Comparison of different approaches for optimizing nitrogen management in sprinkler-irrigated maize

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Highlights

- Optimized fertilization strategies can reduce up to 236 kg N ha^{-1} compared to actual practices
- Using field-specific information decreased recommended N rates compared to a fixed reduced N rate
- The use of a portable chlorophyll meter device (SPAD) increase NUE in most field situations

Abstract

The gap between scientifically sound nitrogen (N) fertilizer application rates and the actual rates used by farmers in maize is still significant. The improvement of nitrogen use efficiency in such a highly Ndemanding crop is necessary to decrease the negative effects of N fertilization. The objective was to compare the performance of different N management treatments in maize grown under semiarid Mediterranean sprinkler-irrigated conditions to the standard farmer practice. We compared an agronomically sound fixed rate of N fertilizer (FR) with a variable N rate obtained based on a soil mineral balance at pre-planting (SB) or based on a portable chlorophyll meter readings (CM) made just before tasseling. Additional treatments were a N control, without fertilizer (T0), and a non-limiting N (NL) treatment wich was typical of the current farmer practice. The study was replicated at 5 sites in one-year experiments and under 3 pre-planting soil mineral nitrogen environments (SMN, Low, Medium, and High). The results demonstrate the potential to reduce N rates from zero to 236 kg N ha^{-1} compared to the NL in irrigated maize fields without compromising yields in most of the situations with a subsequent increase of NUE. Averaging over sites, the use of fine-tuning N fertilizer strategies that considered field-specific conditions (SB and CM) reduced N rates (38%) compared to the reductions under the FR strategy (26%) relative to the NL conditions, which is the treatment closest to a typical farmer`s application rate.

Keywords: nitrogen use efficiency, chlorophyll meter, soil testing, diffuse pollution

1. Introduction

Maize grown under sprinkler irrigation systems in semiarid conditions in Spain is a very productive crop (15 Mg ha^{-1} of grain and above) but has a high nitrogen (N) demand. This situation is generalizable to all highly productive maize-growing areas around the world where excessive N rates are applied as ‘insurance’. This practice has produced problems of water and air pollution (Vitousek et al., 1997). Management of irrigation and N fertilization have been recognized as the main factors controlling diffuse nitrate pollution in Mediterranean irrigated areas (Isidoro et al, 2006; Cavero et al., 2012; Quemada et al., 2013; Salmerón et al., 2014; Malik et al., 2018). In addition, a recent study under Mediterranean conditions (Alvaro-Fuentes et al., 2016) found significantly higher soil nitrous oxide flux – a potent greenhouse gas – in nitrogen over fertilized maize fields compared to that over control unfertilized plots. Data from surveys in the Ebro River Basin (Spain) indicated that farmers apply rates of 318 - 453 kg N ha^{-1} yr^{-1} every year (Cavero et al., 2003; Isidoro et al, 2006), i.e., maize is often over-fertilized to reduce the risk of yield losses. More recent studies (Jimenez-Aguirre et al., 2014) in irrigation districts in the same area show a significant tendency to reduce the averaged rates of N applied to maize associated with the shift from flood (431 kg N ha^{-1}) to the more efficient sprinkler irrigation systems (338 kg N ha^{-1}). However, based on the crop nitrogen balance concept, there is still potential to improve nitrogen use efficiency when appropriate management practices for N fertilizer are incorporated.

Although there is a significant amount of information available about the nitrogen requirements of the maize crop, many farmers apply the same amounts of N fertilizer every year without considering the real needs of each specific field. Different decision tools and strategies have been proposed to guide N fertilizer applications in maize. Recommendations relying exclusively on nitrogen crop uptake values present the limitation of not considering the site-specific soil conditions of each field (Berenguer et al., 2009) and tend to overestimate N fertilizer doses. Extensive studies in different areas around the world (Blackmer et al., 1989; Binford et al., 1992, Berenguer et al., 2008; Cui et al., 2008ab; Cela et al., 2013; Martinez et al., 2017) indicate the necessity of assessing the pre-plant SMN content to optimize N fertilizer rates. Other studies emphasize the evaluation of the nutritional status of the crop in adjusting the N fertilizer rates. This approach can involve different methodologies, ranging from simple measurements with a portable chlorophyll meter to the use of visible or multispectral aerial images from unmanned aerial vehicles or small airplanes. Thus, several studies (Piekielek et al., 1995; Varvel et al., 2007; Schmidt et al., 2011; Rambo et al. 2011; Akhter et al., 2016) proposed the use of SPAD 502 chlorophyll meter (Minolta Camera Co., Ltd., Osaka, Japan) to improve N management in maize. Rorie et al. (2011) and Nguy-Robertson et al. (2015) found that the use of inexpensive leaf colour charts are also useful for assessing leaf chlorophyll content. Some limitations of this methodology are the need to have a non-limiting N (overfertilized) area in the field to use as a reference, and the potential interferences of irradiance and plant water status with chlorophyll meter readings (Martinez and Guiamet, 2004). More sophisticated methodologies using chlorophyll fluorescence techniques (Bredemeier and Schmidhalter. 2003), aerial images (Maresma et al., 2016; Gabriel et al., 2017) have been proposed but mainly focused on the establishment of relationships between the nutritional status of crops and the vegetation indices, but with less emphasis on the development of practical methodologies for using these new technologies as decision tools.

The interaction between irrigation and nitrogen management is also critical to maximize NUE in irrigated agrosystems (Quemada and Gabriel, 2016). Therefore, a correct comparative approach of different N management practices must consider an efficient use of irrigation water using the available methodologies. However, as recognized by a recent review by Morris et al (2018), in spite of the numerous studies dealing with nitrogen fertilization of maize, there is still the need to improve N management techniques due to the excessive amounts of nitrogen applied to maize and the low nitrogen recovery efficiencies observed. In addition, few studies (e.g. that by Ferguson et al., 2002) have compared different N fertilizer management strategies under field irrigated conditions and their effect on crop performance and NUE. Therefore, the objective of the present study was to evaluate, in two different sprinkler-irrigated areas of Spain, the performance of three existing N management treatments in maize that can be easily implemented by maize growers, without the need to manage a complex knowledge base. The evaluation was made under three different pre-plant SMN conditions to compare the performance of these treatments under different potential field situations.

Materials and methods

2.1. General description of experimental sites

Five field experiments were carried out between 2010 and 2012 in two different irrigated maize production areas of Spain. Three fields were located in the middle Ebro Valley in the NE Spain (named as sites #1, #3, and #5), and the other two fields were located in the south-eastern end of the Central Plateau of Spain (named as sites #2 and #4) in the region of Castilla-La Mancha (Table 1). The climate in both regions of Spain is Mediterranean-continental semiarid with high summer temperatures, reduced precipitation in summer, cold winters, and rain evenly distributed throughout the year except during the summer. Thus, the historical average annual temperatures are 14.5 (site #1), 13.0 (sites #3 and 5), and 13.8°C (sites #2 and #4). The historical precipitation levels are 347 (site #1), 443 (sites #3 and 5), and 342 mm year^{-1} (sites #2 and #4). The years of the experiment presented temperature patterns close to the historical averages but all sites presented lower annual precipitation than the historical average (28% of reduction averaging over sites). A more detailed meteorological information is presented in Table S1 (Supplementary material). The physical-chemical characteristics of the soils were different among the five sites (Table 2). There are relatively deep and fine-textured soils in the selected Ebro Valley fields (#1, #3, and #5), classified as Typic Xerofluvent (Soil Survey Staff, 2014), and shallow and coarse-textured soils in the Central Plateau sites (#2 and #4), classified as Petrocalcic Calcixerept. In both areas, soils had high carbonate content, high pH, and low organic matter content (less than 2.5%), which are the prevalent characteristics in most of the irrigated maize growing areas of Spain. The fields were managed using standard management practices, including weed and pest control; key dates of management practices are presented in Table 1. The maize FAO 600 hybrid '*Pioneer PR34N43*' was used in the five experimental sites. Conventional tillage practices to prepare soil beds such as using shredder to chop the residues from the previous crop and chisel ploughing before sowing were used. The five fields were sprinkler irrigated using a solid-set system providing a pluviometry of approximately 5.5 mm h^{-1}. The irrigation rate and frequency, were adjusted to satisfy crop requirements based on the FAO methodology (Allen et al., 1998) and regionally adapted crop coefficients (Martinez-Cob, 2008) used to minimize nitrogen leaching during the maize growing period. Once the maize was established (two unfolded leaves) and until physiological maturity, irrigation was applied between two to five times per week to compensate for the water evapotranspiration from the previous week. Irrigation was distributed in 55 to 70 events per year depending on the site and years. No visual water-stress symptoms were observed during the maize growing period in the different experiments.

