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## ESTIMATING THE OPTIMAL NITROGEN FERTILISER APPLICATION OF SORGHUM [SORGHUM BICOLOR (L.) MOENCH] IN THE BULGARIAN THRACIAN PLAIN

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### Abstract

Sorghum (*Sorghum bicolor* (L.) Moench) is an important grain crop around the globe. Although a tropical plant, it can be grown in temperate climate zones. In Bulgaria, sorghum is one of the first ten cultivated crops. It is planted on non-irrigated fields since it is more drought-resistant than other crops. There are many studies devoted to the technology of growing sorghum. All of them find that it is more adaptable to rapid climatic changes that have been manifested in recent years. However, there are insufficient studies on nitrogen use efficiency in sorghum in the scientific literature. The article aims to determine the optimal nitrogen fertiliser rate for sorghum. The production function is estimated using experimental data, and the challenges associated with model design are discussed. The optimisation process is carried out, and conclusions relevant to business and improvement of the estimation process are discussed. Although the tendency is to grow crops with fewer chemicals, changing the current technology may take 10 to 15 years. In this respect, the results presented are important. In addition, the information from the presented study may help to set new experiments that include nitrogen-fixing crops in crop rotation.

**Keywords:** sorghum, fertiliser use, drought-resistant crop

### INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is among the most important grain crops (Fernandes et al., 2013). It can be used for food, fodder, and paper production. Sorghum is usually planted on non-irrigated fields since it is more drought-resistant than other crops. The largest producers are the USA, India, China, and Mexico. In the European Union, approximately 600,000 tons are produced in France, Italy, and Spain. Sorghum is grown in Romania, Hungary, the former USSR, and Yugoslavia.

The total consumption of 850,000 tons in Europe exceeds production. Imports are mainly from the USA.

The absence of gluten, high protein content, and neutral taste make grain sorghum an excellent feed for all kinds of animals, and it is comparable in nutritional value to corn. It is rich in antioxidants and vitamin B (Mosse et al., 1988). Regarding amino acid composition, it is also not significantly inferior to corn but contains less lysine and carotene. On average, 100 kg of grain contains 11 kg N, 6.2 kg P<sub>2</sub>O<sub>5</sub> and 4.5 kg K<sub>2</sub>O (Stewart, 2012). Sorghum is also a raw material for bioethanol production (Krastev & Kikindonov, 2002; Smit & Frederiksen, 2000).

Sorghum exhibits high drought tolerance, and its production is more stable than that of crops such as corn and soybeans (Wenzel, 1999). Sorghum can survive harsh natural conditions, but in this case, the yields are low at 0.50-1 t/ha. World average yields under non-irrigated conditions are 3.00-5.00 t/ha, and maximum yields are 13.00-15.00 t/ha (Espinoza & Kelley, 2004; Wichmann, 1992). In hydrometeorological regions with insufficient rainfall, sorghum can be a preferred crop to improve the forage balance (Zarkov, 1995; Enchev, 2011; Wenzel, 1999).

Nitrogen is the primary nutrient for sorghum growth and productivity (Gerik et al., 2014). The efficient use of nitrogen is important both economically and ecologically, and it must be considered in good agricultural practices (Dobermann et al., 2005). Nitrogen fertilisation rates for grain sorghum vary from 60 to 320 kg/ha, depending on region and growing conditions.

Under non-irrigated conditions, sorghum is fertilised with 100-120 kg/ha (Gorbanov, 2018; Nikolova, 2010). According to Kissel (2008), to obtain yields above 6.70 t/ha, nitrogen fertilisation at a rate of 150 kg/ha is necessary. In the USA, 90-120 kg/ha are commonly used to fertilise grain sorghum (Diaz, 2014; Ciampitti et al., 2014; Paul, 2009). With irrigation, fertilisation rates are 150-240 kg/ha. In 100 kg of grain and the corresponding by-product, sorghum exports an average of 220 kg N/ha, 1.3 kg P<sub>2</sub>O<sub>5</sub>/ha and 250 kg K<sub>2</sub>O/ha (Valeva et al., 2020).

