Почвознание агрохимия и екология, 55, 2/2021
Bulgarian Journal of Soil Science Agrochemisty and Ecology, 55, 2/2021

Method for estimation of pre-sowing soil moisture of winter wheat and suitable planting dates

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Citation: Sadovski, A., & Ivanova, M. (2021). Method of estimation of pre-sowing soil moisture of winter wheat and suitable planting dates. Bulgarian Journal of Soil Science, Agrochemistry and Ecology, 55(2),49-57.

Abstract

The pre-sowing soil moisture is a determining factor at the beginning of the growing season for winter wheat. The publication describes a method for its estimation based on meteorological and soil-physical information. The application of the method is illustrated with data from different locations and soils in the country. Also are investigated planting dates of winter wheat grown on the territory of selected USA states, which have similar homoclimates with Bulgaria. A simple solution approach was applied for the determination of suitable planting dates by solving a general fuzzy system of linear equations with mixed fuzzy crisp explanatory variables and fuzzy unknown variable vectors.

Key words: winter wheat, soil moisture, climate data, homoclime, planting dates, fuzzy sets

Introduction

Wheat is the most important grain worldwide based on grain acreage and is ranked second when it comes to the total production volume. The global amount of wheat produced came to about 765.41 million metric tons in the crop year 2019/2020 (Shahbandeh, 2020). Winter wheat is usually planted from September to November (in the Northern Hemisphere) and harvested in the summer or early autumn of the next year.

Crop growth (or yield) is directly affected by the climate. Weather conditions have a marked influence on the growth of wheat as well as on the yield and quality of its grain. The pre-sowing soil moisture is a determining factor at the beginning of the growing season for crops sown in autumn. Dates of sowing, emergence, heading, and ripening of pure-line varieties of wheat are the kind of phenological data assembled and utilized in this study. Preliminary investigations have shown that such data, when properly organized and analyzed in the light of some of the potent climatic and latitudinal factors governing and conditioning the cycles of plant growth and development, appear to provide a means for quantitative expression of the thermal or photo-thermal requirements of wheat (M. Nuttonson, 1955).

The time and conditions which are required for the completion of the phases of plant development determine the growing period of each plant. The rate at which these phases are completed depends entirely upon the complex of external conditions and the internal peculiarities of the plant organism. Temperature, light supply, and water supply all interact in the process of conditioning the plant through each of the stages of its development.

Under favorable soil moisture conditions, and when the mean temperature lies between 14° and 17°C, wheat appears to sprout and emerge in 7 to 10 days after sowing. When the mean daily temperature falls below 4°C, growth almost ceases as the plant becomes practically dormant. It remains in this condition throughout the winter season and resumes its growth and development with the advent of warm weather in early spring. Winter wheat must be allowed time to tiller adequately and become well rooted before the beginning of winter, as adequate tillering determine to a high degree its yield.

According to Large (1954) cereals develop as follows via physiological Feekes Growth Stages: tillering, stem extension, heading, flowering, and ripening (Fig. 1).

The planting date of wheat determines the stage of tillering, which occurs in autumn. The entire developmental cycle of the plants is subdivided into ten clearly recognizable and distinguishable longer-lasting developmental phases. Phenological growth stages are described in (Meier, 2001). Important factors in this process are temperature and precipitations. The molecules of capillary water are free and mobile and are present in a liquid state. As it is held firmly by the soil particle, plant roots can absorb it. Capillary moisture is, therefore, known as soil moisture (SM). The plant available water content is determined by the precipitation (PS) for the period - September - December and the corresponding soil wilting point.

The temperature factor manifests itself by a thermal threshold, growing degree days, and the sum of degree days for the last four months of the year. The thermal threshold approximately is set to 4°C, which initializes wheat growth. Growing degree days (abbreviated GDD or DD) is a way of assigning a heat value to each day. The values are added together to give an estimate of the amount of seasonal growth your plants have achieved. The resulting "thermal time" more consistently predicts when a certain plant stage will occur. When summed together, these thermal times are sometimes referred to as a "thermal calendar" (Miller et al., 2018). Growing degree days, which are based on actual temperatures, are a simple and accurate way to predict when a certain plant stage will occur (Table 1).