2.2. Pre-plant soil mineral nitrogen scenarios and fertilizer management treatments

Each site included three different scenarios of pre-planting SMN (henceforth referred as pre-plant SMN), designated as 'Low', 'Medium' and 'High' SMN. To obtain these scenarios, different doses of

N fertilizer in the form of urea were applied during the previous growing season relying that these different amounts of applied N would remain in the soil N content of the following growing season. Thus, when barley was the precedent crop (site#1), 0, 100, and 200 kg N ha^{-1} were applied to create the three SMN levels. When maize was the precedent crop, 100, 200, and 300 kg N ha^{-1} were applied to create the three SMN levels.

In each scenario, five N fertilizer management treatments were established:

T0: a control with no fertilizer

NL (non-limiting N treatment) representing the usual doses applied by farmers in each area; a total rate of 300 kg N ha^{-1} split into three equal applications, except at site #1 where, by mistake in the third application, a total of 400 kg N ha^{-1} was applied.

Three N fertilizer management treatments (FR, SB, CM) or decision tools were defined as follows:

FR (fixed rate): a fixed rate according to the recommendations of extension services in the two regions (Isla and Quilez, 2006; Maturano and Garcia-Serrano, 2011) derived from yield-N rate experiments conducted in these regions. The total rate was split into three applications: 50 kg N ha^{-1} at pre-planting, half of the remainder applied at V6 (6 unfolded leaves; Ritchie et al., 1986) and the other half applied at V15 (15 unfolded leaves). The fixed rate was established as 225 kg N ha^{-1} in site #1, 250 kg N ha^{-1} in sites #3 and #5, and 200 kg N ha^{-1} in sites #2 and #4.

SB (soil balance): following a classical approach (Stanford, 1973) that considers main N inputs and N outputs. A simplified N balance was performed (Eq. [1]) for each experimental plot.

$$Nrequirements = \frac{(Outputs - Inputs)}{Nef} \quad [1]$$

- The Output considered was the total N extracted by the plant for an estimated yield of 14 (Ebro Valley) and 15 Mg ha^{-1} (Castilla La Mancha), with maize plant uptake of 21 kg N for each ton of expected grain yield (14% of grain moisture).
- The inputs considered were: (a) mass of soil nitrate in the upper layer (0-60 cm depth in Ebro Valley and 0-40 cm in Castilla La Mancha) measured at each experimental plot by soil sampling just before sowing, (b) estimation of N applied with the irrigation water (site #1: 11 kg N ha^{-1}; site #3 and #5: 4 kg N ha^{-1}; sites #2 and #4: 40 kg N ha^{-1}, (c) estimate of N released by mineralization in the upper part of the soil profile from previous unpublished experiments in the region through soil balance approach with unfertilized plots (sites #1, #3, #5: 73 kg N ha^{-1}; sites #2 and #4: 52 kg N ha^{-1}).
- The N fertilizer efficiency (Nef) was a fertilizer efficiency of 0.7 obtained from previous experiments under similar sprinkler-irrigated conditions (Isla and Quílez, 2006).

All plots from SB treatment received 50 kg N ha^{-1} at preplanting. The remaining N was split in two sidedress applications to reach the established N requirements according to the following distribution: 2/3 at the V6 stage and 1/3 at the V15 stage.

CM (SPAD criteria): in these treatments, all plots received 50 kg N ha^{-1} before planting, and 100 kg N ha^{-1} at V6. A second sidedress application was made at V15 depending on the relative SPAD readings (SPADr). The SPADr was obtained at the V14-V15 stage from SPAD readings at each plot relative to the SPAD reading in the non-limiting N treatment (NL) in each scenario. If SPADr > 95%, no N was applied; if 90%< SPADr < 95%, 50 kg ha^{-1} was applied; and if SPADr < 90%, 100 kg N ha^{-1} was applied. The critical level of relative chlorophyll necessary to trigger supplemental N is uncertain, but Shapiro et al. (2006) proposed a value of 95% to avoid yield losses and that criteria has been used in this study.

The experimental design was a split-plot with correlated plots with 4 replications, except in site #1, which had 5 replicates. In sites #1 and #2 the NL treatment had only one replication. To make the application of fertilizer the precedent year feasible, the pre-plant SMN factor was not randomized, and all plots from the same SMN level were grouped together in a split-plot design with correlated whole plots. The size of the experimental unit was 3.75 m x 10 m (experiments #2 and #4) or 4.5 m x 12 m (experiments #1, #3 and #5).

2.3. Plant and soil variables analysed

To monitor the N status of plants, leaf greenness was evaluated in all plots at the growth stages V15, and R1-R2 (silking-blister) using a portable chlorophyll meter (SPAD-502, Minolta Camera Co., Ltd., Osaka, Japan), averaging 30 chlorophyll meter readings in different plants within each plot. The readings came from the central part of the ear leaf.

At maize harvest at sites #1, #3, and #5, the lower portion of the maize stalks was sampled to perform the end-of-season nitrate test according to the methodology of Binford et al. (1990). The test has been successfully used under irrigated conditions (Isla et al., 2015) to evaluate the maize nitrogen sufficiency and is especially suited to detect N over-fertilisation. This is a post-harvest test that is useful as a feedback information tool for comparing different N management strategies.

Soil from each experimental plot was sampled three times during the maize growing period: before planting (0-120 cm at sites #1, #3 and #5 and 0-40 cm in #2 and #4), at the V6 maize growth stage (0-30 cm depth), and after harvest (0-120 cm only at sites #1, #3 and #5) to estimate the residual SMN. Three soil cores from each experimental plot were taken with a 5 cm diameter hand auger (Eijkelkamp Agrisearch Equipment BV, The Netherlands) and the three samples were combined per depth in 0.3 m increments (0.2 m in sites #2, #4, and #6) to the lower part of the soil profile. The soil was fresh-sieved to pass through a 2 mm sieve, and 10 g was extracted with 30 mL of 2 N KCl solution for colorimetric determination of NO_3^-–N and NH_4^+–N concentrations with a continuous flow analyser (AA3, Bran + Luebbe, Norderstedt, Germany). Another subsample was dried at 105°C to a constant weight for gravimetric water content determination. To convert SMN concentration to SMN mass, averaged measured bulk soil densities of 1.45 (sites #1, #3, #5) and 1.36 (sites #2 and #4) were used.

Maize was harvested manually (see dates in Table 1) by collecting all ears in the two center rows of each plot (12 m^2). The ears were threshed and grain yield was reported based on 14% moisture content. In a subarea of 3 m^3, the rest of the plant material (leaves + stalks + shanks + husks) was sampled to estimate the weight of the total aboveground dry matter (including grain). A subsample of grain and a subsample of the rest of the aboveground material was oven dried at 65° until constant weight, ground and analysed for total N by combustion (TruSpec CN, LECO, St. Joseph, MI, USA); in site#2, the total N uptake in the NL plots was not measured.

For a given site and scenario, the nitrogen use efficiency (NUE) and the apparent nitrogen recovery (ANR) in each plot "Px" were calculated according to Eq 2. and Eq 3., respectively, using the average grain yield and total plant N uptake of the unfertilized treatment (T0).

$$NUE = \frac{Grain\ yield\ in\ Px - Grain\ yield\ in\ T0}{N\ applied\ in\ Px} \qquad [1]$$

$$ANR = \frac{N\ uptake\ in\ Px - N\ uptake\ in\ T0}{N\ applied\ in\ Px} \qquad [2]$$

2.4. Statistical analysis

Analysis of variance were performed separately for each site, considering the pre-plant SMN scenario as random and fertilizer treatment as a fixed factor. For a given site, the experimental design was analysed as a split-plot with correlated whole plots (pre-plant SMN scenarios). The effect of the two factors on the different measured variables was modelled using the GLIMMIX procedure (SAS software, University Edition 3.8, SAS Institute Inc., Cary, NC, USA), according to the procedure proposed by Littell et al. (2006) and considering a first-order autocorrelation structure among the whole plots. When the factor fertilizer treatment was significant, multiple comparisons among treatments for each SMN scenario were performed using the Tukey test at p = 0.05. When the distribution of residuals of the analysis was not normal (Shapiro-Wilk test), the variables were transformed using a Box-Cox (leaf CM readings) or log x (pre-plant SMN, harvest SMN, nitrate content in basal stalks) transformations. After these transformations, the variances were reasonably homocedastic (Levene test) and no further transformations were applied.