In Bulgaria, sorghum is among the first ten cultivated crops. It is used to produce fodder grain, green mass, and silage. The changes in Bulgaria's area planted with sorghum can be separated into three periods. Between 1990 and 2009, the areas gradually declined; between 2010 and 2018, they gradually increased; after 2019, they sharply declined. During all three periods, the average yield increases. The peak of production is in 2019. The grain yields vary depending on the genotype, agrotechnical and soil-climatic conditions. Without irrigation, yields range between 6.00 and 10.00 tons per hectare (Slanev et al., 2015).

Several elements of the technology of growing grain sorghum have been studied in Bulgaria: (1) sowing density (Shentov, 1980; Zarkov, 1995; Krastev & Kikindonov, 2002; Kikindonov et al., 2005); (2) intra-row and inter-row spacing of sowing (Tanchev, 1989); (3) the influence of climatic factors on the productivity (Kertikov, 2007; Kikindonov et al., 2008; Kikindonov & Slanev, 2011). In summary, all these studies find that the climatic changes manifested in recent years necessitate the selection of varieties with a broader range of ripening periods and greater adaptability to extreme abiotic factors (Slanev et al., 2012). The authors recommend grain sorghum as suitable for growing in extreme deviations from agro-climatic conditions (Krastev & Kikindonov, 2002; Slanev et al., 2012). American

hybrids imported until the 1980s (Shentov, 1980; Tanchev, 1989) were successfully replaced by varieties from European selection, which have shorter growing seasons. However, there are still insufficient studies on nitrogen use efficiency in sorghum in the scientific literature (Baozhen et al., 2014). Genotypic differences in performance indicators can exceed 20 % and are highest in nitrogen allocation between grain and straw (Maranville et al., 2008).

The article aims to determine the optimal nitrogen fertiliser rate for sorghum. First, the experiment is described, and data are presented. Second, the production function is estimated, and the challenges for the model design are discussed. Third, the optimisation process is explained, and the results are analysed. Finally, conclusions related to business and improvement of the estimation process are presented.

## MATERIALS AND METHODS

The field experiment was conducted at the Agricultural University – Plovdiv's experimental field under non-irrigated conditions. The medium-early hybrid EU Alize of the French agricultural group "Euralis Semences" was tested. It is the most widespread hybrid in Bulgaria because it provides a stable and reliable yield in dry conditions. The hybrid is resistant to lodging and exhibits low grain spillage during harvesting.

The soil at the experimental field is alluvial-meadow-*Mollic fluvisols* (FAO, 2006), slightly colonic, with horizon A 25 - 28 strength. The soil is sandy, with a clay content of 33% in the A horizon, and contains a moderate amount of calcium carbonate, which improves its physicochemical and water properties. The arable horizon's humus content is, on average, 3.7%, but gradually decreases in depth. The soil reaction is slightly alkaline (pH 7.0 to 7.2). The content of nitrogen is low, and the content of potassium and phosphorus is good. The maximum field moisture for the 0-30 cm layer is approximately 27%, and for the 30 - 60 cm layer, it is 28%. The groundwater level during the growing season is below 1.5-2 m due to the existing drainage system.