Too early sowing, as well as too late sowing, may cause considerable lowering or sometimes complete loss of yield of winter wheat. Too early sowing may result in excessive growth and vegetative development during fall, which leads to a lowering in winter hardiness, and the wheat plants may rot under a heavy winter snow cover (Nuttonson, 1955). The appropriate pre-sowing humidity of winter wheat depends on the first significant precipitation after the summer drought, and its date is a criterion for autumn drought (Sabeva et al., 1968).

During the years 2011-2013 on the cinnamon-brown forest soil three sorts of durum wheat were tested in two sowing periods and two periods of the introduction of the nitrogen fertilizer with 3x2x2 full factorial design (Samodova, 2020). Our analysis of the data obtained shows that the first variety "Progress" gives the highest average yield and sowing time between 25 – 30 October is preferable than late after 20 November. Contrary to the author's conclusion that a better effect is obtained with a single application of nitrogen fertilizer, the analysis shows that 1/3 of the nitrogen applied after germination, and the remaining 2/3 as spring feeding (February, March) is recommended.

In our study about suitable winter wheat planting dates, we are not dealing with exact numerical data, but with data that are uncertain in some well-defined statistical sense (Diamond, 1988). Fuzzy set theory has been regarded as a

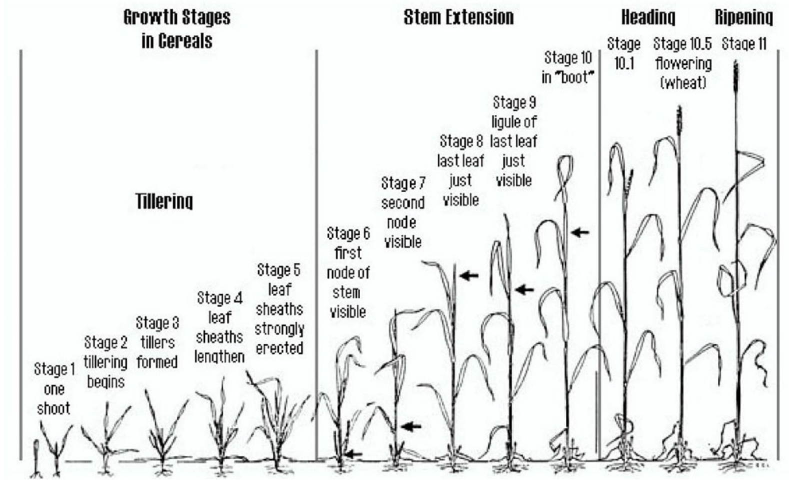

Fig. 1. Development of cereals according to Large (1954)

Table 1. Phenology calculations for wheat (P. Miller et al., 2018)

Phase	Stage		GDD°C
Emergence	Leaf tip just emerging from above-ground	1	125-160
Leaf development	Two leaves unfolded	1.1	169-208
Tillering	First tiller visible	2.1	369-421
Stem elongation	First node detectable	3.1	592-659

natural way of describing data of this type (Zadeh, 1965). In this paper, the main aim is to use a method where the right-hand side is a fuzzy vector, and the coefficients matrix is also fuzzy.

Following (Zimmermann, 1991), a fuzzy number may be defined as $F = (b, g, h)$; where b denotes the center (or mode), g and h are the left spread (L) and right spread (R), respectively, L and R denote the left and right shape functions. A popular fuzzy number is the triangular fuzzy number.

In this paper, we extend the simple linear regression model to the multiple ones adding both fuzzy and crisp predictors to the linear regression model, and the resulting model is called the mixed fuzzy crisp (MFC). Crisp means - something clearly defined, deterministic in character.

The term "homoclime" is used by Prescot (Prescot, 1938) for areas with a similar climate. A recent study (Sadovski, 2019) reveals the similarity of Bulgarian conditions for growth and development of crops with the corresponding USA states: North Dakota (ND), Washington (WA), South Dakota (SD), Wyoming (WY), Oregon (OR), Colorado (CO) and Utah (UT). The main tasks of the study are the estimation of pre-sowing soil moisture necessary for the development of winter wheat in autumn and the determination of planting dates valid for Bulgaria (BG) by fuzzy regression.