3. **Results**

3.1. Rate of N fertilizer applied with the different N-decision tools

The application of three rates of N fertilizer in the precedent year created different pre-plant SMN scenarios ($p<0.05$) before maize planting for the experiment (Fig. 1). In the 5 sites, SMN scenarios represented three different situations that can occur in actual maize fields depending on field management history (crop, N fertilization, organic inputs, residue management) and leaching conditions before planting. Thus, averaging over sites, the pre-plant SMN in the upper part of the soil profile was 58 (SE=16), 90 (SE=20), and 179 (SE=34) kg N ha^{-1} in the Low, Medium, and High pre-plant SMN scenarios, respectively. For a given site and SMN scenario, no significant ($p>0.05$) differences in pre-plant SMN between fertilizer treatments were found (data not shown), which indicates comparable available pre-plant SMN.

The treatments affected the total N applied in the different plots included in the study (Fig. 2). Overall, the SB treatment (soil criteria) used lower N application rates than the FR treatment (fixed rate) in 9 out of the 15 considered combinations (5 sites x 3 pre-plant SMN scenarios). However, averaging over sites, SB increased the N applied (by 8%) in the low SMN scenario while reducing the N applied in the medium SMN (by 7%) and high SMN scenario (by 35%) compared to those applied in FR. The CM treatment also used lower N rates than FR in 13 out of the 15 situations. Averaging over sites, CM reduced the N applied by 20% (low SMN), 22% (medium SMN), and 24% (high SMN) compared to the N applied in the same scenarios in the FR.

Comparing the two variable decision tools (SB vs CM), the CM produced a similar ($p>0.05$) N fertilizer dose as SB in 5 out of 15 SMN x site combinations, while in 6 situations, CM produced a 34% ($p<0.05$) lower N fertilizer dose than SB. However, at three sites (#1, #3, and #5), all in the high

SMN scenario, the calculated dose was higher for the CM (166 kg N ha^{-1}) than for the SB treatment (81 kg N ha^{-1}) showing that the two methods can differ significantly.

Only in two situations (Site #2 and #4 , low SMN), the calculated amount of N fertilizer using any of the decision tools (FR, SB, CM) was similar to that used in the NL treatment. In other thirteen situations, the NL plots received greater N doses than the other treatments, proving the advantage of using any of the proposed decision tools to determine the N rate.

More detailed information of pre-plant SMN, CM reading at V14, and N fertilizer rates in the different treatments are presented in Table S2 (Supplementary material).

3.2. Nutritional status of maize (SPAD readings and nitrate content of basal stalk)

Pre-plant soil nitrate levels affected SPAD readings across the sites at R1 stage. SPAD values were lower for the T0 treatments than for the decision tool treatments at all sites under low SMN (on average 38% lower), in 3 out 5 sites under medium SMN (on average 21% lower), and not significantly different under high SMN. At none of the 15 situations did the NL treatment produce greater SPAD readings than those in the three decision tools treatments. There were no differences in the SPAD readings among the three decision tool treatments (Table 3).

For basal stalk nitrates, three of the nine cases had significant differences among the four fertilizer treatments (Table 4), although according to a previous study under similar edapho-climatic conditions (Isla et al., 2015), most of the values observed in the table can be considered low. Plots from the control treatment without fertilizer (T0) tended to present lower nitrate in stalks than the other treatments although the differences were not significant in most cases. For a given treatment, the nitrate in basal stalks increased as the pre-plant SMN increased (from low to high), indicating differences in plant nitrogen uptake associated with the different SMN scenarios. In general, SB treatment (adjusting N fertilizer using soil analysis) tended to yield lower nitrate stalk values than FR (fixed N rate) and CM (adjusting N fertilizer using CM readings), although differences were not always significant and depended on scenarios x sites.

3.3. Residual soil mineral nitrate

No significant differences between treatments were found in residual SMN after harvest in the high pre-plant SMN scenario at any of the three sites (Table 5). The residual SMN tended to be lower in the T0 (no N fertilizer) and SB treatments and higher in the NL treatment compared to those in the other treatments, but in most of the cases the differences among treatments were not significant.

3.4. Grain yield and N uptake

Maximum grain yield across sites ranged from 12.5 to 17.7 Mg ha^{-1} (Table 6), averaging 15.4 Mg ha^{-1}, indicating that high maize grain yields can be obtained under sprinkler-irrigated conditions in the two Spanish irrigated areas included in our study and are within the range normally found in these areas for long-season maize fields. Under low pre-plant SMN conditions, grain yield differed significantly ($p<0.01$) among treatments at all sites. However, these differences were associated with the lower yields observed in the T0 treatment across the 5 sites. Averaging over the 5 sites, the grain yield in the T0 treatment was reduced by 53% compared to that in NL (ranging from 34 to 77%). This significant reduction emphasizes the need to use adequate nitrogen fertilization to obtain maximum yields. No significant differences in grain yield were observed among the 3 different optimized N fertilizer treatments (FR, SB, and CM). Moreover, grain yield in these three treatments was not significantly lower than that obtained in the NL treatment.

Under medium pre-plant SMN conditions, in 4 of the 5 sites there were significant differences ($p<0.05$) in grain yield among treatments but, similar to those observed under low pre-plant SMN conditions, the differences are due to the lower yields obtained in the T0 treatment. In the medium pre-plant SMN, the non-fertilized plots yielded, averaging over sites, 31% less than the over-fertilized NL plots. No significant differences in grain yield were observed among the three different fertilization treatments. In addition, the grain yield of these treatments were not significant different from those obtained in the NL treatment.

Under high pre-plant SMN conditions, no significant ($p>0.05$) differences were found among any of the evaluated treatments at the five sites. Averaging over sites, the non-fertilized plots yielded a non-significant 4.9% less than the non-limiting N plots.

The total nitrogen uptake across all experimental plots ranged from 37 to 373 kg N ha^{-1} confirming the high maize N requirements under high yield conditions. The total N uptake was related to grain yield (R^2=0.61, p<0.001), although the slope (and the R^2) of the relationship between total N uptake and grain yield decreases as the SMN increases (Fig. 3). This effect was mainly associated with a dilution effect due to the decrease in grain and plant N concentrations as grain yield increases (data not shown). Averaging over sites (Table 7), the total N uptake in T0 was 112, 173 and 227 kg N ha^{-1}, which is 45, 65 and 75% of the total N uptake in the NL treatment for the low, medium and high pre-plant SMN scenarios, respectively.

3.5. Nitrogen use efficiency (NUE) and apparent nitrogen recovery (ANR)

Significant differences in NUE between some of the treatments were observed for the low and medium pre-plant SMN scenarios, but those differences disappeared in the high pre-plant SMN scenario except at site #5 (Fig. 4). In this way, significant differences ($p<0.05$) in NUE among treatments were found in 3 out of 5 sites in the low SMN and in the medium SMN scenarios. As expected, NUE decreases as pre-plant SMN increases. Thus, excluding the NL treatment, the average NUE was 35, 19, and 5 kg grain kg^{-1} N in the low, medium and high pre-plant SMN scenarios. Averaging over the 5 sites, the three decision tools (FR, SB, and CM) increased the NUE compared to that in the NL treatment. The increase tended to be higher in the medium SMN scenario (70% average increase in NUE) than in the low SMN scenario (37% average increase). Comparisons between the two variable rate methods (SB and CM) and the FR show different results among the sites, and there was no consistent difference in NUE due to the use of one variable rate method across the sites. However, under low and medium SMN scenarios, the CM increased NUE 23 and 29%, respectively, compared to SB (soil balance method). Under high SMN conditions, the NUE was low for all the evaluated treatments, although the SB method tended to present higher values than the other methods.

The apparent nitrogen recovery (ANR) was significantly affected by the pre-plant SMN. Averaging over sites ANR was 0.54, 0.35, and 0.27 kg N kg^{-1} N applied for the low, medium and high SMN scenarios, respectively. ANR behaved similarly to NUE since a strong relationship was observed between the two variables (averaged R^2 across sites of 0.83; $p < 0.01$). Thus, differences in ANR between treatments followed the same pattern than those observed for NUE.

4. **Discussion**

This study demonstrates the necessity of applying significant amounts of N in the highly productive irrigated areas to achieve the yield potential for the region. Under commonly found spring soil nitrates, at the low and medium pre-plant SMN levels, no N application reduced yield 28 and 46% relative to the non-limiting treatments.