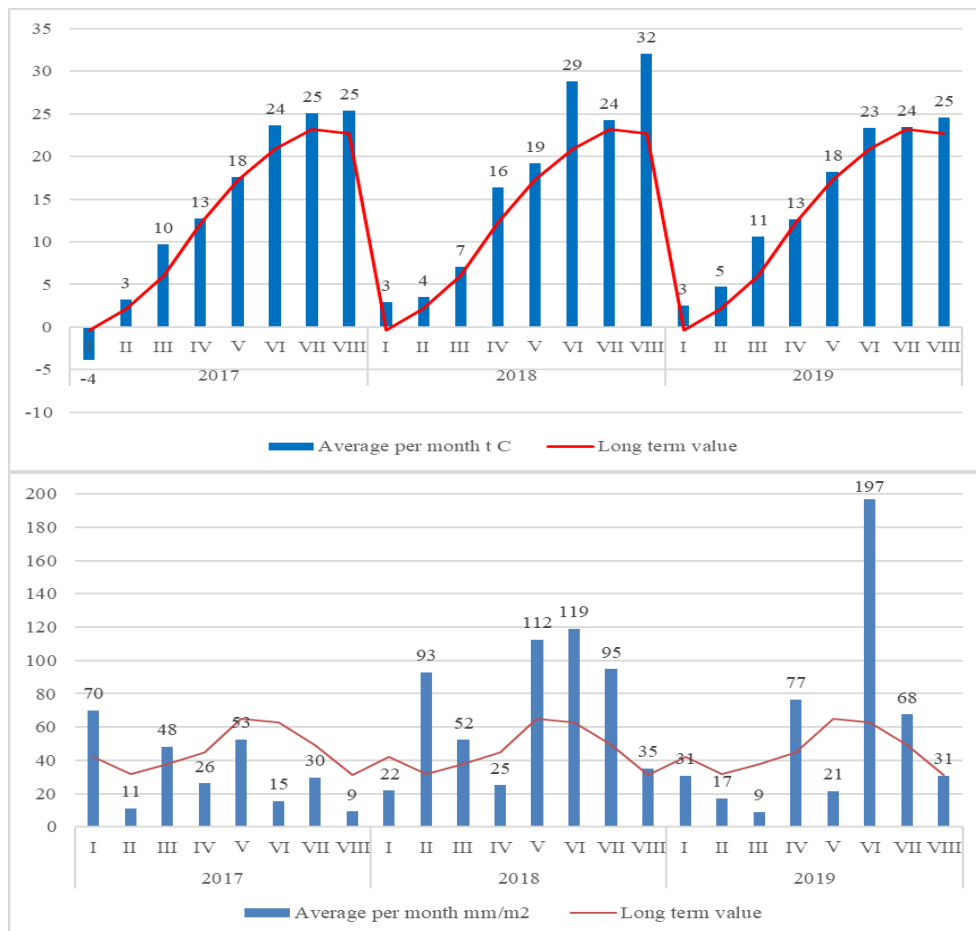
The climate in the region is transitional-continental. The average annual air temperature is 12°C. Winters are mild with frequent warming. Spring arrives relatively early, with an average monthly temperature of 6.5°C. Summers are hot, with the highest temperature in July. Autumns are usually warmer than spring. The annual precipitation in the region is less than the national average (512 mm) and unevenly distributed throughout the year. Droughts are widespread from the beginning of summer until the end of October.

The most critical factors in climatic conditions are temperature and precipitation during the vegetation period (February-August). The levels of these two factors for 2017-2019 are presented in Figure 1, along with their long-term values. The average temperature during the experiment is close to its long-term value for 2017 and 2019, but deviates substantially in 2018 for two months (June and August). In these two months, the temperature has been higher than the long-term average. The average precipitation during the experiment appears to be volatile and deviates substantially from the long-term value. In 2018, rainfall was higher than the long-term average for most months. In June 2019, there was nearly three times as much

rain as in the other months. Therefore, the model should account for these differences over the years.

The experiment used six levels of nitrogen fertiliser: 0, 60, 120, 180, 240, and 300 kg/ ha. It was set on a block method of four repetitions, with an experimental plot size of 20.16 m<sup>2</sup> (7.20 m length × 2.80 m width). The predecessor of sorghum was wheat. Nitrogen (NH<sub>4</sub>NO<sub>3</sub>) was applied pre-sowing, along with background fertilisation of 50 kg/ha triple superphosphate (P<sub>2</sub>O<sub>5</sub>) and 50 kg/ha potassium chloride (K<sub>2</sub>O).

The production function describes the yield obtained from applying different levels of nitrogen fertiliser. The biological optimum is the nitrogen application level that maximises the average yield. The economic optimum is the level of fertiliser application that maximises the profit. The production function has three distinct phases.