Material and Methods

The material on the physical properties of a large number of Bulgarian soils, which was used in this study, was taken from an excellent source containing valuable data (Dilkova, 2014). The complete set of data on field capacity and wilting point includes 57 determinations. Long-term average monthly climatic data for the period 1991-2016 are used (World Bank, 2020).

Variation of precipitation was approximated with a B-spline curve.

The curve of the average monthly temperature was presented with a Gaussian three parameters equation

$$Taver=a\ exp(-0.5((Day-b)/c)^2), \text{(Day = 1,...365)} \quad (1)$$

where a = 22.0701, b = 202.4063 and c = 73.6305, with R^2 = 0.9794 and fit Std.Err. = 1.3129.

The temperature factor manifests itself by the thermal threshold, growing degree days, and the sum of degree days (DD) for the last four months of the year (September - December) are calculated from the data for 57 locations in Bulgaria. It is determined by the formula (Elnesr & Alazba, 2016)

$$DD = \sum_{1}^{n} GDD_i \quad ,$$

where GDDi is the sum for the period from 1 September until 31 December,

$$GDD_i = Max(0, Tav\text{-}4), \text{ (i=244 to 365 day)} \quad (2)$$

Tav is the average monthly temperature and the thermal threshold approximately is set to 4°C, which initializes wheat growth. The value of the thermal threshold differs for different crops.

Tillering begins in wheat around 400 GDD and typically lasts until roughly 600 GDD (Mathesius & Lundy, 2020). In Table 2 are given the required and accumulated GDD for wheat in the conditions of North Dakota.

The relationship between the dependent variable plant available water content (PAW) and independent variables sum of degree days, the sum of precipitation, field capacity, and the wilting point was sought in the form of the following regression equation:

$$Y=b_o+b_1.DD+b_2.PS+b_3.FC+b_4.WP \quad (3)$$

The method of backward stepwise regression allows us to find only those independent variables that actually participate in the equation.

An extensive compilation of observations was made of crop planting dates from around the world to make a single, comprehensive crop calendar data set (Sacks et al., 2010). We shall use this data set for comparison with our results.

It is completely justified and natural to use data from other territories to solve local problems. This justifies the application of the homoclimate method.

Materials for analysis are data for the usual planting dates of field crops in the USA (USDA, 2010). Data for winter wheat from the above-mentioned states are analyzed using available usual planting dates (begin, most active period, and end). For analysis purposes, the given begin and end calendar dates must be converted to the corresponding serial number during the year (Table 3). It should be noted that these are typical triangular fuzzy data.

To solve the fully fuzzy linear system $\tilde{A} \otimes \tilde{x} = \tilde{b}$ with a new notation $\tilde{A}$(A, M, N)where A, M, and N are three crisp matrices, with the same size $\tilde{A}$, the matrices A, M, and N are called the center matrix, the left, and right spread matrices, respectively we follow Mosleh et al. (2011).

MATLAB implementation (2005) to solve totally fuzzy linear regression problems is given in (Sadovski, 2019a). All calculations by the method described are done with the free software package GNU Octave, Version 5.2.0.

Results and Discussion

First, all descriptive statistics of all climatic input data have been calculated. The results are given in Table 4.

Next step the correlations between all variables are estimated and discussed. Significant correlations exist only between wilting point

Table 2. Growth stages of wheat - excerpt from NDAWN (2020)

Name	Description	GDD Required	Accumulated GDD
Planting date	Data crop was planted	0	0
Emergence date	Emergence is defined here as the date leaf 1 reaches half of its length	180	180
Leaf 1 fully extended	Leaf 1 is fully developed when the second leaf is visible in the rolled part of leaf 1	72	252
Leaf 2 fully extended	Leaf 2 is fully developed when the third leaf is visible in the rolled part of leaf 2	143	395
Leaf 3	Tillers begin to emerge	143	538
Leaf 4	Leaf 4 fully extended	143	681
Leef 5	Tillering ends	143	824