Our results clearly demonstrate that with any of the three methods used to adjust N fertilization, the nutritional status of the plants, measured through SPAD readings and nitrate in the basal stalks, was not significantly affected compared to that in the non-limited N plots. More importantly, our study shows that there are several treatments (FR, SB, or CM) that will reduce N inputs and maintain yields over a range of initial soil conditions.

Recent studies in irrigated areas of Spain (Jimenez-Aguirre et al., 2014) indicate that the N fertilizer dose applied by farmers to maize is close to or even higher than the doses applied in the non-limited treatments (NL) included in our study. Depending on sites and pre-plant SMN, the use of any of the evaluated treatments to optimize N management (FR, SB, or CM) allows an absolute reduction of N application ranging between -6 (no reduction) to 236 kg N ha^{-1} (average reduction of 102 kg N ha^{-1}) compared with that used in non-limiting N plots without a significant decrease in grain yield (except at one site). According to our study, averaging over sites, optimizing N management led to a 28%

reduction in the residual SMN after maize harvest compared to that of the NL plots. This means a significantly lower risk of losses by leaching during the intercrop period. The possibility of significant reductions in the N applied to maize crops using estimation of pre-plant SMN compared to the average traditional farmer's practice (263 kg N ha^{-1}) was also described for the non-irrigated North China Plain area (Cui et al, 2008a) in maize, although that study was performed in non-irrigated conditions and with lower yield potential conditions (< 9 Mg grain ha^{-1}).

A fixed reduction of N rates according to regional rcommendations (FR) were able to reduce N rates and no yield penalties were observed. Therefore, it can be considered a good, although conservative practice to improve NUE in maize fields. The use of field specific information (SB and CM) were able to further improvement compared to the FR recommendation although require an additional effort for the maize producers. No clear advantage was observed between the two variable treatments (SB and CM) in terms of productivity, although CM tended to provide lower N rates under low and medium SMN conditions and higher N rates under high SMN.

Similarly to our study, Scharf (2001) found, under conditions in the Midwestern United States, that N rate recommendations for maize based on soil tests or using chlorophyll meter readings were able to reduce N rates with no negative effect on profitability. However, the decrease in the N rates obtained was significantly lower than the estimated N rates in our study due to the lower potential grain yields (less than 10 t ha^{-1}) in the mentioned study.

Under similar irrigated Mediterranean conditions to those included in our study, Cela et al. (2013) showed the feasibility of predicting N fertilizer needs to maximize yields using pre-plant (or pre-sidedress) soil nitrate tests. In their study, a CNC (minimum nitrate in 0-30 cm soil depth before planting + N applied as fertilizer necessary to reach maximum yield) of 193 kg N ha^{-1} was obtained for maize plots with a non-legume as the precedent. A comparison of the doses of N fertilizer proposed by the empirical approach of that study and the doses applied in our study (Fig. 5) by the soil balance method shows better agreement (averaged difference of 25 kg N ha^{-1}) for the plots located in the same region (Ebro Valley), but larger differences between the two approaches for the Castilla-La-Mancha

(CLM) region plots (averaged difference of 116 kg N ha^{-1}). This result emphasizes the necessity of using regional information to derive useful N management tools and the risk of using pre-plant SMN critical values derived from different soil types and environmental conditions. This study raises the question of whether a relatively more sophisticated approach of using a soil N balance (as used here), with estimation of potential yield, N mineralization rate, N from irrigation water, and soil sampling, is preferable compared with the approach exclusively based on mineral (Nmin) proposed by Cela et al. (2013). In our opinion, the soil balance method, due to his greater complexity compared to that of the CNC method, can provide a better fine-tuning of the actual N needs when the fields deviate from the predominant conditions in the region. In addition, SB can take into account the high (or low) yield potential of some specific fields. However, the application of the SB method as used in our experiment, requires a reasonable previous knowledge of the soil mineralization rate during the maize growing period, the amount of N in irrigation water, and an acceptable estimate of the efficiency of the N fertilizer.

The cost of implementing the evaluated N management treatment is not easy to estimate. It may vary with, among other factors, the selected treatment, the expected soil field variability and the field size, which impact the soil and plant sampling number necessary to obtain an accurate estimation of soil availability or crop nutritional status. If we consider a rough estimation of 15-20 €/ha (cost of laboratory determination plus labour of soil or plant sampling), the economic viability of introducing the studied N management tools seems possible, due to the substantial reductions associated with the lower N fertilizer rates . The estimated cost of using a chlorophyll meter can be similar to that of using a methodology that relies on pre-planting SMN (SB) and will mostly depend on the total maize area in which the equipment is used. Implementation-cost comparisons among countries are questionable due to significant differences in labour and device prices among countries. As the pre-planting SMN increases, the potential benefits of using methods that rely on soil or plant analysis increase due to the higher possibility of reducing the standard N fertilizer rates. The use of active decision tools (SB and CM) can be of special interest in maize sown after an alfalfa crop (Cela et al., 2011), when the soil availability of N increases significantly due to the higher soil N-mineralization rate compared with a maize grown after maize. Under these situations, it could be advantageous to perform the soil sampling before the first sidedress application (aproximately V6 stage) instead of at pre-planting. This delay in soil sampling would help to better capture the high N mineralization rates from alfalfa residue. The differential N-fertilizer response of maize cropped after alfalfa compared to maize after maize has been demonstrated in the Ebro Valley (Cela et al., 2011) and other areas and could be incorporated as further adjustment to the SB treatment, while the CM methodology already is able to detect the higher SMN available at later maize growth stages.

Considering an average value of 813 €/t N for the urea fertilizer (2010-2018, MAPAMA 2019), the potential fertilizer cost reduction associated with the use of the three different treatments, compared to that of the NL treatment, ranged from 53 to 131 € ha^{-1} (Fig. 5) depending on the selected treatment and the pre-plant SMN. However, despite this potential cost reductions from the implementation of the presented N-fertilizer decision tools, the use of such tools is very limited, probably due to the risk-adverse tendencies of many farmers. Thus, most of farmers prefer to over-apply N as an insurance cost to prevent yield reductions in the whole field or in some specific areas. According to surveys in recent years, N rates applied to maize fields have been reduced (Jimenez-Aguirre et al., 2014). This likely reflects an increased awareness by farmers of the issues surrounding N over-applications and the shifting from flood to sprinkler irrigation systems allowing higher efficiencies of N applied. However, the adoption of fine-tuned N-management strategies (SB or CM treatments) is extremely rare. The promotion of more environmentally friendly but productive and economically sustainable agriculture must be a shared public/private responsibility, especially in the case of European Union countries in which farmers receive significant subsidies. More efforts must be made through farmers' extension programmes to progressively improve the farmers' N management practices.

5. **Conclusions**

Our results emphasize the technical viability of reducing the actual N rates used by maize growers under high productivity irrigated conditions, maintaining yields and reducing the potential negative effects of excessive N in agroecosystems. In most of the situations, the use of fine-tuned recommendation tools, such as a the soil balance approach or the use of a portable leaf chlorophyll meter, can reduce the dose of N applied compared to the dose from a standard reduction that does not consider the site-specific conditions of the field. Although the associated costs of using these fine-tuning tools are not large compared to the potential decrease in costs from using lower amounts of N fertilizer, the inclination of farmers to use these tools on a routine basis is difficult to predict due their particular idiosyncrasies, aversion to risk, and acceptance of over-fertilization as an insurance cost. To expect the general adoption of the presented methodologies without public incentives (or penalties), assuming an increase in ecological awareness, may be too optimistic, but continuous outreach should be made to maize producers to persuade them about the possibility of simultaneously reducing their costs and the negative effects of the misuse of nitrogen fertilizers on air and water resources.

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Table 1. Summary of general crop management characteristics of field trials

Site	#1	#2	#3	#4	#5
Year	2010	2010	2011	2011	2012
Location	Zaragoza	Albacete	Almudévar	Albacete	Almudévar
Coordinates	41º44’N	39º 3´N	42º02’N	39º 3´N	42º02’N
	0º49’W	2º 5´W	0º34’W	2º 5´W	0º34’W
	222 m	695 m	456 m	695 m	456 m
Number of plots	63	51	60	60	60
Plot size (m)	4.5x12	3.75x10	4.5x12	3.75x10	4.5x12
Plant density	74782	85432	73333	70733	72125
Previous crop	barley	maize	maize	maize	maize
Sowing date	10 May	5 May	12 April	28 April	26 April
Harvest date	7 Oct.	8 Oct	25 Oct.	25 Oct.	3 Oct.
N sidedress 1	June 29	June 21	June 9	June 21	June 6
N sidedress 2	July 23	July 23	July 12	June 30	July 16
Irrigation + Rain (mm)[1]	669	606	926	747	765
Crop E.T. (mm)[2]	683	559	789	717	755

[1] – during the growing period; [2] – estimated by Penman-Monteith and FAO methodology

Table 2. Main soil characteristics of the different experimental sites

Site	#1	#2, #4	#3, #5
Soil depth (m)	1.20	0.60	>1.20
pH[1] (1:2.5; H_2O)	8.42	8.4	7.8
USDA texture class[1]	loam	sandy-clay-loam	silty-clay-loam
Coarse portion (%)[1,2]	0-20	40	< 1
Organic matter (%)[1]	1.47	1.74	1.91
Carbonates[1] (%)	37	48	34
Olsen P[1] (mg kg^{-1})	11	26	24
K[1] (ammonium acetate, mg kg^{-1})	106	290	386

[1] – upper part of the soil profile; [2] - % particles >2 mm

Table 3. Mean values of SPAD readings during the reproductive stage of maize (R1-R2). For a given site and N scenario, least square means followed by the same letter are not significantly different (p>0.05; Tukey's test).