**Figure 1.** Temperature and precipitation during the experiment  
*Source: Own presentation*



		Sanitary area							
		N60	N240	N0	N120	N300	N180		
Sanitary area		N180	N120	N300	N240	N60	N0	Sanitary area	
		N240	N300	N180	N60	N0	N120		
		N0	N60	N120	N180	N240	N300		
	Sanitary area								

**Figure 2:** Area and scheme of the field experiment.

*Source: Own presentation*

During the first phase, the return to fertiliser application is increasing. During the second phase, the return to fertiliser application decreases. The economic optimum is reached in this phase. During the third phase, the return to fertiliser application is negative. The biological optimum marks the beginning of this phase.

The demand for nitrogen fertiliser is derived from the different prices of sorghum and fertiliser. This approach is well described in standard Production Economics textbooks and has been employed by Penov (2017), Kirchev and Penov (2019), and Dechev and Penov (2009). The estimation procedure is presented in Table 1. The definitions of the variables are presented in Table 2. To account for the differences in climatic conditions, we use dummy variables for the years 2018 and 2019.

**Table 1:** Calculation procedure for determining the biological and economic optimum

Biological optimum	Economic optimum
Average yield maximisation	Profit maximisation
$\max y = f(x) + D_{2018} + D_{2020}$	$\max \Pi = p f(x) - vx + D_{2018} + D_{2020}$
FOC: $y' = f'(x) = 0$	FOC: $\Pi' = pf'(x) - vx = 0$
SOC: $y'' = f''(x) < 0$ for max	SOC: $\Pi'' = pf''(x) < 0$ for max

Source: Own presentation

**Table 2:** Definition of variables

Variable	Definition	Measure
Average yield	Dependent variable	kg/ha
Nitrogen fertiliser	Independent variable	kg/ha
Nitrogen fertilizer^2	Independent variable	kg/ha
2017	Base category	
D 2018	Dummy variable	1 -if 2018 year
D 2019	Dummy variable	1 -if 2019 year

Source: Own presentation

## RESULTS AND DISCUSSION

The descriptive statistics for the experiment are presented in Table 3. The average yield for the whole period and all fertilisation levels is 5698.2 kg/ha. The lowest yield of 4489 kg/ha was observed when no fertiliser was applied in 2017, and the highest of 7140 kg/ha was observed when 240 kg/ha of nitrogen was used in 2018.

**Table 3:** Descriptive statistics of the experiment

Year	Indicators	Fertiliser rate kg/ha					Average	
		0	60	120	180	240		300
2017	Average yield kg/ha	4 572	4 897	5 378	5 750	5 455	5 355	5 234
	Max	4 690	5 051	5 503	5 820	5 672	5 507	5 820
	Min	4 489	4 791	5 199	5 671	5 311	5 215	4 489
	StdDev	96	124	133	73	155	126	410
	Count	4	4	4	4	4	4	24
2018	Average yield kg/ha	5 020	5 440	6 090	6 810	6 950	6 180	6 082
	Max	5 150	5 610	6 220	7 010	7 140	6 350	7 140
	Min	4 870	5 330	5 910	6 520	6 800	5 900	4 870
	StdDev	115	122	131	210	142	199	716
	Count	4	4	4	4	4	4	24
2019	Average yield kg/ha	4 890	5 163	5 762	6 337	6 583	5 936	5 779
	Max	4 947	5 211	5 811	6 401	6 672	6 103	6 672
	Min	4 802	5 098	5 693	6 257	6 500	5 840	4 802
	StdDev	63	48	50	60	70	118	615
	Count	4	4	4	4	4	4	24
2017-2019	Average yield kg/ha	4 827	5 167	5 743	6 299	6 329	5 824	5 698
	Max	5 150	5 610	6 220	7 010	7 140	6 350	7 140
	Min	4 489	4 791	5 199	5 671	5 311	5 215	4 489
	StdDev	214	250	320	469	675	387	684
	Count	12	12	12	12	12	12	72

Source: Own presentation

The production function was estimated using EXCEL and is shown in Table 4. All coefficients are statistically significant. In addition, R-squared is 0.86 and F = 106.24, which means that the model reasonably reflects the relationship between fertiliser application and yield. Due to the climatic conditions, the average yield in 2018 was 847.5 kg/ha, higher than in 2017. Similarly, the average yield in 2019 was 544.4 kg/ha higher than in 2017.