Table 3. Winter wheat usual planting dates

State	Usual planting dates							
	Begin	P-g	Most active	P-g	P-b	P-h	End	P-h
ND	Sep-06	249	Sep 10 - Sep 25	253	262	268	Oct-02	275
WA	Aug-30	242	Sep 1 - Oct 10	244	268	283	Oct-20	293
SD	Sep-01	244	Sep 9 - Oct 5	252	267	278	Oct-16	289
WY	Aug-25	237	Sep 4 - Sep 20	247	254	263	Sep-28	271
OR	Sep-15	258	Oct 10 - Nov 10	283	297	314	Dec-01	335
CO	Sep-01	244	Sep 11 - Oct 2	254	264	275	Oct-11	284
UT	Aug-20	232	Aug 25 - Oct 5	237	273	278	Nov-10	314
BG	Sep-20	263	Oct 5 - Oct 31	278	288	304	Nov-10	314

and soil moisture. This is presented in Table 5.

The application backward stepwise regression resulted in the following regression equation for soil moisture (Table 6). It is obvious that the pre-sowing soil moisture (PAW) depends on the amount of precipitation for the period and the indicator soil wilting point.

$$SM=0.0180PS + 0.8025WP,$$

with R = 0.9694, F(2,55) = 429.02, Std. Err. = 6.1445.

Here are examples of calculated values of pre-sowing soil moisture (PAW) for two locations in Bulgaria.

Bozhurishte experimental field, Sofia district, leached smolnitsa soil. PS = 158, FC = 40.90, WP = 21.20.

The calculated value of soil moisture is: SM

= 0.0180*158+0.8025*21.20 = 19.86.

Bostan, Targovishte district, gray forest soil. PS = 169, FC = 41.50, WP = 9.85.

The calculated value of soil moisture is: SM = 0.0180*169+0.8025*9.85 = 10.95.

To find soil moisture in a select soil, the corresponding sum of precipitation, field capacity, and wilting point should be known. The values of the sum of precipitation can easily be calculated from real meteorological data for September to December.

In order to assess the heat and moisture supply for the germination of winter wheat, calculations are made for different sowing dates in ten days interval from September 1 to November 1. Table 7 presents the average climatic values of precipitation, temperatures, and the corresponding growing degree days (GDD).

When the mean daily temperature falls below 4°C the values of GDD stop rising. It is clear that the value of GDD at the date of sowing November 1, is not sufficient for the development of the tillering phase. When sowing wheat as of September 10, it is possible to complete the tillering phase at GDD values above 600.

The "usual planting dates" shown are the times when crops are usually planted in the fields. The unknown variable vectors we are looking for are:

Planting = (P-b, P-g, P-h),

Explanatory variables for the analysis are:

Lat-g (φ°N), Lat-b (φ°N), Lat-h (φ°N), Elevation above sea level (m), Season length (days), Average daily temperatures September - December (°C), Average amount of precipitation September - December (mm). Data for analysis are shown in Table 8.

The solution to the problem is accomplished by ST decomposition following (Mosleh et al., 2011). The minimal solution of the mixed fuzzy crisp linear system is presented in Table 8. The estimated statistical characteristics: average, median, and standard deviation allow easily the results of analyzed fuzzy sets to be interpreted. The comparison of the data for winter wheat sowing indicated in this database (Sacks et al., 2010) is close to that obtained from the present analysis (start - end: respectively 242 - 306 and 261 - 301).

As can be expected, the dates for winter wheat from the selected states are close to the average values obtained. Table 9 shows that the sowing dates for winter wheat in Bulgaria (261 = 18 September, 281 = 8 October, 301 = 28 October) are relatively close to those of the state of Oregon.

