for its use.

CONCLUSIONS

Based on the study carried out it is concluded that for the estimation of wheat yield the developed model can be used for the known input values. The developed model can also be used as decision supporting tool for known values of model inputs to decide whether to go for wheat or not, based on the estimated value of wheat yield.

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Received : July 2015 ; Accepted : September 2015