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A Two-Dimensional Nitrogen Fertilization Model for Irrigated Crops in Turkey

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Abstract

The main aim of this scientific work was to develop a theoretical model for calculation of nitrogen (N) fertilization of crops. The model is based on the N fertilization plans which had been prepared for the requirements of the Technical Assistance Project entitled "Implementation of Nitrates Directive in Turkey". It was compiled and tested in irrigated corn crop. This has the possibility to calculate the amount of nitrogen which is required in a wide range of mean annual rainfall. It was tested for areas which receive mean annual rainfall 500-1500 mm and nitrates content in irrigation waters was 10 mg/L. Crop requirements in water are not covered by rainfall in the growing period of crops, due to uneven annual distribution during growing period and additional water is needed by mean of irrigation. Soil texture affects strongly the required quantity of soil nutrients and irrigation water and for this reason, the following textural soil classes were used: light, moderate, heavy texture and soils with organic matter 6% and clay 30%.This model is the basis for the development of auser friendly graphic environment which was built in Python 3.5. This tool can calculate the required Nitrogen for all possible triplets(soil class, annual rainfall, nitrogen from irrigation water) required for every annual crop. The user has simply to choose the crop type, the soil class, then to type the annual rainfall and the N content of irrigation water. The model uses as inputs three variables, namely the qualitative soil class and two quantitative annual rainfall (in mm/y) and nitrates inputs from irrigation (content in mg/L) and returns as an output the required Nitrogen in kg/da (1 da=1000 m^2) for the described instance. Results have indicated that the requirements of nitrogen fertilization for corn varied among soil classes although irrigation water had the same nitrates concentration. This can be attributed mainly to different potential of nitrates leaching and N mineralization.

Keywords: nitrogen; nitrates; fertilization; irrigation; soil; crop.

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1. Introduction

It has been documented that irrational or excessive use of N fertilizer can lead to nitrate pollution of ground or surface water and affects crops quality. A considerable decreasing of applied nitrogen can be achieved, due to increased nitrogen use efficiency. Various models of different complexity regarding nitrogen fertilizer recommendations have been developed in last decades. However, their practical application has been limited due to the high site specific data requirements, which are commonly not available [1]. Computer models capable of simulating the effects of weather, agronomic practices, soil properties and cultivar characteristics on the N dynamics of agricultural systems can contribute significantly to our understanding of crop responses and fertilizer behavior [2].

The main aim of this work is the creation of an automated nitrogen fertilization model for irrigated crops, in different climatic zones of Turkey. Its application is expected to decrease the pollution risk of waters in the nitrates vulnerable zones of Turkey and minimize the undesirable phenomenon of eutrophication. Water needs for irrigation vary greatly and requirements depend mainly on the crop species, soil type, and the specific climatic conditions in each region of Turkey. Nitrate is always present in the soil solution and its movement depends on the soil moisture regime. In addition, nitrates concentration in irrigation waters play a significant role for the suggested quantity of applied nitrogenous fertilizers. Model approaches are inherently more consistent regarding calculation schemes, but without validation, have a risk of not accounting for regional differences in response of crop removal and water quality to nitrogen fertilization [3]. Rational fertilization that increases use efficiency of soil nutrients, means that the application of fertilizers is performed under the proper conditions required to prevent runoff during plant growth stages [4]. While the yield goal recommendations were based on a mass balance approach, several studies have shown a low correlation of corn yields and optimal N rates [5,6].

Nitrogen fertilization plans were created for most crops of Turkey [7], to mitigate nitrates pollution of waters in Turkey, originating from agricultural sources. These plans were compiled for the main crops of Turkey and rainfall regimes with mean annual precipitation 500, 1.000, 1.500 and 2.000 mm/y [7].Taking into consideration the availability of data, this attempt was focused on rational nitrogen fertilization aiming to decreasing N fertilization, under various soil conditions, inputs from irrigation with different nitrates content and input from rainfall. Also, the suggested amount of applied nitrogen for corn was based on the required N by the crop, N inputs to the soil from other sources without fertilization, and N losses (emissions, leaching). In order to calculate the required nitrogen per each crop, a Microsoft Office Excel spread sheet had been compiled.