Table 4. Descriptive statistics of variables: degree days sum (DD °C), precipitations sum (PS mm), field capacity (FC %), wilting point (WP %), soil moisture (SM %)

Variable	Valid N	Mean	Median	Minimum	Maximum	Std.Dev.	Skewness	Kurtosis
DD	57	774.968	770.40	603.30	980.30	89.4649	0.3099	0.2042
PS	57	202.912	184.00	153.00	416.00	62.6661	2.8550	7.5192
FC	57	44.015	44.02	16.50	81.00	11.7134	0.5378	1.2102
WP	57	11.920	11.92	3.35	29.25	4.5577	1.3491	4.0852
SM	57	23.854	23.85	10.45	43.95	6.0304	0.3511	2.3037

Table 5. Correlations between variables (* Correlation significant at the 0.05 level)

Variable	DD	PS	FC	WP	SM
DD	1	0.0390	0.0857	-0.0630	-0.2545
PS	0.0390	1	-0.0769	0.0273	0.0583
FC	0.0857	-0.0769	1	0.2591	0.0760
WP	-0.0630	0.0273	0.2591	1	0.4437*
SM	-0.2545	0.0583	0.0760	0.4437*	1

Table 6. Regression summary for dependent variable soil moisture

N=57	b*	Std.Err. of b*	b	Std.Err. of b	t(55)	p-value
PS	0.5713	0.0879	0.0180	0.0028	6.4957	0.0000
WP	0.4160	0.0879	0.8025	0.1697	4.7299	0.0000

Table 7. Heat and moisture supply at different winter wheat sowing dates

Date	Prec	Taver	GDD						
			01-Sep	10-Sep	20-Sep	01-Oct	10-Oct	20-Oct	01-Nov
01-Sep	70.4	18.2	16.3						
10-Sep	67.4	17.6	155.7	14.9					
20-Sep	63.5	16.9	295.8	154.9	13.2				
01-Oct	60.2	15.9	430.0	289.2	147.4	11.2			
10-Oct	57.4	15.0	523.3	382.5	240.8	104.6	9.7		
20-Oct	52.7	13.8	610.1	469.3	327.5	191.3	96.5	7.9	
01-Nov	46.2	12.2	691.3	550.4	408.7	272.5	177.6	89.0	5.8
10-Nov	41.2	10.8	736.7	595.8	454.1	317.9	223.0	134.4	51.2
20-Nov	36.1	9.2	772.4	631.5	489.8	353.6	258.7	170.1	86.9
01-Dec	33.1	7.2	796.1	655.3	513.5	377.4	282.5	193.9	110.6
10-Dec	32.7	5.4	805.0	664.2	522.4	386.2	291.4	202.8	119.5
20-Dec	35.0	3.2	806.5	665.6	523.9	387.7	292.8	204.2	121.0

Table 8. Winter wheat usual planting dates input data

State	Explanatory variables							Planting		
	Lat-b	Lat-g	Lat-h	Elev	Slth	Tav	Pav	P-b	P-g	P-h
ND	45.93	47.47	49.00	580	129	10.30	50.75	249	262	275
WA	45.55	47.28	49.00	520	153	13.56	40.75	242	268	293
SD	42.48	44.21	45.93	670	145	10.33	67.25	244	267	289
WY	41.00	43.00	45.00	2040	123	11.08	41.00	237	254	271
OR	42.00	44.15	46.30	1000	188	14.01	33.25	258	297	335
CO	37.00	39.00	41.00	2070	157	13.63	37.00	244	264	284
UT	37.00	39.50	42.00	1860	165	16.14	28.50	232	273	314
BG	41.35	42.75	44.35	472	178	10.18	43.00	263	288	314

Table 9. Winter wheat planting dates output results

State	Planting		
	P-b	P-g	P-h
ND	243.9	253.1	261.9
WA	243.9	265.3	286.0
SD	246.4	260.6	274.1
WY	241.0	246.5	252.4
OR	262.0	289.8	317.2
CO	240.2	260.1	279.9
UT	230.5	258.8	286.7
BG	261.0	281.3	301.4
Average	246.1	264.4	282.5
Median	243.9	260.3	282.9
St. dev.	10.62	14.35	20.72

Conclusion

A method for the evaluation of capillary moisture based on meteorological and soil-physical information is described in the paper. The coefficients of the regression models are calculated with data from different locations and soils in the country. This method allows based on current meteorological and soil texture data to determine the pre-sowing soil moisture. Further studies are needed to refine the coefficients of the regression models obtained.