Treat./ Site#	#1	#2	#3	#4	#5
	---------------------- Low pre-plant SMN -----------------------				
T0	34.5 a	34.2 a	45.6 a	44.5 a	45.3 a
FR	52.7 b	51.5 b	58.8 b	55.9 ab	60.1 b
SB	52.6 b	52.6 b	54.9 b	56.1 ab	60.2 b
CM	53.1 b	50.9 b	55.7 b	57.5 b	60.3 b
NL	55.8[1] b	57.8[1] b	55.8 b	57.5 b	59.8 b
	---------------------- Medium pre-plant SMN -----------------------				
T0	39.3 a	41.7 a	51.8	56.3	48.2 a
FR	54.9 b	52.0 b	56.3	58.9	60.0 b
SB	54.7 b	51.2 b	57.6	59.7	59.7 b
CM	55.1 b	52.5 b	59.0	58.8	58.5 b
NL	53.9[1] b	56.9[1] b	58.3	61.2	62.0 b
	---------------------- High pre-plant SMN -----------------------				
T0	53.9	51.8	55.0	56.2	56.9
FR	57.5	50.9	56.7	58.7	59.6
SB	56.7	54.3	54.2	59.1	58.1
CM	56.2	52.4	56.3	58.0	55.9
NL	55.3[1]	56.0[1]	57.0	62.1	61.9
SMN	**	ns	Ns	**	ns
Treatment	**	**	**	**	**
SMN x Treat.	**	**	ns	ns	**

T0 – No fertilizer; FR – Fixed rate; SB – Soil balance; CM – SPAD reading; NL – Non limiting

[1] – only one replication available; ns p>0.05; * p<0.05; ** p<0.01

Table 4. Mean values of nitrate (mg NO_3^-–N /kg) in the base of the maize stalk at harvest in the different treatments and pre-planting soil mineral nitrogen scenarios. For a given site and N scenario, the least square means followed by the same letter are not significantly different (p>0.05, Tukey's test).

Treat./Site	#1	#3	#5
	----- Low SMN -----		
T0	62	17 a	11 a
FR	222	859 c	139 ab
SB	59	114 ab	67 ab
CM	215	157 ab	43 ab
NL	-	1048 c	390 b
	----- Medium SMN -----		
T0	56 a	198 a	19 a
FR	873 b	820 ab	380 abc
SB	416 ab	187 a	83 ab
CM	393 b	955 ab	188 ab
NL	1062[1] ab	2128 b	696 b
	----- High SMN -----		
T0	787	197 a	209
FR	2345	1245 b	859
SB	1698	112 a	271
CM	1374	1199 b	196
NL	4685[1]	1794 b	1151
SMN	**	ns	*
Treat.	**	**	**
SMN x Treat.	ns	*	ns

T0 – No fertilizer; FR – Fixed rate; SB – Soil balance; CM – SPAD reading; NL – Non limiting

[1] – only one replication; ns p>0.05; * p<0.05; ** p<0.01

Table 5. Average of soil nitrate content after harvest (kg NO_3^--N ha^{-1}; 0-120 cm depth) in the different treatments and in three sites where soil measurements were taken. For a given site and SMN scenario, the least square means followed by the same letter are not significantly different (p>0.05, Tukey's test).

	------- Site #1 -------			------- Site #3 -------			------- Site #5 -------		
Treat.	Low	Medium	High	Low	Medium	High	Low	Medium	High
T0	73 a	23 a	273	78 ab	101	123	50	58	136
FR	131 ab	76 b	367	116 b	113	106	73	92	138
SB	101 ab	67 ab	321	69 a	82	137	66	75	82
CM	121 ab	132 b	332	83 ab	137	113	56	64	135
NL	461[1] b	143[1] b	663[1]	85 ab	186	126	55	139	198
Signif.	*ns*	*	*ns*	*	*ns*	*ns*	*ns*	*ns*	*ns*

T0 – No fertilizer; FR – Fixed rate; SB – Soil balance; CM – SPAD reading; NL – Non limiting

[1] – only one replication for this treatment

Table 6. Average of maize grain yield (Mg ha^{-1}) for the different sites, scenarios, and fertilizer treatments. For a given site and scenario, the least square means followed by the same letter are not significantly different (p > 0.05, Tukey's test).

Treat./Sites	#1	#2	#3	#4	#5
	---------------- Low pre-plant SMN ----------------------				
T0	3.33 a	4.05 a	9.92 a	8.57 a	7.66 a
FR	9.41 b	14.12 b	15.89 b	15.60 b	15.16 b
SB	9.32 b	15.72 b	15.18 b	16.03 b	14.57 b
CM	8.82 b	14.58 b	14.91 b	15.70 b	13.60 b
NL	9.82[1] b	17.04[1] b	15.12 b	14.66 b	15.29 b
	---------------- Medium pre-plant SMN ----------------------				
T0	5.69 a	10.70 a	13.28	14.25 a	8.99 a
FR	11.01 b	16.80 b	15.28	16.14 b	14.31 b
SB	10.54 b	15.41 b	15.81	16.38 b	14.46 b
CM	10.67 b	16.03 b	16.24	16.59 b	14.35 b
NL	11.92[1] b	16.34[1] ab	15.93	15.87 ab	15.85 b
	---------------- High pre-plant SMN ----------------------				
T0	12.31	15.19	13.24	15.44	13.34
FR	12.33	16.40	14.48	15.67	14.46
SB	12.45	17.03	13.78	16.02	15.22
CM	12.49	16.67	14.45	15.44	13.76
NL	11.46[1]	18.46[1]	13.95	16.20	14.92
SMN	**	ns	<0.1	**	**
Treatment	**	**	**	**	**
SMN x Treat.	**	**	<0.1	**	**

T0 – No fertilizer; FR – Fixed rate; SB – Soil balance; CM – SPAD reading; NL – Non limiting

[1] – one replication available; ns $p>0.05$; * $p<0.05$; ** $p<0.01$

Table 7. Total N uptake (kg N ha^{-1}) of the unfertilized treatment (T0) and in brackets, the percentage compared to the total N uptake in the over-fertilized treatment (NL). Data are presented for the different sites and pre-plant SMN scenarios.

	SMN		
Site	Low	Medium	High
#1	56 (34)	83 (43)	203 (89)
#2[1]	66 (-)	163 (-)	261 (-)
#3	116 (48)	195 (69)	178 (71)
#4	118 (44)	195 (75)	226 (72)
#5	124 (43)	153 (52)	240 (82)
Mean	96 (46)	158 (65)	221 (78)

[1] – Not available

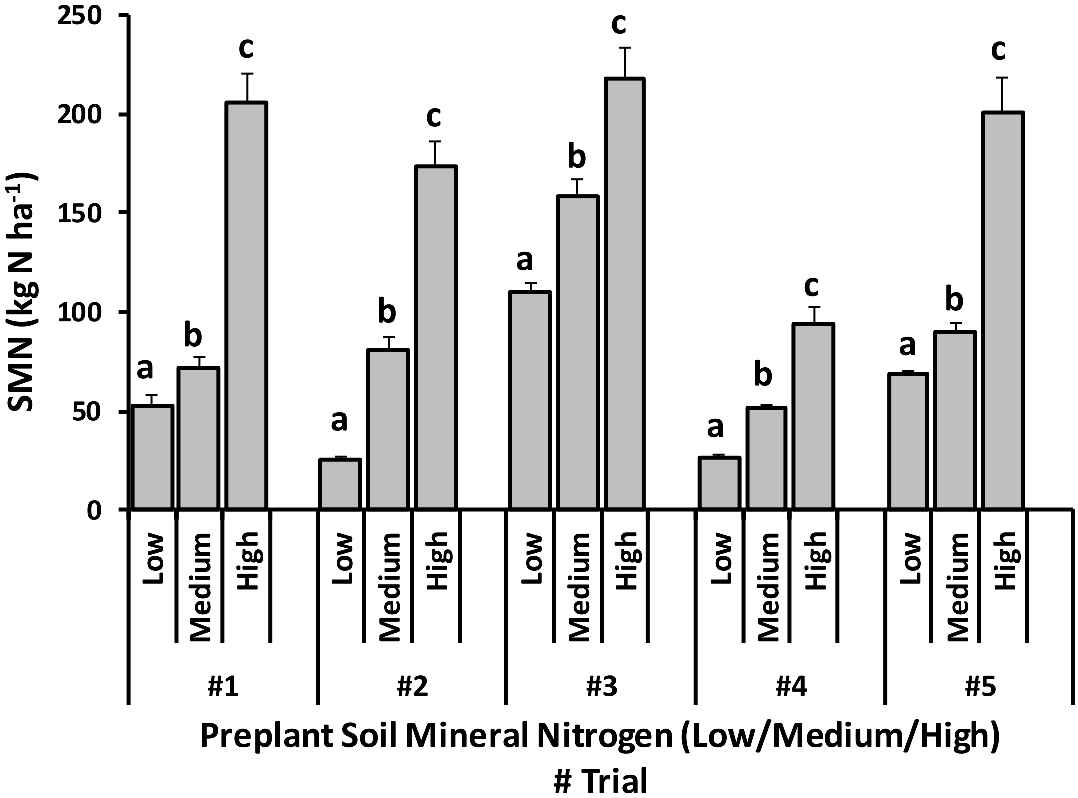

Figure 1. Mass of soil mineral nitrogen (SMN; mean ± standard error, kg N ha^{-1}) before maize planting in the upper part of the soil profile (0-60 cm in trials #1, #3, #5 and 0-40 cm in #2, #4) in the five trials and for the three scenarios of pre-planting soil nitrate content (Low, Medium, and High).The vertical bar indicates the standard error. Bars followed with the same letter are not significantly different (p>0.05, Tukey's test).

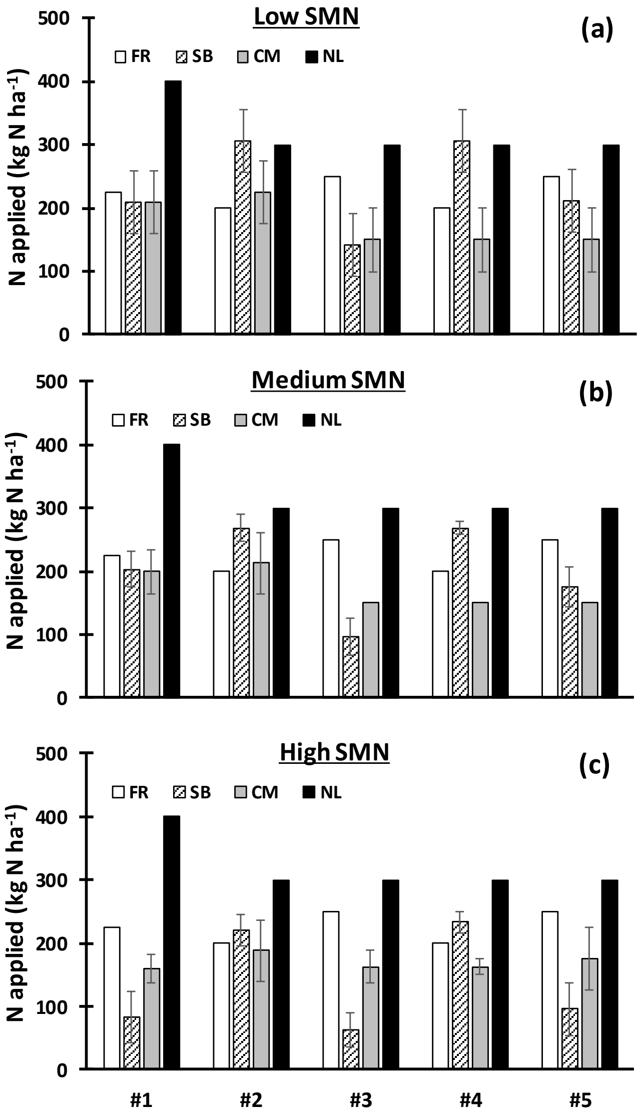

Figure 2. Average of the total dose of N fertilizer (kg N ha^{-1}) applied to the different treatments in the six trials. The vertical line indicates the standard deviation. Treatments: FR- fixed rate; SB – soil balance; CM – chlorophyll meter reading; NL – non-limiting treatment.

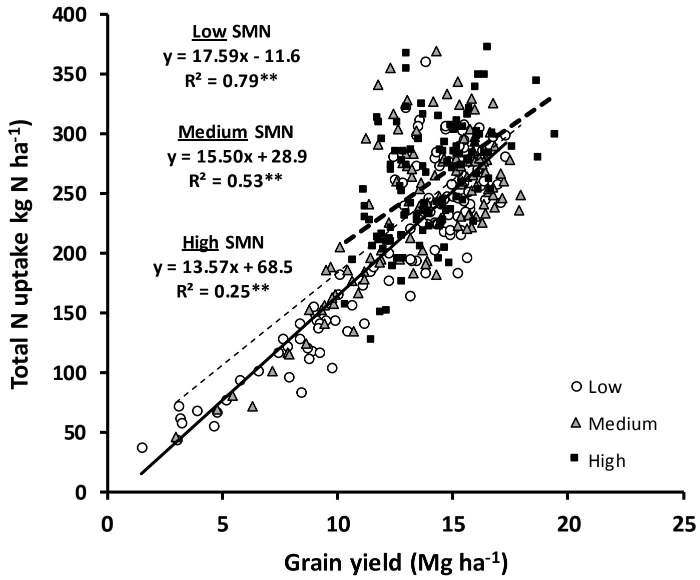

Figure 3. Relationship between total nitrogen uptake and grain yield for the different pre-planting SMN scenarios. Data from different sites were pooled.

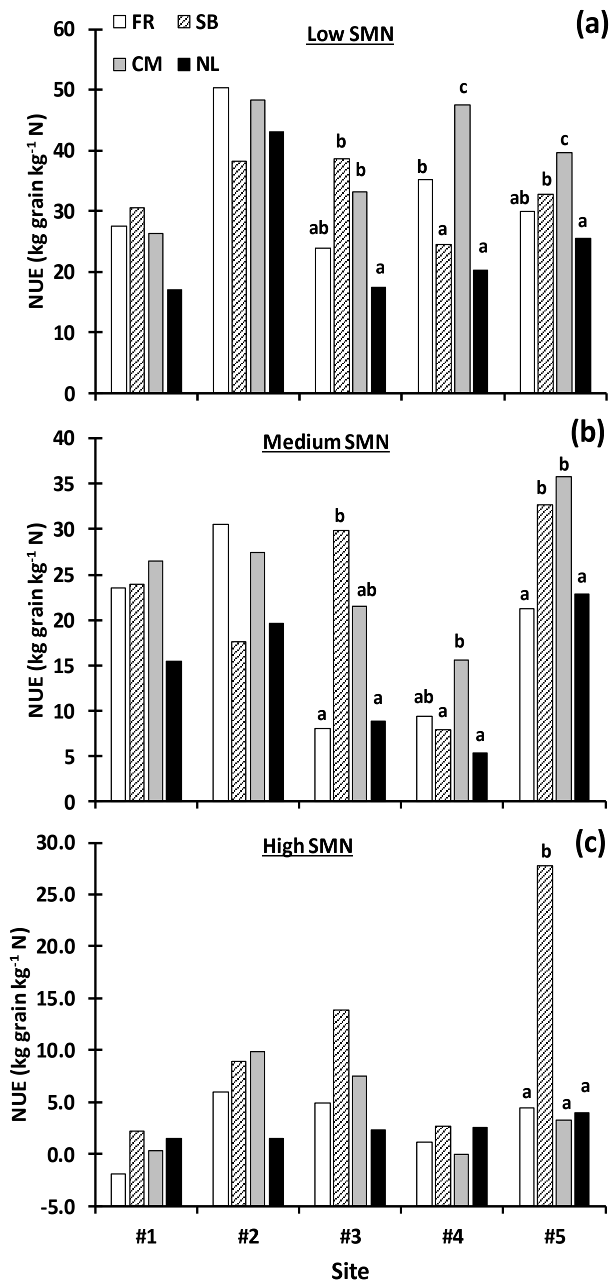

Figure 4. Nitrogen use efficiency (NUE, kg grain in Ti – kg grain in T0 kg^{-1} N applied) for the different sites, SMN scenarios (a, b, and c), and fertilizer treatments (FR: fixed rate; SB: soil balance; CM: chlorophyll meter; NL: non-limiting). For a given site and scenario, the least square means followed by the same letter are not significantly different (P > 0.05, Tukey's test).

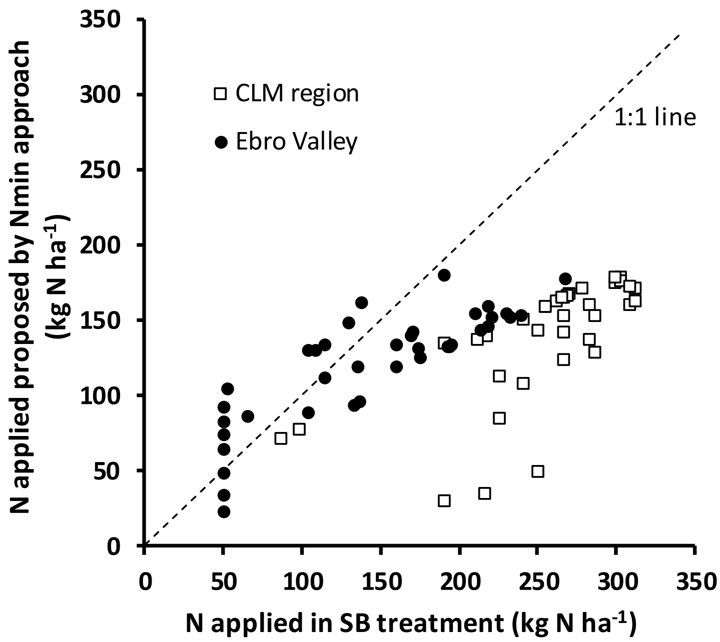

Figure 5. Relationship between the N rates (kg N ha^{-1}) proposed by the N min method (Cela et al., 2013) and the N rates applied in the present study using the SB criteria separately for the two regions studied (Castilla La Mancha-CLM and Ebro Valley). A critical value of 193 kg N ha^{-1} of N available (SMN at 0-30 cm depth at preplanting + N applied with fertilizer) was used to calculate the doses (sprinkler-irrigated plots with cereal as preceding crop).

Supplementary Material

Table S1. Monthly meteorological data in the experimental sites. Cumulative potential evapotranspiracion (Eto, Penman-Monteith), pluviometry (P) and average air temperature (Tmed).

	-------- Site #1 -------			-------- Site #2 -------			-------- Site #3 -------			-------- Site #4 -------			-------- Site #5 -------		
Month	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**
Jan	34.7	35.8	5.5	30.1	55.4	4.4	26.4	19.4	3.6	31.1	16	4.5	46.0	1.6	5.4
Feb	43.6	27	6.1	40.5	65.6	5.8	58.5	13.3	6.8	53.4	25.2	5.8	76.2	0.8	4.0
Mar	80.9	34.7	9.2	69.0	61.4	7.6	76.3	90.5	9.0	67.5	40.4	7.9	98.5	12.0	10.0
Apr	101.1	30.2	13.5	100.7	55.8	11.9	124.3	16.2	14.5	106.5	46.2	13.8	100.4	72.0	11.0
May	149.7	26.1	15.7	132.1	39.4	13.9	166.5	35.5	17.8	130.2	39.4	16.6	161.0	7.9	17.8
Jun	170.5	35.2	20.5	156.1	43.2	19.3	189.9	0.7	20.6	185.0	13.2	21.3	196.4	37.7	22.4
Jul	210.1	6.4	25.1	218.2	0	25.5	217.9	6	22.1	209.8	0.4	23.8	215.2	8.3	23.1
Aug	180.0	17.8	23.4	184.5	14.4	24.2	177.4	4.57	23.8	196.9	2.6	24.4	196.2	30.3	25.0
Sep	113.6	28.6	19.1	122.4	44	19.1	127.3	8.82	20.5	132.6	4.6	20.4	129.3	18.0	19.4
Oct	77.6	28.9	13.9	81.8	35.4	12.8	79.9	32.44	14.5	81.0	0	15.1	71.5	162.7	14.3
Nov	41.2	22.4	8.3	39.9	39.2	7.0	27.3	51.06	10.2	32.4	1.8	9.3	36.5	29.7	8.9
Dec	27.4	11.6	4.3	27.5	94.8	4.8	36.4	5	6.4	31.3	6	4.8	33.9	17.4	6.2
Total:	1230	305	13.7	1203	549	13.0	1308	283	14.2	1258	196	14.0	1361	398	14.0

Table S2. Averaged values of pre-plant soil mineral nitrogen (0-60 cm, SMN), pre-plant N fertilizer, total N fertilizer, N applied with irrigation water, and SPAD reading at V14.

Treat.	Pre-plant SMN kg N ha^{-1}	Pre-plant N applied kg N ha^{-1}	Total N applied kg N ha^{-1}	N irrig. wáter kg N ha^{-1}	SPAD
		-------------------------------- Site #1 -------------------------------			
			---------- Low pre-plant SMN ----------		
T0	64	0	0	11	36.8
FR	31	50	225	11	54.6
SB	68	50	209	11	54.1
CM	41	50	210	11	54.1
NL	79	100	400	11	55.2
			---------- Medium pre-plant SMN ----------		
T0	90	0	0	11	42.4
FR	62	50	225	11	55.2
SB	71	50	203	11	54.3
CM	61	50	200	11	54.6
NL	91	100	400	11	57.6
			---------- High pre-plant SMN ----------		
T0	234	0	0	11	57.3
FR	200	50	225	11	56.3
SB	181	50	83	11	57.6
CM	230	50	160	11	56.9
NL	102	100	400	11	59.0
		Site #2			
			---------- Low pre-plant SMN ----------		
T0	21	0	0	40	37.4

FR	23	50	200	40	48.6
SB	29	50	306	40	48.9
CM	27	50	225	40	46.5
NL	n.a.	100	300	40	53.9
		---------- Medium pre-plant SMN ----------			
T0	93	0	0	40	44.6
FR	79	50	200	40	48.4
SB	85	50	269	40	48.4
CM	66	50	213	40	49.0
NL	n.a.	100	300	40	52.8
		---------- High pre-plant SMN ----------			
T0	204	0	0	40	48.5
FR	140	50	200	40	50.2
SB	191	50	221	40	50.3
CM	158	50	188	40	51.1
NL	n.a.	100	300	40	55.0

Table S2. (cont.). Averaged values of pre-plant soil mineral nitrogen (0-60 cm, SMN), pre-plant N fertilizer, total N fertilizer, N applied with irrigation water, and SPAD reading at V14.

Treat.	Pre-plant SMN kg N ha^{-1}	Pre-plant fert. kg N ha^{-1}	Total N applied kg N ha^{-1}	N irrig. wáter kg N ha^{-1}	SPAD
		-------------------------------- Site #3 --------------------------------			
		---------- Low pre-plant SMN ----------			
T0	105	0	0	4	48.8
FR	121	50	250	4	57.7

SB	114	50	142	4	56.6
CM	118	50	150	4	56.6
NL	93	100	300	4	56.8
		---------- Medium pre-plant SMN ----------			
T0	147	0	0	4	53.0
FR	164	50	250	4	55.5
SB	151	50	96	4	57.5
CM	157	50	150	4	56.8
NL	173	100	300	4	56.7
		---------- High pre-plant SMN ----------			
T0	243	0	0	4	54.6
FR	213	50	250	4	56.2
SB	205	50	64	4	54.1
CM	258	50	163	4	54.6
NL	171	100	300	4	55.5
			Site #4		
		---------- Low pre-plant SMN ----------			
T0	27	0	0	40	44.5
FR	24	50	200	40	55.7
SB	27	50	306	40	56.7
CM	29	50	150	40	56.1
NL	22	100	300	40	57.5
		---------- Medium pre-plant SMN ----------			
T0	50	0	0	40	55.4
FR	56	50	200	40	58.0
SB	51	50	269	40	58.6
CM	46	50	150	40	57.5
NL	54	100	300	40	59.4

		---------- High pre-plant SMN ----------			
T0	88	0	0	40	54.5
FR	114	50	200	40	58.0
SB	85	50	233	40	57.9
CM	98	50	163	40	57.0
NL	86	100	300	40	59.7

Table S2. (cont.). Averaged values of pre-plant soil mineral nitrogen (0-60 cm, SMN), pre-plant N fertilizer, total N fertilizer, N applied with irrigation water, and SPAD reading at V14.

Treat.	Pre-plant SMN kg N ha^{-1}	Pre-plant fert. kg N ha^{-1}	Total N applied kg N ha^{-1}	N irrig. wáter kg N ha^{-1}	SPAD
		------------------------------- Site #5 -------------------------------			
		---------- Low pre-plant SMN ----------			
T0	63	0	0	4	50.6
FR	69	50	250	4	58.5
SB	69	50	212	4	57.5
CM	72	50	150	4	58.5
NL	69	100	300	4	59.1
		---------- Medium pre-plant SMN ----------			
T0	90	0	0	4	51.3
FR	88	50	250	4	57.1
SB	95	50	175	4	57.7
CM	95	50	150	4	58.3
NL	79	100	300	4	59.7
		---------- High pre-plant SMN ----------			
T0	194	0	0	4	57.5
FR	169	50	250	4	57.3
SB	164	50	96	4	59.4
CM	203	50	175	4	56.2
NL	285	100	300	4	59.8

Table S1. Monthly meteorological data in the experimental sites. Cumulative potential evapotranspiracion (Eto, Penman-Monteith), pluviometry (P) and average air temperature (Tmed).

	-------- Site #1 -------			-------- Site #2 -------			-------- Site #3 -------			-------- Site #4 -------			-------- Site #5 -------		
Month	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**	**Eto (mm)**	**P (mm)**	**Tmed °C**
Jan	34.7	35.8	5.5	30.1	55.4	4.4	26.4	19.4	3.6	31.1	16	4.5	46.0	1.6	5.4
Feb	43.6	27	6.1	40.5	65.6	5.8	58.5	13.3	6.8	53.4	25.2	5.8	76.2	0.8	4.0
Mar	80.9	34.7	9.2	69.0	61.4	7.6	76.3	90.5	9.0	67.5	40.4	7.9	98.5	12.0	10.0
Apr	101.1	30.2	13.5	100.7	55.8	11.9	124.3	16.2	14.5	106.5	46.2	13.8	100.4	72.0	11.0
May	149.7	26.1	15.7	132.1	39.4	13.9	166.5	35.5	17.8	130.2	39.4	16.6	161.0	7.9	17.8
Jun	170.5	35.2	20.5	156.1	43.2	19.3	189.9	0.7	20.6	185.0	13.2	21.3	196.4	37.7	22.4
Jul	210.1	6.4	25.1	218.2	0	25.5	217.9	6	22.1	209.8	0.4	23.8	215.2	8.3	23.1
Aug	180.0	17.8	23.4	184.5	14.4	24.2	177.4	4.57	23.8	196.9	2.6	24.4	196.2	30.3	25.0
Sep	113.6	28.6	19.1	122.4	44	19.1	127.3	8.82	20.5	132.6	4.6	20.4	129.3	18.0	19.4
Oct	77.6	28.9	13.9	81.8	35.4	12.8	79.9	32.44	14.5	81.0	0	15.1	71.5	162.7	14.3
Nov	41.2	22.4	8.3	39.9	39.2	7.0	27.3	51.06	10.2	32.4	1.8	9.3	36.5	29.7	8.9
Dec	27.4	11.6	4.3	27.5	94.8	4.8	36.4	5	6.4	31.3	6	4.8	33.9	17.4	6.2
Total:	1230	305	13.7	1203	549	13.0	1308	283	14.2	1258	196	14.0	1361	398	14.0

Table S2. Averaged values of pre-plant soil mineral nitrogen (0-60 cm, SMN), pre-plant N fertiliser, total N fertiliser, N applied with irrigation water, and SPAD reading at V14.

Treat.	Pre-plant SMN kg N ha^{-1}	Pre-plant N applied kg N ha^{-1}	Total N applied kg N ha^{-1}	N irrig. wáter kg N ha^{-1}	SPAD
		-------------------------------- Site #1	-------------------------------		
			---------- Low pre-plant SMN ----------		
T0	64	0	0	11	36.8
FR	31	50	225	11	54.6
SB	68	50	209	11	54.1
CM	41	50	210	11	54.1
NL	79	100	400	11	55.2
			---------- Medium pre-plant SMN ----------		
T0	90	0	0	11	42.4
FR	62	50	225	11	55.2
SB	71	50	203	11	54.3
CM	61	50	200	11	54.6
NL	91	100	400	11	57.6
			---------- High pre-plant SMN ----------		
T0	234	0	0	11	57.3
FR	200	50	225	11	56.3
SB	181	50	83	11	57.6
CM	230	50	160	11	56.9
NL	102	100	400	11	59.0
			Site #2		
			---------- Low pre-plant SMN ----------		
T0	21	0	0	40	37.4
FR	23	50	200	40	48.6
SB	29	50	306	40	48.9
CM	27	50	225	40	46.5
NL	n.a.	100	300	40	53.9
			---------- Medium pre-plant SMN ----------		
T0	93	0	0	40	44.6
FR	79	50	200	40	48.4
SB	85	50	269	40	48.4
CM	66	50	213	40	49.0
NL	n.a.	100	300	40	52.8
			---------- High pre-plant SMN ----------		
T0	204	0	0	40	48.5
FR	140	50	200	40	50.2
SB	191	50	221	40	50.3
CM	158	50	188	40	51.1
NL	n.a.	100	300	40	55.0

Table S2. (cont.). Averaged values of pre-plant soil mineral nitrogen (0-60 cm, SMN), pre-plant N fertiliser, total N fertiliser, N applied with irrigation water, and SPAD reading at V14.

Treat.	Pre-plant SMN kg N ha^{-1}	Pre-plant fert. kg N ha^{-1}	Total N applied kg N ha^{-1}	N irrig. wáter kg N ha^{-1}	SPAD
		------------------------------- Site #3 -------------------------------			
		---------- Low pre-plant SMN ----------			
T0	105	0	0	4	48.8
FR	121	50	250	4	57.7
SB	114	50	142	4	56.6
CM	118	50	150	4	56.6
NL	93	100	300	4	56.8
		---------- Medium pre-plant SMN ----------			
T0	147	0	0	4	53.0
FR	164	50	250	4	55.5
SB	151	50	96	4	57.5
CM	157	50	150	4	56.8
NL	173	100	300	4	56.7
		---------- High pre-plant SMN ----------			
T0	243	0	0	4	54.6
FR	213	50	250	4	56.2
SB	205	50	64	4	54.1
CM	258	50	163	4	54.6
NL	171	100	300	4	55.5
			Site #4		
		---------- Low pre-plant SMN ----------			
T0	27	0	0	40	44.5
FR	24	50	200	40	55.7
SB	27	50	306	40	56.7
CM	29	50	150	40	56.1
NL	22	100	300	40	57.5
		---------- Medium pre-plant SMN ----------			
T0	50	0	0	40	55.4
FR	56	50	200	40	58.0
SB	51	50	269	40	58.6
CM	46	50	150	40	57.5
NL	54	100	300	40	59.4
		---------- High pre-plant SMN ----------			
T0	88	0	0	40	54.5
FR	114	50	200	40	58.0
SB	85	50	233	40	57.9
CM	98	50	163	40	57.0
NL	86	100	300	40	59.7

Table S2. (cont.). Averaged values of pre-plant soil mineral nitrogen (0-60 cm, SMN), pre-plant N fertiliser, total N fertiliser, N applied with irrigation water, and SPAD reading at V14.

Treat.	Pre-plant SMN kg N ha^{-1}	Pre-plant fert. kg N ha^{-1}	Total N applied kg N ha^{-1}	N irrig. wáter kg N ha^{-1}	SPAD
		-------------------------------- Site #5 --------------------------------			
		---------- Low pre-plant SMN ----------			
T0	63	0	0	4	50.6
FR	69	50	250	4	58.5
SB	69	50	212	4	57.5
CM	72	50	150	4	58.5
NL	69	100	300	4	59.1
		---------- Medium pre-plant SMN ----------			
T0	90	0	0	4	51.3
FR	88	50	250	4	57.1
SB	95	50	175	4	57.7
CM	95	50	150	4	58.3
NL	79	100	300	4	59.7
		---------- High pre-plant SMN ----------			
T0	194	0	0	4	57.5
FR	169	50	250	4	57.3
SB	164	50	96	4	59.4
CM	203	50	175	4	56.2
NL	285	100	300	4	59.8