Based on data regarding nitrogen fertilization plans for each Nitrates Vulnerable Zone in Turkey, it was necessary to take into consideration the rainfall range because affects significantly irrigation, hence has an impact on the required quantity of N fertilization. This model had to be updated taking into account any mean annual rainfall between 500 and 1500 mm/y.

2. Material and Methods

2.1 Nitrogen balance sheet

A comprehensive set of factors was suggested to formulate a nitrogen balance sheet. Nitrate concentration in the irrigation water, nitrogen uptake by plants for optimum yield, nitrogen losses (leaching, emissions), residual nitrogen and the amount of nitrogen mineralization had been taken into consideration, in order to suggest the required N fertilization in the main crops of Turkey [7].

To create a rational nitrogen fertilization plan for the main crops of Turkey, the main components for N fertilization plans are included in the following formula:

$$N_f = N_{req} - [(N_m + N_{in} + N_r + N_{ir}) - (N_l + N_d + N_v + N_{runoff})]$$

where: N_f is the quantity of recommended N fertilizer

N_{req} is the total N required to produce a crop of a given yield

N_m is N released from crop residues and mineralized from SOM

N_{in} is the residual plant available inorganic N

N_r is the N input from rainfall

N_l, N_d, and N_v are N losses through leaching, denitrification, and volatilization

N_{runoff} is the quantity of N lost by runoff in the sloping areas

With regard to texture, soils were classified into main groups: coarse, medium and heavy. An additional soil class was suggested in which a threshold value 6% of soil organic matter was proposed for medium soil texture (Table 1). This fertilization model includes additional components and factors and covers rainfall regimes with different annual precipitation.

Table 1: Textural soil classes used for N fertilization

Soil class	soil texture	clay% used for calculation of N leaching	SOM %
I	Light texture	15	1%
II	Moderate texture	30	2%
III	Heavy texture	40	3%
IV	Org. Matter 6%	30	6%

For each soil class, a factor concerning decreased biomass production was also used, which is -30%, -20%, - 10% and -10% for the respective Soil Classes I, II, III and IV. Pedotransfer functions were used for other N inputs and losses such as N input from rainfall, or N_2O emissions, denitrification and ammonia volatilization. In the absence of data concerning net nitrogen mineralisation rates in various soil types, results from studies under field conditions must be taken into account.

The values for yield, total requirements for nitrogen and water provide an estimation and the respective values are 1200 kg/kg, 24 kg N/da and 780 mm/y for the total water requirements (Soils, Fertilizers and Water Resources Research Institute, Ankara).

Nitrogen inputs from rainfall per year are likely to be in the order of 3–5 kg N/ha in drier environments [8] and much higher in wet and polluted environments. A value 0.3 kg N da/y was used concerning the amount of nitrogen from the rainfall regime which exceeds 500 mm/y. Furthermore, value used for areas with rainfall 1000 mm was 0.8 kg N da/y and for humid areas with rainfall 1500 mm the respective value was 1.0 kg N da/y.

The use of synthetic and organic fertilizers enriches nitrogen to soils and increases natural emissions of N_2O to the atmosphere. The emission coefficient of 0.0117 tons N/ton N-applied represents the percent of nitrogen applied as fertilizer that is released into the atmosphere as nitrous oxide. This emission coefficient was obtained from the Agricultural Research Service of the U.S. Department of Agriculture, and has been estimated that 1.84 kg N_2O or 1.17 kg of N was emitted per 100 kg of nitrogen applied as fertilizer. If we take into consideration the average N/da suggested for the main crops of Turkey, calculations indicated that the mean amount of potential emitted N is 0.195 kg.

Denitrification values are needed to calculate N mass balances because of high N inputs and agricultural soils are considered critical pools [9]. In soils with good drainage, the median denitrification values were 29 kg N ha^{-1} when based on mass balance and 11 kg N ha^{-1} when based on core and chamber techniques. In this fertilization plan an average value 16.8 kg N ha^{-1} (equivalent to 1.68 kg N da^{-1}) is suggested.