This data set could be used in different ways. The dependence of planting dates on the climate in the season is important to bear in mind if we hope to predict how climate change might affect these dates. As a future research direction, it would be desirable to consider the fuzziness of not only observations on the dependent variable but also on explanatory variables.

In this article, we show the efficiency of the proposed method for solving linear fuzzy regression. This scheme for finding the positive solution of the fuzzy systems, when parameters are positive, it turns out quite satisfactory. The application of the homoclimates approach combining with the mathematical apparatus of fuzzy regression can reveal qualitative and quantitative dependencies in soil science, agriculture, and environmental research.

References

Diamond, P. (1988). Fuzzy least squares. *Information Sciences, 46*, 141-157.

Dilkova, R. (2014). *Structure, Physical Properties and Aeration of Bulgarian Soils*. Publish SciSet-Eco (Bg).

Elnesr, M. N., & Alazba, A. A. (2016). An integral model to calculate the growing degree-days and heat units, a spreadsheet application. *Computers and Electronics in Agriculture, 124*, 37-45.

Large, E. C. (1954). Growth stages in cereals. *Plant Pathol. 3*,128-129.

Mathesius K., & Lundy, M. (2020). Top dressing wheat: Growing degree models help optimize nitrogen application timing. ANR Blogs, UC Agriculture and Natural Resources.

MATLAB (2005). Function Reference. LU matrix factorization, The MathWorks, Inc.. http://matlab.izmiran.ru/help/techdoc/ref/lu.html

Meier, U. (ed). (2001). *Growth stages of mono- and dicotyledonous plants. BBCH. Monograph*, 2nd edition. Federal Biological Research Centre of Agriculture, Germany.

Miller, P., Lanier, W., & Brandt, S. (2018). *Using Growing Degree Days to Predict Plant Stages.* MT200103AG Reprinted 7/18, MSU Extension Service.

Mosleh, M., Abbasbandy, S. & Otadi, M. (2011). A method for solving fully fuzzy linear system. *Mathematics Scientific Journal, 7*(2), 2011, 59-70.

Nuttonson, M. Y. (1955). *Wheat-climate relationships and the use of phenology in ascertaining the thermal and photo-thermal requirements of wheat.* American Institute of Crop Ecology, Washington.

Prescot, J. A. (1938). The climate of tropical Australia in relation to possible agricultural occupation. *Trans. Roy. Soc. S. Australia, 67,* 312-318.

Sabeva, M., Stefanov, St., Hershkovich, E., Dilkov, D., Zhechev, P., & Markov, G. (1968). *The nature of droughts and the changing irrigation regime of crops*. Ed. BAS. Sofia (Bg).

Sacks, W. J., Deryng, D., Foley, J. A., & Ramankutty, N. (2010). Crop planting dates: an analysis of global patterns. *Global ecology and biogeography, 19*(5), 607-620.

.

Sadovski, A. (2019a). Solving Fuzzy Linear Regression with ST Decomposition. *J. of Multidisciplinary Eng. Sci. and Technology, 6*(3), 9615-9618. JMESTN 42352851

Sadovski, A. (2019). Detection of similar Homoclimates by Numerical Analysis. *Bulgarian Journal of Soil Science, 4*(1), 69-75.

Samodova, A. (2020). Influence of the period of sowing and the period of fertilizing on the elements of yield of durum wheat in the region of Pazardzhik. *Rastenievadni nauki, 57*(5) 3-7 (Bg).

Shahbandeh, M. (2020). Wheat - Statistics & Facts. https://www.statista.com/topics/1668/wheat/

USDA (2010). *Field Crops Usual Planting and Harvesting Dates*. Agricultural Handbook Number 628, p. 51.

World Bank (2020). Bulgaria 1991-2016. Climate change knowledge portal. https://climateknowledgeportal.worldbank.org/download-data (last accessed at 10.07.2020).

Zadeh, L .A. (1965). Fuzzy sets. *Inf. Control, 8*, 338–353.

Zimmermann, H. J. (1991). *Fuzzy Set Theory and its Application.* Kluwer Academic Press, Dordrecht, p. 407.