The initial optimisation was done with the price of sorghum at 0.30 BGN /kg and that of one of the nitrogen fertilisers at 1.13 BGN/kg. The results are presented in Table 5. The biological optimum is reached using 217.6 kg/ha nitrogen fertiliser, while the economic optimum is reached by fertilising with 158 kg/ha.

**Table 4:** The model for the relationship between average yield and nitrogen fertilisation in sorghum

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	4208.039	80.595	52.212	0.000
Fertiliser	13.835	1.066	12.983	0.000
Fertilizer^2	-0.0318	0.003	-9.324	0.000
D-2018	847.458	75.000	11.299	0.000
D-2019	544.422	75.000	7.259	0.000

R Square=0.86; F=106.24.

Source: Own presentation

**Table 5.** Parameters of the biological and economic optimum

Indicators	Measure	Biological optimum			Economic optimum		
		max y = 4208.039+13.835x - 0.318x^2+847.458D2018+ 544.422D2020			max Π =0.3 (4208.039+ 13.835x -0.318 x^2)- 1.131x+847.458D2018+ 544.422D202		
		2017	2018	2019	2017	2018	2019
<b>REVENUE</b>	<b>levs/ha</b>	<b>1714</b>	<b>1968</b>	<b>1877</b>	<b>1680</b>	<b>1935</b>	<b>1844</b>
Average yield	kg/ha	5713	6561	6258	5602	6449	6146
Price of Sorghum	levs/kg	0.30			0.30		
<b>COST</b>	<b>levs/ha</b>	<b>246</b>	<b>246</b>	<b>246</b>	<b>179</b>	<b>202</b>	<b>179</b>
Fertiliser rate	kg/ha	217.6			158		
Price of fertiliser	levs/kg	1.13			1.13		
<b>PROFIT</b>	<b>levs/ha</b>	<b>1468</b>	<b>1722</b>	<b>1631</b>	<b>1501</b>	<b>1732</b>	<b>1665</b>

1 BGN Lev=0.51 Euro

Source: Own presentation

Determining the "right prices" of fertilisers and sorghum is challenging. Fertiliser and output prices in a market economy are constantly changing. These changes do not affect the biological optimum, but they do impact the economic optimum. The prices depend on many factors. The most important is how demand and supply interact in the markets. Second is whether producers operate in the wholesale or retail market. The fertiliser demand curve is derived from the production function.

$$\text{The demand for fertiliser}(x) = 217.592 - 15.727 \frac{\text{Priice of fertilizer}}{\text{Price of sorghum}}$$

We provide a more extensive range of price combinations to answer this challenge in Table 6. The numbers in the table indicate the nitrogen application level for different sorghum and fertiliser prices. The empty cells are those where the numbers are negative. In our framework, negative numbers do not have economic meaning.