This is the average value derived from 10 years experiments [10] in arable areas and seems to be at normal level. For arable land in countries with calcareous soils (e.g. Greece, Spain e.t.c.) a loss of 0.16 kg NH_3 per kg applied N has been recorded [10]. A coefficient 10% of the required N fertilization is used in the suggested fertilization plans.

Nitrates leaching is a significant loss mechanism which plays a dominant role in the pollution of waters, especially of shallow aquifers. Research on leaching of the model below is based on international literature which was reviewed. De Willigen [11] developed a regression model to calculate the amount of leached N, and is valid for a wide range of soils and climatic conditions.

The equation was edited slightly for perennial crops by multiplying the amount of N in soil organic matter by 0.5. This prevented overestimation of N leaching, because perennials can take up N throughout the year. The De Willigen 2000 model is based on an extensive literature review [11].

$$N_{leaching}\ (kg/ha) = 21.37 + (P/C \times L) \times (0.0037 \times N_{f,}r,m + 0.0000601 \times O_c - 0.00362 \times N_u)$$

Table 2: Factors which included to calculate the $N_{leaching}$

P =	annual precipitation (mm/year);
C =	clay content (percent);
L =	rooting depth (m);
$N_{f,r,m}$=	applied inorganic, residual and mineralized fertilizer N;
O_c=	organic carbon content of the soil (percent);
N_u=	N uptake by the crop (kg/ha/year).

In the absence of experimental results concerning the N mineralization dynamics, the following values were used in the fertilization plans (Table 3) which are almost similar with values used in the proposed fertilization plans for Greece [12].

Table 3: Nitrogen mineralization and residual N in various soil classes

Soil class	SOM %	SOC %	Nmin (kg/da)	Residual N (kg/da)
ClassI	1	0.58	1.0	2.0
Class II	2	1.16	3.0	3.0
Class III	3	1.74	4.0	4.0
Class IV	6	3.49	6.0	6.0

Values regarding residual nitrogen were used for the arable soils of Turkey (Table 3) and these are mainly based on literature and results from Mediterranean countries [13].

Residual soil nitrogen (RSN) is the amount of inorganic nitrogen that remains in the soil at the end of the growing season after crops have been harvested. Five years data were used to calculate the residual N and average values varied between 11.2 to 11,7 kg N/ha/y [14]. Residual nitrogen in arable land was higher and ranged between 30 and 60 kg N/ha/y.

The values used for residual nitrogen in the arable soils of Turkey are mainly based in international literature. The effective root depth of irrigated corn is 100 cm [15], and this depth was used to calculate the amount of nitrates leaching below the root zone. Table 4 illustrates the coefficients of nitrates leaching for each selected soil class (kg N/ha) which have been calculated from the pedotransfer function. Pedotranfer functions were also used for other N inputs and losses of minor importance such as N input from rainfall, or N_2O emissions, denitrification and ammonia volatilization.

Table 4: Calculated values of nitrates leaching per soil class of crops (kg N/ha)

Rainfall mm/year	Class I clay 15%	Class II clay 30%	Class III clay 40%	Class IV SOM 6% +clay 30%
CORN				
500	25.8	25.4	25.3	29.1
1000	30.2	29.5	29.3	36.9
1500	34.7	33.6	33.3	44.7

The above components for N fertilization were used to calculate the recommended nitrogen for corn. The results for recommended amount of nitrogen in the proposed soil class I for corn in the rainfall regime 500 mm/year, with 10 mg/L concentration of nitrates in irrigation waters are presented in Table 6. Furthermore, the recommended nitrogen for fertilization in the rainfall regimes 1.000 and 1.500 mm/y were calculated 19.6 kg N/da and 20.1 kg N/da, respectively.

2.2 The development of the calculator - Definition of the model

To calculate the recommended nitrogen (N_F) for each annual rainfall between 500 and 1.500 mm/y, another approach was used. To calculate the $N_{F,}$ from the above parameters which were used for the mass balance N model, the values of three of them need to be redefined, since the other six depend only to the Soil class and to crop characteristics. So, do not need any change for possible alterations of rainfall and nitrogen content of irrigation water. The three parameters that need to be estimated are N_r, N_{ir} and N_l. These parameters will be described as functions of rainfall (denoted as R) and Nitrogen content of irrigation water (donated as N_{cont}). The procedure for the definition of these functions for Soil Class I, is described clearly in the following paragraph. It is well known that water and nitrates can be transported through the soil profile. Understanding this process, it is important for efficient irrigation and nutrient management, and farming practices should minimize nitrate leaching to groundwater.

The main idea to create a 2-dimensional nitrogen fertilization model for irrigated crops was to develop a technique to calculate the required nitrogen for every value of annual rainfall (mm/y) taking into consideration a standard NO_3 concentration of irrigation water (mg/L). During irrigation, a significant amount of nitrates inflows to the soil and denoted as N_{ir}. This parameter depends on the amount of applied water and nitrogen concentration of irrigation water. Since the mass balance method requires vast typing – demanding effort, it was decided to develop a Graphic User Interface – calculating tool, by using Python [16], version 3.5.This 2-dimensional nıtrogen fertilization model contains a number of factors which can easily be adapted in the future, because certain coefficients may be substituted by other which may be derived from field experiments under different climatic regions.

Results derived from four soil textural classes (Table 1) and an indicative example of nitrates content in irrigation waters 10 mg/L is included. The targeted yield for corn was 1200 kg/da, and the required nitrogen to obtain this yield was 24 kg/da. The relationship between N_l and rainfall is a function with domain which has the possibility to set any value of annual rainfall (in mm/y) and the product of the function will be the nitrogen losses through leaching, expressed in kg/da. The function that should be defined was the $N_l(R)$ where R is the rainfall. The leaching values corresponding for R= 500, 1000 and 1500 mm/y are 2.5, 3.0 and 3.5 kg N/da, respectively. It can be observed in Figure 1, these three points are linear and the straight line that connects them is

$$y = 0.001 \cdot x + 2$$

As a result, $N_l(R) = 0.001 \cdot R + 2$, for $R \in [500{,}1500]$

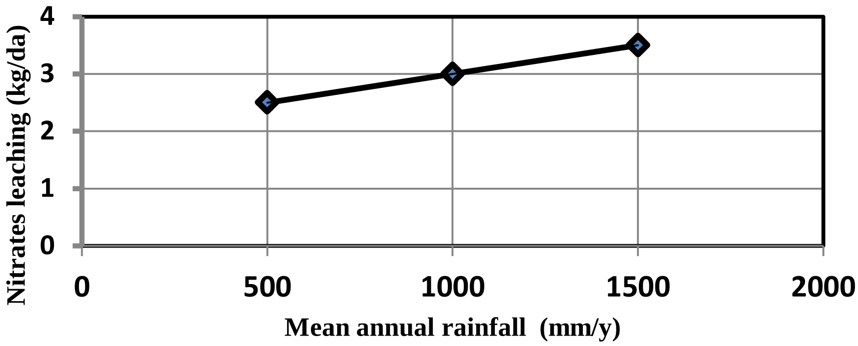

Figure 1: Nitrates leaching within a rainfall range of 500 and 1500 mm/y

According to the relationship between rainfall and nitrogen input from rainfall (Figure 2), the three points do not belong to the same straight line for 500, 1000 and 1500 mm/y because the N inputs from rainfall for corn and soil class I varied and the respective used values were 0.5, 0.8 and 1.0kg N/da/y [17].

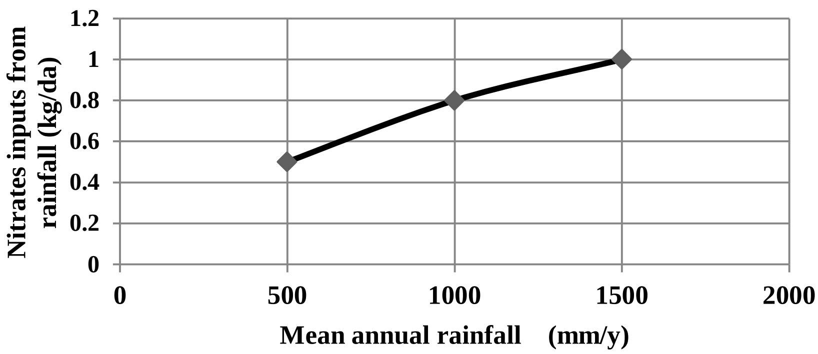

Figure 2: Estimation of nitrate inputs within rainfall range of 500 and 1500 mm/y

In this case, a polynomial curve of degree three was interfered that passes from all three lines and the calculated equation is

$$y = \frac{4}{3} \cdot 10^{-10} \cdot x^3 - 6 \cdot 10^{-7} \cdot x^2 + 1.27 \cdot 10^{-3} \cdot x$$

So, the function will be

$$N_r(R) = \frac{4}{3} \cdot 10^{-10} \cdot R^3 - 6 \cdot 10^{-7} \cdot R^2 + 1.27 \cdot 10^{-3} \cdot R$$

As a final step, the calculation of the $N_{ir}(R, N_{cont})$ is needed, where N_{cont} is the Nitrogen content of irrigation water. This function will give as an output the kg/da of nitrogen input from irrigation.

The first step for the procedure will be the estimation of the amount of water needed to be used for irrigation for the corresponding rainfall. For rainfall 500, 1000 and 1500 the corresponding amount of water needed is 500, 300 and 200 tons of water. So, an auxiliary function that estimates the water needed according to the annual rainfall is introduced and it is

$$Irrigation(R) = 6944.04212786 \times \ln(R) - 2869.6057 \times \ln(R)^2 + 402.690349542 \times \ln(R)^3 - 19.0926739868 \times \ln(R)^4$$

The final step will be the calculation of the linear relation between the Nitrogen input from irrigation, the amount of irrigation water and the N_{cont}:

$$N_{ir}(\mathrm{R}, N_{cont}) = -0.000226 \times Irrigation(R) \times N_{cont}$$

At this point, the estimation of Nitrogen required can be calculated as a sum of the known and the calculated parameters as follows:

$$N_f(\mathrm{R}, N_{cont}) = N_{req} + \left[\left(N_m + N_{in} + N_r(R) + N_{ir}(R, N_{cont})\right) - \left(N_l(R) + N_d + N_v + N_{runoff}\right)\right]$$

In order to fully describe the model for corn, the procedure for the other three soil classes must be completed again. This set of four equations is the model needed. This tool contains all quadruples of models demanded for every crop in a user friendly graphic environment. The user will only be asked to choose the crops type, the soil class and then to type the annual rainfall and the Nitrogen content of irrigation water. Based on this model, a Python program was implemented and results are shown in the following section.

3. Results and discussion

In order to calculate the required nitrogen per each crop, a Microsoft Office Excel spread sheet was compiled [7], which contains a number of factors (Table 6) and most of them can be adjusted if data from field experimentation are available. However, in the absence of certain coefficients, values from pedotransfer functions were used and/or from respective values proposed by other countries [9,11]. The value used for residual N in the root before sowing date was 2.0 kg /da. This parameter is very sensitive and varies strongly among years, depending by climatic conditions and crop history. For instance, research conducted in Canada indicated great variability for the period 1981-2007 and values of residual nitrogen varied between 9.3 and 66.9 kg N/ha [18] (18). However, incorporation of spatial and temporal variability in nitrogen recommendations are required to increase fertilizer use efficiency [19]. For this reason soils were grouped into four different classes according to texture and organic carbon. Other Fertilizer-recommendation systems based on expected yields often advise farmers to make their N applications with the expectation of a good year [20]. This is done in order to avoid limiting yields, since the N requirement in a favorable growing season is larger than under poor conditions [21].

Several fertilizer-recommendation systems based on the soil mineral-N content (nitrate and ammonium), available at growth stages of a crop. In climates with low rainfall, it may be sufficient to consider only the soil mineral N content at planting date [22, 23]. However, in humid and sub-humid climates, large N-losses can be expected via leaching and denitrification during early growth if the N is applied in one dose at planting. Most existing N fertilizer-recommendation programs use one or a combination of the following indicators: expected crop-yield, soil-test information (SOM, total soil N, mineral soil N, mineralization potential, soil nitrate content, etc.), and plant analysis data i.e. total N, nitrate in plants [2]. Classical recommendations are based on results from field experiments established at several sites oriented to quantify crop response to N fertilizer.

In this investigation, N fertilization plans were compiled and the targeted yield for corn was proposed 1200 kg/kg.

The quantity of N requirements provided by the Soils, Fertilizers and Water Resources Research Institute of Ankara was 24.0 kg/da. For soil class I, a factor concerning decreased biomass production was also -30% (Table 5). Tables were prepared in which the quantity of N from irrigation water has been calculated according to nitrates content of irrigation water. The applied quantity of water for irrigation in this example was 500 tn/da.

Table 5: Example for recommended N fertilization of corn in rainfall regime 500 mm/year

CORN	Soil Class I
Required nitrogen (kg/da)	24.00
Soil texture(decreased biomass production)	(-30%)
Decreased fertilization (kg/da)	-7.20
Nmineralization (SOM) (N kg/da)	-1.00
Residual N in the root before sowing date (kg/da)	-2.00
N input from irrigation (NO_3 content 10 mg/L)	
Nitrogen from irrigation with 500 (tn/da) (N g/m^3)	-1.13
Leaching R=500 mm/y (kg N/da)	2.50
N input from rainfall (kg/y/da)	-0.50
N_2O emissions kg/da	0.195
N_2 emission from denitrification (kg/da)	1.68
Ammonia volatiliz. (10% of req. Nitrogen) (kg/da)	2.40
N recommended (slope <6%) (kg N/da)	18.95

Taking into account the N inputs and outputs, the results has shown that the recommended amount of nitrogen in the proposed soil class for corn was 18.9 kg N/da. Table 6 shows the calculated nitrogen fertilization of corn which is required for each soil class with same nitrates content 10mg/L in irrigation water. Regarding N recommended (kg N/da) which was calculated with Nitrogen balance sheet, (Table 6), similar value was recorded for fertilization plan for corn after calculation with results derived from the two dimensional model (Table 6). It should be stressed that the error is less than 1% for the respective values within a rainfall range between 500 and 1500 mm/y and nitrates content 10 mg/L. In contrast to Nitrogen balance sheet, this two dimensional model can calculate the N which is suggested for rational fertilization under different rainfall regimes for any rainfall annual value (Figure 3). In other words, it is a simple, more precise, easy to be used and the suggested N values are calculated automatically. Furthermore, results can be more accurate depending on reliable experimental inputs at farm scale level.

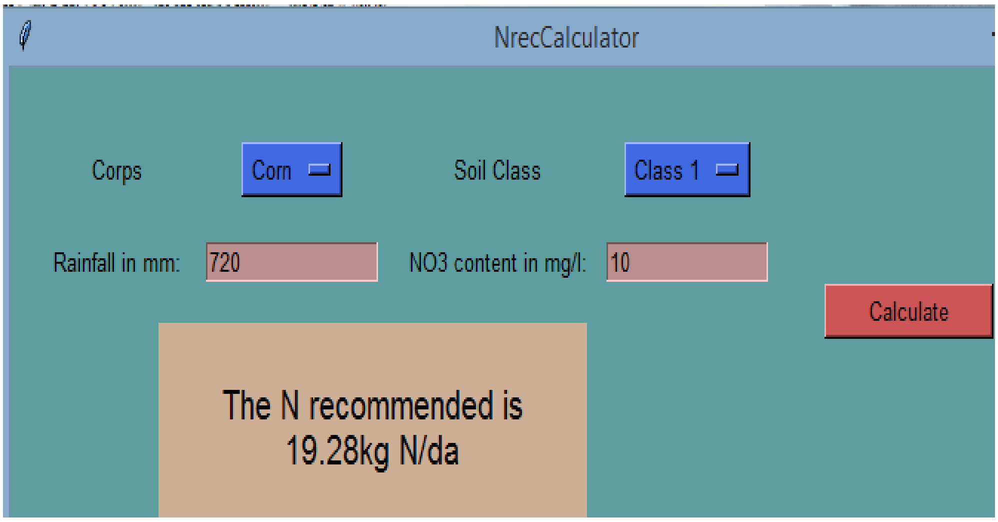

Figure 3: Example of suggested N for fertilization of corn with application of the two dimensional model

Table 6: Results of suggested nitrogen fertilization of corn in various soil classes and nitrates content 10mg/L in irrigation water (soil slope <6%)

Soil class 1

Rainfall in mm	500	600	700	800	900	1000	1100	1200	1300	1400	1500
required irrigation (mm)	500	430	390	350	330	300	280	260	240	220	200
Algorithm's results (2-dimensional model)	18,95	19,12	19,26	19,38	19,49	19,59	19,7	19,8	19,91	20,01	20,12
N suggestion under three different rainfall regimes	18,95	N/A	N/A	N/A	N/A	19,60	N/A	N/A	N/A	N/A	20,10
Difference	0,00	N/A	N/A	N/A	N/A	-0,01	N/A	N/A	N/A	N/A	0,02

Soil class 2

Rainfall in mm	500	600	700	800	900	1000	1100	1200	1300	1400	1500
required irrigation depending on rainfall	500	430	390	350	330	300	280	260	240	220	200
Algorithm's results (2-dimensional model)	18,15	18,31	18,43	18,54	18,64	18,73	18,83	18,92	19,02	19,12	19,22
N suggestion under three different rainfall regimes	18,15	N/A	N/A	N/A	N/A	18,70	N/A	N/A	N/A	N/A	19,22
Difference	0,00	N/A	N/A	N/A	N/A	0,03	N/A	N/A	N/A	N/A	0,00

Soil class 3

Rainfall in mm	500	600	700	800	900	1000	1100	1200	1300	1400	1500
required irrigation depending on rainfall	500	430	390	350	330	300	280	260	240	220	200
Algorithm's results (2-dimensional model)	17,45	17,62	17,76	17,88	17,99	18,09	18,2	18,3	18,41	18,51	18,62
N suggestion under three different rainfall regimes	17,45	N/A	N/A	N/A	N/A	18,10	N/A	N/A	N/A	N/A	18,62
Difference	0,00	N/A	N/A	N/A	N/A	-0,01	N/A	N/A	N/A	N/A	0,00

Soil class 4

Rainfall in mm	500	600	700	800	900	1000	1100	1200	1300	1400	1500
required irrigation depending on rainfall	500	430	390	350	330	300	280	260	240	220	200
Algorithm's results (2-dimensional model)	14,07	14,58	15,01	15,37	15,67	15,92	16,12	16,27	16,38	16,43	16,44
N suggestion under three different rainfall regimes	14,05	N/A	N/A	N/A	N/A	15,90	N/A	N/A	N/A	N/A	16,43
Difference	0,02	N/A	N/A	N/A	N/A	0,02	N/A	N/A	N/A	N/A	0,01

It should be emphasized that this model, has taken into account the approach for sustainable plant nutrition, and factors which may have a negative impact to nitrates pollution of waters. A socially acceptable fertilization process must be based on basic and logical rules in order to maintain and sustain soil fertility and enhance crop productivity in an ecologically compatible, and economically viable way.

4. Conclusions

A Graphic User Interface tool was compiled in Python programming language, version 3.5. This is an applicable model, and results strongly depend on availability and reliability of data. An advantage is that calculates the recommended amount of Nitrogen in kg/da, for every rainfall range, any N content in irrigation waters, and can be used for annual irrigated crops.The suggested model can be easily used for all irrigated crops, climatic conditions, soil slopes (after proper adjustments), N inputs and outputs into the soil system. This model showed that required N fertilization for a targeted yield, can be calculated as a result of rainfall and irrigation for crops growing at various soil classes. This model is applicable and easy to be used because requires only the actual values of the following factors: crop, soil class, rainfall and nitrogen content in irrigation waters.

For more precise fertilization plans, soil textural classes can be increased by using detailed soil maps (1:20.000) although for practical reasons soil units can be grouped. This is an open model and can be adapted according to site specific conditions. Moreover, substantial changes can be made in cases when results or coefficients from field experimentation are available (N mineralization, N leaching, e.t.c.). Also, can be adapted properly for cultivated soils in hilly areas, or rainfed crops in areas with water scarcity.

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