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Approaches for increasing nitrogen and water use efficiency simultaneously

Miguel Quemada*, Jose L. Gabriel

Technical University of Madrid, Department of Agricultural Production, Avd. Complutense s/n, 28040 Madrid, Spain

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ABSTRACT

Enhancement of water and nitrogen use efficiency simultaneously may provide advantages over optimization of water and nitrogen inputs separately. In addition, water is the driver of the main environmental problems caused by excessive nitrogen use, such as nitrate contamination of water bodies or increasing emissions of the greenhouse gas nitrous oxide. Therefore, management practices oriented towards reducing nitrogen losses and maintaining farm productivity should rely on optimizing nitrogen and water inputs at the same time. This manuscript identifies agricultural systems with strong interactions between water- and nitrogen-use efficiency. Measurements and approaches for applying new technologies to increasing nitrogen and water efficiency simultaneously are discussed.

1. Introduction

Water and nitrogen (N) availability remain, globally, the most limiting crop growth factors (Mueller et al., 2012). The additional demand for food by the growing population will require that we increase resource use efficiency of water and N for crops. Without underestimating the role of plant genetics, efficient management of water and N has been identified as crucial for closing the yield gap of main cereal crops (Sinclair and Rufty, 2012). Sustainable intensification of agriculture should rely, therefore, on defining management strategies towards increasing water and N use efficiency.

Plant growth is linearly related to water transpiration by the plant (Tanner and Sinclair, 1983). Therefore, crop water deficit leads to yield and biomass reductions and diminished N uptake. On the other hand, a good crop N nutritional status enhances crop tolerance to drought, and a moderate increase in N supply improves water use efficiency (WUE) in semiarid environments (Cossani et al., 2012). Biomass production is a function of the relationship between N and water availability and this relationship has been described it as co-limitation (Sadras, 2004). Co-limitation means that the plant growth response to water and N is greater than its response to each factor in isolation, and implies that strategies to maximize plant growth should ensure that both resources are equally available. In addition, nitrogen transport in the soil and absorption by roots are water limited. