FertiliCalc: a decision support system for fertilizer management

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Published **in Int. J. Plant Production, 2020**

Highlights

- A stand-alone program to calculate the N, P and K requirements is presented
- The tool also determines the most cost-effective combination of fertilizers
- This decision-making tool is interesting for farmers, students and other users
- Its robustness was successfully tested against real data from field experiments

Abstract

Rational fertilizer management is crucial in the efficient use of resources that are basically non-renewable and that can have a great environmental impact when used without scientific basis. The availability of scientifically sound decision-making tools for rational fertilization is scarce. We have developed a Windows program to calculate the required seasonal N, P and K rates, and the most cost-effective combination of commercial fertilizers. The tool also provides estimates of the Ca, Mg and S balances in the field resulting from the fertilizer program chosen. Novel aspects of the calculations include the development of stochastic flexible fertilizer programs for N and the calculation of acidification and N losses. Regarding P and K, estimations are provided on the grounds of threshold values of usual availability indexes, something frequently unknown by final users. Also, it allows the users to determine the best complex fertilizer for pre-plant applications to avoid blending of simple fertilizers at the farm, a task usually complex for farmers. The application may be useful both to the fertilizer supply and demand sides. In addition, it may be used for teaching as it helps understanding the rationale behind this management practice.

Keywords: decision-making; fertilization; nitrogen; nutrient requirement; phosphorus; potassium

1. Introduction

Fertilizer management is critical for efficient crop production. For instance, N is assumed to be the second limiting factor in agriculture (Connor et al., 2011), and P is deemed the second nutrient after N limiting ecosystems productivity (Delgado and Scalenghe, 2008). N, P, and K are considered non-renewable resources; this is because N fertilizers production relies on high energy consumption, while that of P and K on finite mineral reserves (Schröder et al., 2016). In fact, fertilizers are the main energy consumers in many agroecosystems (Grassini and Cassman, 2012), thus contributing significantly to agricultural CO_2 emissions, and are a major source for pollution in both surface (N, P) and groundwater (N) when inadequately used. Traditionally, little attention has been paid to the estimation of accurate fertilizer rates, and the trend was always to over-fertilize crops in developed countries. Only the environmental concerns ascribed to N and P moved policy toward stricter control of fertilization since the 1970's (Delgado and Scalenghe, 2008). Now, the increasing trend in fertilizer prices is an additional driving-force for more accurate estimations. Therefore, decision-making tools for improving fertilizer management may have a huge potential for enhancing the sustainability and productivity of crops, while allowing farmers to comply with ever stricter regulations. Solutions for sustainable fertilizer management should take into account that farmers do not always have the technical skills for estimating accurately fertilization rates. The complex technical framework for current fertilization, its integration with other management practices, and specific needs of final users were highlighted by Peragón et al. (2017) as crucial issues in the development of decision-making tools targeted at fertilizer management.

Specific software has been developed for fertilizer management. For instance, the International Plant Nutrition Institute developed Nutrient Expert (Xu et al., 2016) which has different versions for several crops (maize, rice, wheat, and soybean) and regions of the world. On the other hand, available commercial software is rather expensive and does not always provide enough information on the basic data and calculation methods. Thus, free software applications for estimating fertilizer requirement with a solid mechanistic basis are not available in general for agronomists, farmers and fertilizer dealers.

One specific problem of N management is the partitioning of the total N needs between pre-plant and post-plant applications under uncertainty of expected yield. That would be the case of cereals sown in autumn, when most rainfall is expected after sowing so actual rainfall and thus target yield is unknown at the time of sowing (Quemada et al., 2016a). In addition, the magnitude of processes affecting N cycle in the soil and thus the efficiency in the use of applied N by crops, such as losses through leaching or to the atmosphere, range widely depending on environmental conditions, and consequently are not easy to quantify (Quemada et al., 2016b). On the other hand, precise P management is constrained by the complex biogeochemistry of this nutrient in soil (Delgado and Scalenghe, 2008). Only an unknown fraction, frequently minor, of applied P remains available for crops. As a consequence, despite applying high P rates, this nutrient remains as a yield limiting factor when the soil available P before sowing is not able to cover the crop needs. For K, the management constraints are similar to P, but its dynamics and use efficiency are usually more predictable.

Although the cost of fertilization using straight fertilizers is lower than that of using complex fertilizers, additional benefits from using the later have been known for a long while (e.g. Prummel, 1960). More recently, the advantages of complex over blended fertilizers in terms of distribution uniformity have been shown (Virk et al., 2013). Therefore, in many cases the farmer may require a single product including N, P and K for a single application before sowing and then the additional N is to be applied as topdressing of a straight fertilizer. Selection of the best nutrient equilibrium in the complex fertilizer is not a simple issue, particularly for farmers, and requires accurate estimates of rates for nutrient application.

Other macronutrients (Ca, Mg, S) have never been included in fertilizer calculation software. However, fertilizer practices may lead to long term excess or deficit in Ca, Mg and S for specific crops (Scherer, 2001). It should be kept in mind that these are also essential nutrients for crops, being taken up at relatively high amounts from soil, and some environmental conditions may be particularly prone to their deficiencies, such as acidic soils for Ca and Mg.

Therefore, simple decision-making tools are required for rational fertilization management under the current perspective of increased technical complexity in agricultural systems management. This is the objective of the system that we describe here: to be a useful tool for farmers and agronomists in estimating N, P, and K rates for different crops and in the selection of pre-plant complex fertilizers. This tool has also an educational aim, helping students to better understand the rational basis behind fertilizer management.

2. Materials and methods

2.1. Background

2.1.1. Software specifications

The tool (FertiliCalc) is a Windows program, developed with Visual Basic 2015. The program is a single file of 1.6 Mb which can be downloaded freely at the official web page of U. Cordoba http://www.uco.es/fitotecnia/fertilicalc.html. Versions in 29 languages have been developed so far, including English, Spanish, Portuguese, French, German, Persian, Arabic, Basque, Catalan, Italian, Japanese, Chinese, Polish, Turkish, Uzbek, Finnish, Galego, Russian, Dutch, Indonesian, Bengali, Hindi, Greek, Albanian, Urdu, Korean, Danish, Bulgarian and English-US units which is the only one not using the Metric System. The program has been tested in computers having Windows 7, 8 and 10 and requires Adobe Acrobat Reader to display the Manual and Reading Material embedded in the program. To ensure the integrity of the program the executable file is digitally signed by University of Cordoba. Tutorials for the main versions of FertiliCalc are available in YouTube (channel ID UCuKxm6RHrAeLZ8-xvPdr1OQ)

2.1.2. Calculation of nutrient requirements

The program includes a list of 149 crops. The user picks as many crops for the rotation as needed. The selected crops are shown along with data on Harvest Index, N, P and K concentrations in harvested organs and percent of residues remaining in the field after harvest. These crop data shown in the application are average values from different sources compiled by Sadras et al. (2016), Quemada et al. (2016a), and Delgado et al. (2016a) and may be modified by users in order to adapt them to their specific conditions. The user has to define the expected yield and mark if residues are incorporated and thus can be considered as nutrient inputs. If the Coefficient of Variation of yield (%) is specified it will be used to calculate the distribution of expected N requirements between pre-plant and topdressing applications (see section **Flexible N fertilizer programs**).
Once the crop input information is filled, the user has to supply soil data, namely P, K, organic matter, pH, Cation Exchange Capacity (CEC), method of P analysis and soil texture type (Fig. 1). He is also expected to indicate whether tillage is performed or not. Finally, the user has to select among 3 strategies of fertilization:

- Sufficiency strategy: apply P or K only when the soil test level (STL) is below the defined threshold value for fertilizer response for the specific test used to assess the nutrient availability in soil. This threshold varies depending on environmental conditions (e.g. soil properties) or land productivity. In addition, it should be taken into account that there are many soil tests for P adapted to particular soil conditions since there is not a universal soil P test. The model used in the application is based on the Olsen P (Olsen et al., 1954), a widely used soil P test which may be useful in soils with a pH range from slightly acidic to alkaline. The soil K test may also vary depending on the region, but the difference among different tests is smaller than that found for P. The reference K test for FertiliCalc is based on exchangeable K estimation (e.g. neutral ammonium acetate extraction). More information is available in Delgado et al. (2016a)
- Buildup and maintenance (minimum fertilizer) strategy: Add fertilizer to compensate for P and K exported from the farm and also to progressively rise the STLs to the threshold values when the current STL is below the threshold. For more details, see Delgado et al. (2016a). If any parameter related to the calculation (e.g. threshold of P) lies in an interval, then the program takes the extreme leading to the lowest fertilizer rate.
- Buildup and maintenance (maximum yield) strategy: Similar to the previous strategy but now using the parameters leading to maximum yield, i.e., preventing the risk of nutrient deficiency at the cost of higher fertilizer input.

If no soil tests are available, the program offers a fourth alternative consisting of adding fertilizers to compensate for the P and K exported by harvested parts of crops. Here we assume that the user considers that P and K levels in the soil are not limiting for crop yields, the approach being a “zero balance”.

The nutrient requirements are then calculated according to Quemada et al. (2016b) and Delgado et al. (2016a). Briefly, N requirements are calculated from a simple balance that explicitly considers nitrogen fixation according to Quemada et al. (2016a) (a summary of the procedure is also presented in Appendix A1). With regard to P, the requirements (*P rate*) are proportional to the difference between the current soil P test value (*STL*) and the threshold value (STL_t):

$$P\ rate = A + B\ x\ (STL_t - STL) \qquad (1)$$

Where A is a factor related to the exported P, while *B* is a factor that depends on soil properties (i.e. those related to P dynamics, such as clay or carbonates). In the sufficiency strategy, A is neglected. For Olsen P, and for simplicity, we have considered *B* = 1 when *STL* values are expressed in kg ha^{-1} for a given depth of the surface horizon. To avoid excessive P rates, the model considers a maximum value of 100 kg P ha^{-1}. This will not provide the accurate rate for reaching the STL_t in soil, but will be effective in avoiding excessive P rates. For other soil P tests, the value of B will depend on the equivalence between P extraction from soil with the Olsen method and the other test. The conversion factors adopted in FertiliCalc when using soil P tests different from the Olsen method have been calculated from data reported by Neyroud and Lischer (2003) and are presented in Appendix A2.

For K, the model is similar to that for P, but considering an efficiency factor f_k ranging from 1.1 to 5 depending on the clay content of soil (increases with increased clay):

$$K\ rate = A + (f_k\ x\ B)\ x\ (STL_t - STL) \qquad (2)$$

For this nutrient, it is assumed that B values are the same for different soil K tests. To avoid excessive K rates, the model considers a maximum value of 275 kg K ha^{-1}.

2.1.3. Calculation of fertilizer requirements

Once the N, P and K requirements are known, a list of available fertilizers (Delgado et al., 2016b) is shown, allowing the user to pick and add products to a list of selected items. Since fertilizer prices change with time and may be different depending on the region, the prices considered in the application are only provisional values, and the application allows the user to update them. The concentrations of N, P, K, Ca, Mg and S are also shown and are also customizable, making possible the use of fertilizers not included originally in the program. All this allows a total flexibility in the use of different types of fertilizers.

In order to calculate N fertilizer amounts the rates of volatilization of ammonia, denitrification and leaching are determined according to Quemada et al. (2016b).

Calculation of potential acidification as a function of the source of N and the export of nutrients is based on Bolan and Hedley (2003).

After selecting possible fertilizer products, the program will determine the cheapest combination to satisfy the N, P and K requirements. The application also evaluates the adequacy of the fertilizer program by indicating the possible excess or deficit of N for each crop. The excess of P or K is evaluated for the whole rotation. If information is available in the application database, the Ca, Mg and S balances will be also provided. If no deficit or excess occurs, no information regarding these balances is shown.

2.1.4. Using complex NPK fertilizers

The program includes a set of NPK products including straight and complex fertilizers. If requested by the user, the program will look for the best NPK (available in the full list), i.e. that fits better the requirements of P and K. To this end, the program first calculates the required amount for each NPK fertilizer in the list. The required amount (Q_x) is that that provides the P and K quantities closest to those required (P_r, K_r). This is obtained by minimizing the function:

$$\varphi = (P_r - c_P\, Q_x)^2 + (K_r - c_K\, Q_x)^2 \tag{3}$$

Where C_P and C_K represent the concentration of P and K in the fertilizer, respectively. Equating the first derivative of φ to zero, we can calculate the required amount that minimizes the previous equation:

$$Q_x = \frac{c_P\, P_r + c_K\, K_r}{c_P^2 + c_K^2} \tag{4}$$

Note that N is not considered in the process as it can be supplemented after planting using a straight N fertilizer.

Alternatively, the user may pick a NPK product and a straight N fertilizer so the program determines the doses of both products that fit best the required N, P and K. If this is the case, first Eq. 4 is used to calculate the amount of NPK fertilizer and then the N requirement is completed by using the straight N fertilizer. When dealing with a legume then the amount of NPK fertilizer is calculated as:

$$Q_x = \frac{c_P\, P_r + c_K\, K_r + c_N\, N_r}{c_P^2 + c_K^2 + c_N^2} \tag{5}$$

By using Eq. 5 instead of Eq. 4, an excess of N application is avoided.

2.1.5. Flexible N fertilizer programs

Nitrogen application has to be as close as possible to N needs to avoid deficit (and yield loss) or excess (increased cost, pollution risk). This condition is not that tight for P and K as their concentration in soil changes slowly so we may compensate inputs and outputs on a longer term (several years).

Adjusting N applied to N required is based on the target yield which may show a large inter-annual variability. This would be the case of rainfed crops in arid and semiarid areas. The variability of yield, as characterized by the coefficient of variation (CV, the ratio of standard deviation and mean), can be used to calculate the cumulative distribution function of yield by assuming a normal distribution. For yields corresponding to probabilities of 20 % and 80 % of not exceedance, the N fertilizer requirements for bad (N_{20}) and good years (N_{80}) are calculated by the program. The first marks the maximum advisable amount to be applied as pre-plant fertilizer. The second marks the maximum total N to be applied when climatic conditions do not pose a limitation for crop yield. An example for barley is shown in Table 1. For CV=30 %, which is not uncommon in rainfed Mediterranean areas, the range in N fertilizer is quite large (i.e. 78–140 kg N ha^{-1}). The farmer has to fix a pre-plant N application below N_{20}. If he applies 50 kg N ha^{-1} then the possible range in post-planting application of N will be from 28 to 90 kg N ha^{-1}, depending on how climatic conditions along the season may restrict crop yield. If pre-plant N is 78 kg N ha^{-1}, then he will have to apply 62 kg N ha^{-1} as topdressing fertilizer in very good years and no more fertilizer in bad years.

Table 1. Minimum and maximum nitrogen fertilizer requirements for barley with target yield 3000 kg/ha and different values of coefficient of variation (CV).

CV	Minimum N fertilizer	Maximum N fertilizer
%	kg N/ha	kg N/ha
10	98	119
20	88	129
30	78	140

The N fertilizer requirement provided by FertiliCalc should be corrected by the soil N supply, which is the addition of soil mineral N plus the N mineralized during the crop campaign. Available N can be determined in soil samples taken before planting or before fertilizer application, and should be subtracted from the fertilizer requirements to obtain the actual N fertilizer requirements assuming a high efficiency for this available N (i.e. 90%). The N mineralized during the crop campaign is accounted for in the model, assuming that the soil stable organic matter is in steady state and that the N supply is equivalent to the mineralization of residues and roots from the previous crop. If an organic fertilizer is applied to the field, the mineral N in this fertilizer and N mineralized along the season should be accounted for and subtracted from the fertilizer requirement to avoid over-fertilization. Two other additional sources of N that might be relevant when calculating fertilizer requirements are N atmospheric deposition (usually 2-10 kg N ha^{-1} year, but occasionally >25; the program assumes 10 kg ha^{-1}) and N in irrigation water that can attain high values depending on the water origin. If these additional N contributions can be estimated reliably, the N fertilizer requirement provided by FertiliCalc should be corrected assuming that a fraction (i.e. 70%) is absorbed by the crop. More detail on within-season methods to adjust N management can be found in Quemada et al. (2016b).

2.1.5. FertiliCalc outputs

The main results (nutrient and fertilizer requirements) are included in a text file that is created in the folder containing the application. The application also evaluates the adequacy of the fertilizer program by indicating for each crop the possible excess or deficit of N. The excess or deficit of P or K is evaluated for the whole rotation. If information is available in the application database, the Ca, Mg and S balances are also provided.

2.2. Field trials

Ten field experiments performed during 2003 to 2004 were used to validate results of the application for N fertilization in bread wheat (*Triticum aestivum* L.). This crop was selected for its relevance in terms of planted area and for being a typical rainfed crop with large yield fluctuations depending on weather conditions. Experiments were established at 10 different locations from North (temperate climate without dry season and warm summer, Cfb according to Köppen classification) and Central (cold semi-arid climate, BSk) Spain with different yield potential. Soils in selected sites had a pH between 7.0 and 8.2, soil organic matter content ranging from 1.2 to 2.2 % and presenting a variety of textures (silt loam, silty clay loam, loam, and clay loam). Each experiment, sown with winter (Soissons cv.) or spring (Gazul cv.) wheat, consisted of several N treatments (4 to 6) ranging from 0 to a non-limiting rate, distributed in a completely randomized block design with four replications. Nitrogen was applied as ammonium nitrate broadcast to plots at the beginning of tillering and stem elongation. In July, the 1.5 m central fringe was harvested from each plot with a combiner and the wheat yield was recorded. Grain subsamples were analysed for N concentration by Kjeldahl´s method. The N fertilizer rate to reach the plateau yield was determined by fitting a quadratic-plus-plateau model to the wheat yield for each experiment using R software (R Core team, 2018). Soil mineral N content (NMIN) was determined in soil samples taken before first fertilizer application at 0.3-0.2 m intervals to the effective rooting depth (0.9 m or 0.4 m depending on soil characteristics) in each plot. The samples were extracted with 1 M KCl, centrifuged and in the supernatant nitrate concentration was determined by spectrophotometry after reduction with a cadmium column, and ammonium by the salicylate-hypochlorite method. In four of the ten experimental sites, crops were irrigated. Subsamples of irrigation water were taken periodically for determination of nitrate concentration, and the N applied in irrigation water was calculated as the product of water applied and N concentration determined with the above described method. A detailed description of field experiments and procedures can be found in Arregui and Quemada (2008) and Quemada (2006).

FertiliCalc was run to obtain the recommended N rate for each experiment, introducing the plateau yield reached in each experiment and the corresponding grain N concentration. Other inputs were the precedent crop yield and soil site characteristics. The adjusted N rate was obtained by correcting the FertiliCalc recommended N rate by discounting 90% of NMIN and 70% of N applied in irrigation water to account for the irrigation efficiency.

2.3. Case study

Although FertiliCalc has been conceived as a practical application for agronomists, farmers and students, it may also be extremely useful for the fertilizer supply sector, allowing the estimation of nutrient balances at regional scale. To illustrate that, we evaluated the P and K balances for the Jaen province (Spain). The climate is Mediterranean (temperate semi-arid climate, Csa) and its total agricultural land covers more than 600000 ha, 90 % of which is occupied by olive trees. Using recent statistics of crop production and use of fertilizers available on the web (Anuario Estadístico de Andalucía, 2015), we used FertiliCalc to determine total P and K supplied by fertilizers and total P and K exports in the province in the year 2015, estimating the imbalances between inputs and outputs of these nutrients. The statistics on binary and ternary fertilizers grouped the products as N-P, N-K, P-K and N-P-K, rather than showing values for specific fertilizer compounds. In the analysis, such unspecified products were given the P and K contents of di-ammonium phosphate, potassium nitrate, potassium phosphate and a 15-15-15 NPK fertilizer.

3. Results

3.1. Field trials

The optimum N fertilizer rate estimated from the experimental data (i.e. that required to reach the plateau yield) differed substantially between sites, ranging from 60 to 180 kg ha^{-1}. The adjusted N rate obtained by correcting the FertiliCalc recommended N rate by the contribution of the NMIN and the N applied in the irrigation water was highly significantly related to the optimum N fertilizer rate found in the field experiments (Fig. 1A). The proportion of the variance of the N fertilizer rate in the field experiment explained by FertiliCalc after this correction was 95 %, whereas explained variance without correction was 18% (Fig. 1B).

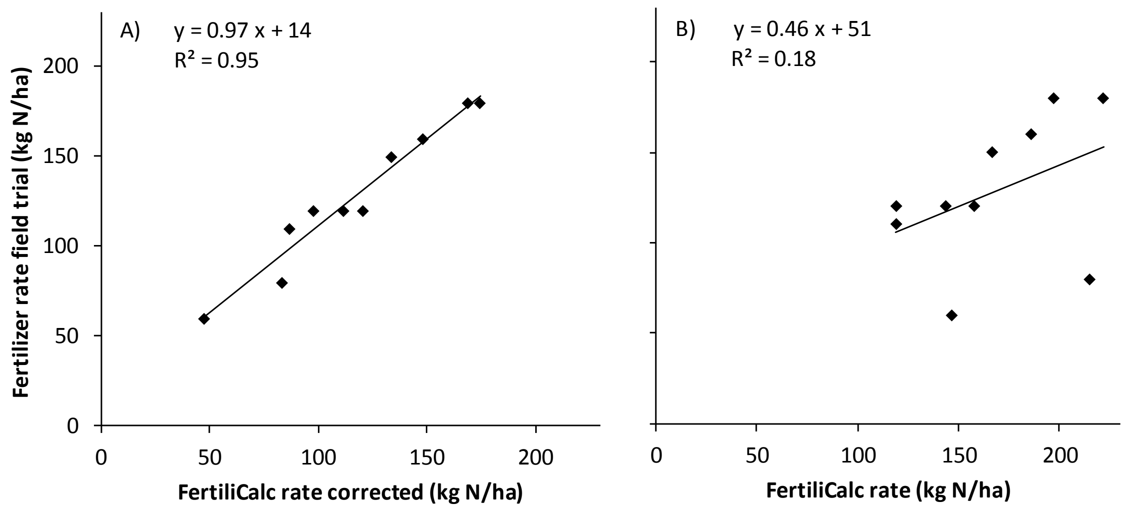

Figure 1. Plots of N fertilizer rates to reach the plateau yield observed in the field experiments versus the fertilizer rates recommended by FertiliCal either corrected (A) or not (B) to account for the contribution of soil mineral N content and N applied in the irrigation water.

3.2. Case study

Table 2 shows the estimates of P and K supplied by the different fertilizers applied in 2015 in the province of Jaen. Around 65 % of the P and K inputs came from ternary NPK fertilizers (assumed as 15-15-15). Overall, the estimated supply of P and K was 3578 and 6676 t, respectively. On the other hand, Table 3 presents the estimated exports of P and K for different crop categories. Unsurprisingly, olive trees were responsible of the most part of P and K exports (75 and 83 %, respectively) due to the predominance of this crop in the studied province, with cereals the first source of P and K outputs (13 and 8 %) after olive trees. Considering all the crops, total calculated P and K exports were 2331 t and 18171 t, respectively.

Comparing the total input and outputs, contrasting results are evident for the two nutrients. In the case of P, the supply of this nutrient by fertilizers exceeded the estimated crop exports by around 50 %. On the contrary, the K applied by fertilizers was far below the calculated exports (K inputs barely covered 37 % of the outputs).

Table 2. Applied P and K fertilizers and their corresponding supply of P and K in 2015 in the Jaen province (Spain). Unspecified fertilizers were given the P and K concentrations of: dicalcium phosphate1, di-ammonium phosphate2, potassium nitrate3, potassium phosphate4, N-P-K (15-15-15)5.

Fertilizer	Fertilizer use	P	K	P input	K input
	t	%	%	t	t
Superphosphate	2 295	8.5	0	195	0
Triple superphosphate	29	20	0	6	0
Other straight P fertilizers1	3 420	17	0	581	0
Potassium chloride	2 370	0	50	0	1 185
Potassium sulfate	198	0	41.5	0	82
Binary N-P 2	667	20	0	133	0
Binary N-K 3	1 650	0	36.5	0	602
Binary P-K 4	1 518	23	28	349	425
Ternary N-P-K 5	35 052	6.6	12.5	2 313	4 381
Total	47 200			3 578	6 676

Table 3. Area devoted to different crop groups and P and K exports calculated from production statistics for 2015 in the Jaen province (Spain).

Crop group	Area	Total P exports	Total K exports
	ha	t	t
Cereals	25 161	313	1 489
Forages	2 734	168	1 188
Fruit trees and vines	6 441	13	39
Horticultural crops	2 533	28	152
Industrial crops	7 169	46	50
Legumes	1 683	5	15

Olive trees	586 074	1 758	15 238
Total	631 795	2 331	18 171

4. Discussion

4.1. Field trials

The results shown in Fig. 1 highlight the predictive capacity of FertiliCalc, but also the need to include the soil and water N contribution to adjust N fertilizer rate to current crop requirements. In these field experiments the average NMIN was 50 kg N ha^{-1} and the N applied with water in the irrigated trials was 19 kg N ha^{-1}. If these contributions are not taken into account, FertiliCalc would predict a higher N rate than that observed in the field experiments (Fig. 1B).

In practice, it is common to take soil samples for NMIN only from the upper layers because of labor or economic constraints. Nevertheless, crop extraction from deeper layers should not be neglected and underestimation of the effective rooting depth could be minimized by preliminary studies with adequate equipment (Arregui and Quemada, 2006; Gabriel et al. 2010). Slight underestimation of N supplied by mineralization may occur as FertiliCalc assumes steady-state for soil organic matter. The program only gives allowance to the N released by decomposition of the precedent crop residues, therefore, it might underestimate N mineralization from soil pools that might be occasionally enhanced by soil management (i.e. tillage) or applied as organic amendments (Quemada and Menacho, 2001). Other sources of N inputs in the field, like N atmospheric deposition, should also be considered for correction if they are relevant. In the studied region N atmospheric deposition was low (2-3 kg N ha^{-1}; EMEP, 2019) and fields had not received organic amendments during four years prior to the beginning of the trials.

4.2. Case study

The large imbalances found in the case study when comparing the P and K inputs with the outputs can be ascribed to the differences in the ratio P: K between fertilizer supply (around 1:2, Table 2) and crop exports (almost 1:8, Table 3). In this regard, the preponderant use of ternary fertilizers over other products makes impossible to simultaneously balance the supply and demand of P and K. In the light of this, a reduction of complex fertilizers and a promotion of binary N-K or straight K fertilizers like potassium chloride should favor a better balance. This is relevant for farmers since K deficiency is deemed a major nutritional disorder in olive orchards in southern Spain. These results reveal that an inadequate selection of fertilizer compounds likely contributes to this extensive problem. Similar analysis using FertiliCalc might be extremely valuable for retailers and other agents of the fertilizer industry, as the generated information could be used to define commercial strategies that cope better with the nutrient requirements of specific crops or regions while maximizing their economic return.

The results of this case study should be taken with care, as some bias might arise from implicit assumptions such as the choice of unspecified binary and ternary fertilizers or the fact that only harvested parts are considered in the calculation of crop exports. However, these assumptions are not expected to make a big impact on our results. With regard to the latter assumption, according to data provided by Anonymous (2005), fresh pruned wood from olive trees should be over 400000 t year^{-1}. Assuming a water content of 0.53 m^{3} m^{-3} (López-Bernal et al., 2014), and P and K concentrations of 0.05 and 0.32 % in the dry matter, respectively (Villalobos FJ, unpublished), the potential annual exports of P and K in the wood of olive trees would be 90 and 580 t, respectively. These values represent a modest contribution to the total P and K in 2015 shown in Table 3, despite olive trees being the most important crop in the case study.

4.3. Further considerations

The reliability of FertiliCalc for providing accurate estimates of P and K requirements is challenged by the complex dynamics of these nutrients in the soil, particularly in the case of P. Periodical soil analyses are required since it is difficult to establish how the soil test is going to evolve in the future on the grounds of the application output provided by the application. This checking is critical in a sufficiency strategy, since a significant decrease of the soil test below the threshold value may imply that P or K would be a constraining factor for yields during a long time. Contrasting with N, which is a mobile nutrient, P and K are essentially retained in the soil, but its availability is the result of reactions of very different nature occurring in the soil after fertilization. Frequently, the efficiency of applied P in increasing the Olsen P level of soil in high P fixing soils such as calcareous soils is less than 10 % after several months. This efficiency may vary widely depending on fertilizer management. For example, high fractionation in P fertilization with fertigation, or the application of P fertilizers with organic matter may increase significantly their efficiency in increasing the available P status of soil (Delgado et al., 2016a). This problem may also occur, usually at a lesser extent, with K. However, the so called “interlayer K fixation” leading to a low efficiency of applied K fertilizer may be very high in clayish soils with illite as dominant clay mineral. Finally, uncertainties about the accuracy of usual soil tests should be taken into account, in particular in the case of P (Recena et al., 2016). Taking into account these facts regarding P and K, and the need of accounting for the mineral N present in soil for correcting data provided by the application, soil analyses represent an important aid for efficient fertilization using FertiliCalc. In any case special caution is recommended when using FertiliCalc for calculating P requirements in soils with high contents of calcium, organic matter or oxides and hydroxides of iron and aluminum.

The program does not take into account the soil water balance which affects strongly nitrate leaching and denitrification. This oversimplification is a must for simplicity as no water balance model (requiring weather data) is required. Tracking the dynamics of soil nitrate concentration or the dynamics of plant N concentration would require much more complex crop simulation models.

In addition to its use for providing advice (extensionists, fertilizer dealers) or taking decisions (farm managers), FertiliCalc may be a learning tool in the class. The student may be assigned a specific case representative of local conditions (e.g. crop rotation) so first there is a need for searching data in terms of fertilizer prices and products available, expected yields, soil types, etc. Depending on the specific teaching/training level, the student should perform the calculations manually and use the program to check the results (e.g. basic agronomy class) or do the calculations directly using the software (e.g. environmental science or agricultural classes in high schools or technical colleges). A more demanding practical task for deeper training in Fertilizer Management that could be proposed to students would imply: a) review local recommendations for fertilizer use and b) contact and interview local farmers about their fertilizer programs to compare them with the results from FertiliCalc. This will allow students to use this decision tool as an effective mean of checking the effectiveness of fertilization practices at a regional scale.

The availability of FertiliCalc in 27 versions covering the most important languages and cultures has been the result of the altruistic contribution of agronomists from many countries (their names and affiliations are shown in the credits of each version). It allows not only the sharing of this simple technology but also provides a tool for young agronomists moving to different countries for extension or cooperation.

Acknowledgements

F. Orgaz, Majid Jami Al-Ahmadi and Behnam Kamkar contributed to improving the earliest version of the program. This work was supported by ERA-NET FACCE SURPLUS [grant number 652615, project OLIVE-MIRACLE], being co-funded by INIA of Spain [PCIN-2015-259].

Conflict of interest

The authors declare no potential conflict of interest for this research.

Appendix A1. Calculation of N requirements

N fertilizer requirements (*N rate*) are calculated from:

$$N\ rate = \frac{N_{end} + (1+f_{NR})(N_{yield}+N_{res}) - k_{im}\, F_{res}\, N'_{res} - f_{NR}\left(N'_{yield}+N'_{res}\right) - N_{other}}{(1-n)} \qquad (6)$$

In this equation, N_{end} represents the final soil inorganic N (residual N). FertiliCalc uses a fixed value of 10 kg N ha^{-1} assuming that crops are unable to recover N below that threshold. f_{NR} is the ratio of N in roots to N in shoots. N_{yield} and N_{res} refer to N accumulated in the harvest organ and residues of the present crop, respectively, while their homologous N'_{yield} and N'_{res} correspond to the previous crop in the rotation. These values are easily calculated from the product of concentrations of N in harvested organs and residues and their biomass (Quemada et al., 2016a). The coefficient k_{im} would have a maximum value of 1 if all the aboveground residues were mineralized with no loss. Lower values are expected if the residues are not incorporated by tillage or when the N concentration in residues is low. FertiliCalc adopts different values depending on whether the crop is a legume and whether it is tilt. F_{res} is the fraction of residues that are left in the field (user-defined input; otherwise the application provides default values depending on the crop). N_{other} is the total N received by atmospheric deposition, symbiotic fixation and irrigation water. In the case of non-legume crops, FertiliCalc adopts a default value. For legume crops, the application calculates N_{other} as a fraction of the crop N (f_{fix}):

$$N_{other} = f_{fix}(1 + f_{NR})(N_{yield} + N_{res}) \quad (7)$$

Where f_{fix} takes different values depending on the type of legume crop (annual or perennial) and the percentage of soil organic matter (Quemada et al., 2016a). Finally, the coefficient *n* in Equation 6 represents the fraction of applied N that is lost (leaching, volatilization, denitrification). Depending on soil texture, FertiliCalc assumes that leaching ranges from 20% (sandy) to 2% (clayish). The rates of volatilization of ammonia and denitrification are determined according to Quemada et al. (2016b).

The model assumes that most of N supplied by mineralization, atmospheric deposition, symbiotic fixation and contained in the irrigation water, are taken up by crops with no losses. Table 4 provides a list with the values of the aforementioned parameter used by FertiliCalc in the calculation of *N rate*.

Table 4: List of parameter values adopted by FertiliCalc for the calculation of N requirements.

Parameter	Definition and units	Value	Restricted to (if any)
N_{end}	Residual inorganic N at the end of the cycle (kg N ha^{-1})	10	
f_{NR}	ratio N in roots/N in shoots	0.2	
k_{im}	Coefficient of mineralization	0.9	Legumes with tillage
		0.7	Legumes left on the ground and non-legumes with tillage
		0.5	Non-legumes left on the ground
N_{other}	Total N received by atmospheric deposition (kg N ha^{-1})	10	
f_{fix}	Fraction of crop N obtained from symbiotic fixation in legumes	0.7	Annual legumes on soils with high organic matter (>3%)
		0.8	Perennial legumes on soils with high organic matter (>3%)
		0.95	Any legume on soils with low organic matter (>3%)

Appendix A2. Conversion factors for soil P tests

When soil P data available have not been determined by the Olsen method, FertiliCalc estimates the equivalent Olsen STL (STL_{Olsen}) as:

$$STL_{Olsen} = k\ STL_i \qquad (8)$$

Where STL_i is the soil test level determined by the method "*i*" and *k* a conversion factor that is method-specific. Values for *k* have been calculated from data reported in Neyroud and Lischer (2003) and are presented in Table 5.

Table 5: Values of the coefficient converting values of a given soil P test into its equivalent for the Olsen method.

Method	**k**
Ammonium lactate	0.25
Mehlich III	0.36
Bray	0.47
Ammonium acetate + EDTA	0.48
Calcium lactate	0.49
Calcium lactate acetate	0.52
Paper strip	1.50
Acid ammonium acetate	1.60
H2O	3.8
Saturated water	15.0
Ca Cl2	25.0

References

Anonymous, 2005. Agenda 21 de la provincia de Jaen, Desarrollo Socioeconómico Agricultura. http://www.agenda21jaen.com/export/sites/default/galerias/galeriaDescargas/agenda21/Aplicaciones/documentacion/Diagnosis-provincial/23._Turismo.pdf (accessed 24 February 2019).

Anuario Estadístico de Andalucía, 2015. Statistics on crop production, land use and fertilizer sales provided by Junta de Andalucía (Andalusian Regional Government). https://www.juntadeandalucia.es/institutodeestadisticaycartografia/badea/informe/anual?CodOper=b3_6&idNode=6049 (accessed 24 September 2019).

Arregui, L.M., Quemada, M., 2008. Strategies to improve nitrogen-use efficiency in winter cereal crops under rainfed Mediterranean conditions. Agron. J. 100, 277-284.

Arregui, L.M. and Quemada, M., 2006. Drainage and nitrate leaching in a crop rotation under different N strategies: application of capacitance probes. Plant Soil. 288: 57-69.

Bolan, N.S., Hedley, M.J., 2003.The role of carbon, nitrogen and sulphur in soil acidification. In: Rengel, Z. (Ed.), Hand Book of Soil Acidification, Marcel and Dekker

Connor, D.J., Loomis, R.S., Cassman, K.G., 2011. Crop ecology: productivity and management in agricultural systems. Cambridge University Press, Cambridge, UK.

Delgado, A., Scalenghe, R., 2008. Aspects of phosphorus transfer in Europe. J. Plant Nutr. Soil Sci. 171, 552–575.

Delgado, A., Quemada, M., Villalobos, F.J., 2016b. Fertilizers, in: Villalobos, F.J, Fereres, E. (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer, Cham, Switzerland, pp. 321-340.

Delgado, A., Quemada, M., Villalobos, F.J., Mateos, L., 2016a. Fertilization with phosphorus, potassium and other nutrients, in: Villalobos, F.J, Fereres, E. (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer, Cham, Switzerland, pp. 381-406.

EMEP (2019). http://www.emep.int/ (accessed 24 September 2019).

Gabriel, J.L., Lizaso, J., Quemada, M., 2010. Laboratory versus field calibration of capacitance probes. Soil Sci. Soc. Am. J. 74, 593-601.

Grassini, P., Cassman, K.G., 2012. High-yield maize with large net energy yield and small global warming intensity. Proc. Nac. Acad. Sci. 109(4), 1074-1079.

López-Bernal, A., Alcantara, E., Villalobos, F.J., 2014. Thermal properties of sapwood of fruit trees as affected by anatomy and water potential: errors in sap flux density measurements based on heat pulse methods. Trees 28(6), 1623-1634.

Neyroud, J.A., Lischer, P., 2003. Do different methods used to estimate soil phosphorous availability accross Europe give comparable results? J. Plant Nutr. 166, 422-431.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorous in soils by extraction with sodium bicarbonate. United States Department of Agriculture, Washington.

Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., 2017. A GIS-based tool for integrated management of clogging risk andnitrogen fertilization in drip irrigation. Agric. Water Manage. 184, 86-95.

Prummel, J., 1960. Placement of a compound (NPK) fertilizer compared with straight fertilizers. Neth. J. Agric. Sci. 8(2), 149-154.

Quemada, M., Menacho, E., 2001. Soil respiration 1 year after sewage sludge application. Biol. Fert. Soils. 33, 344-346.

Quemada, M., 2006. Balance de nitrógeno en sistemas de cultivo de cereal de invierno y de maíz en varias regiones españolas. Monografías INIA Serie Agrícola nº 22, Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria. Madrid, Spain.

Quemada, M., Delgado, A., Mateos, L., Villalobos, F.J., 2016a. Nitrogen fertilization I: The nitrogen balance. in: Villalobos, F.J, Fereres, E. (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer, Cham, Switzerland, pp. 341-368.

Quemada, M., Delgado, A., Mateos, L., Villalobos, F.J., 2016b. Nitrogen fertilization II: Fertilizer requirements. in: Villalobos, F.J, Fereres, E. (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer, Cham, Switzerland, pp. 369-380.

R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Recena, R., Díaz, I., del Campillo, M.C., Torrent, J., Delgado, A., 2016. Calculation of threshold Olsen P values for fertilizer response from soil properties. Agron. Sustain. Dev. 36, 54.

Restrepo-Díaz, H., Benlloch, M., Navarro, C., Fernández-Escobar R., 2008. Potassium fertilization of rainfed olive orchards. Sci. Hort. 116, 399–403.

Sadras, V.O., Villalobos, F.J., Fereres, E., 2016. Radiation interception, radiation use efficiency and crop productivity. in: Villalobos, F.J, Fereres, E. (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer, Cham, Switzerland, pp. 169-188.

Scherer, H.W., 2001. Sulphur in crop production. Eur. J. Agron. 14(2), 81-111.

Schröder, J.J., Schulte, R.P.O., Creamer, R.E., Delgado, A., van Leeuwen, J., Lehtinen, T., Rutgers, M., Spiegel, H., Staes, J., Tóth, G., Wall, D.P., 2016. The elusive role of soil quality in nutrient cycling: a review. Soil Use Manage. 32, 476–486.

Virk, S.S., Mullenix, D.K., Sharda, A., Hall, J.B., Wood, C.W., Fasina, O.O., McDonald, T.P., Pate, G.L., Fulton, J.P., 2013. Case study: distribution uniformity of a blended fertilizer applied using a variable-rate spinner-disc spreader. Appl. Eng. Agric. 29(5), 1-10.

Xu, X., He, P., Pampolino, M.F., Li, Y., Liu, S., Xie, J., Hou, Y., Zhou, W., 2016. Narrowing yield gaps and increasing nutrient use efficiencies using the Nutrient Expert system for maize in Northeast China. Field Crop Res. 194, 75-82.