**Table 6:** Economic optimum nitrogen application rate (kg/ha) at different prices of sorghum and fertiliser

	Price of sorghum -p leva/kg.												
		0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.30	0.25	0.20	0.15	0.10
Price of ammonium nitrate -V leva/kg	0.70	201	199	198	196	193	190	186	181	174	163	144	108
	0.80	198	197	195	192	190	186	182	176	167	155	134	92
	0.90	196	194	192	189	186	182	177	170	161	147	123	76
	1.00	193	191	189	186	183	178	173	165	155	139	113	60
	1.13	190	188	185	182	178	173	167	<b>158</b>	146	129	99	40
	1.20	189	186	183	180	176	170	164	155	142	123	92	29
	1.30	186	184	180	177	172	166	159	149	136	115	81	13
	1.40	184	181	178	174	169	163	155	144	130	108	71	
	1.50	181	178	175	170	165	159	150	139	123	100	60	
	1.60	179	176	172	167	162	155	146	134	117	92	50	
	1.70	176	173	169	164	158	151	141	128	111	84	39	
	1.80	174	170	166	161	155	147	137	123	104	76	29	
	1.90	172	168	163	158	151	143	132	118	98	68	18	
	2.00	169	165	160	155	148	139	128	113	92	60	8	
	2.10	167	163	158	152	144	135	123	108	85	52		
	2.20	164	160	155	148	141	131	119	102	79	45		
	2.30	162	157	152	145	137	127	114	97	73	37		
	2.40	160	155	149	142	134	123	110	92	67	29		
	2.50	157	152	146	139	130	119	105	87	60	21		
	2.60	155	149	143	136	127	115	101	81	54	13		
2.70	152	147	140	133	123	111	96	76	48	5			
2.80	150	144	138	130	120	108	92	71	41				
2.90	147	142	135	126	116	104	87	66	35				
3.00	145	139	132	123	113	100	83	60	29				
3.10	143	136	129	120	109	96	78	55	23				
3.20	140	134	126	117	106	92	74	50	16				
3.30	138	131	123	114	102	88	69	45	10				
3.40	135	128	120	111	99	84	65	39	4				
3.50	133	126	118	108	95	80	60	34					
3.60	130	123	115	104	92	76	56	29					
3.70	128	121	112	101	88	72	51	24					
3.80	126	118	109	98	85	68	47	18					
3.90	123	115	106	95	81	64	42	13					
4.00	121	113	103	92	78	60	38	8					

Source: Own presentation

We also assume that the first phase of the production process occurs at nitrogen application rates between 0 and 60 kg/ha. Each additional kilogram of fertiliser generates more production during this phase than the previous one. Therefore, the producers have an incentive to increase the use of fertilisers. However, we left the numbers smaller than 60 kg/ha in the table because other assumptions are also possible. The second phase of the production process involves applying 60 to 217.6 kg/ha of nitrogen fertiliser. During this phase, each additional kilogram of fertiliser generates less production than the previous one, but it is still positive. Therefore, the optimum fertiliser application rate depends on the prices of sorghum and fertiliser. The third phase of the production process begins with a nitrogen fertiliser application rate exceeding 217.6 kg/ha. During this phase, each additional kilogram of fertiliser suppresses plant development, and production declines. Therefore, fertiliser application rates above this value should be avoided.

### **CONCLUSIONS**

Several conclusions could be derived from this study. First, people often assume that the optimum fertiliser rate application is something fixed once and for all. This assumption is rooted in the understanding that if we do not provide sufficient nutrients to the plants, the yield will be low and the revenue will also be low. This reasoning has a serious flaw because it does not account for production costs. If less fertiliser is used, not only will the revenue be low, but also the production costs. If we operate at the economic optimum, the profit would be higher. It is also essential to understand that the absolute price level does not matter for the economic optimum. What is important is the relative price level (the price of fertiliser divided by the price of output).

Second, the estimated production function is quadratic, and it is not possible to clearly distinguish between the first and second phases of the production process. To do this, we need to estimate a higher degree polynomial, such as a cubic function. However, in this case, we need more experimental data for the first phase. In addition, one needs better mathematical skills to optimise the production function. Therefore, estimating a quadratic production function and defining an interval where the predictions are valid would be more convenient. We assume that this interval is between 60 and 217.6 kg/ha nitrogen fertilisation rate (the second phase).

Third, the economic optimum depends on the prices of the final product and the nitrogen fertiliser. These prices depend on supply and demand, as well as whether producers operate in wholesale or retail markets. Natural conditions do not affect the optimal level of fertiliser application; instead, they affect the yield level. If the natural conditions are favourable, we will receive higher yields with a given fertilisation rate than when the natural conditions are unfavourable. Of course, if the plants are negatively affected by a frost, it would be advisable to provide additional nitrogen to help them recover. However, this is an action to manage the risk.

Fourth, the model could be improved if, instead of using dummy variables to account for the differences in natural conditions, we design variables and estimate the coefficients of the effects of temperature and precipitation on the average yield. However, this will require data for a more extended period.

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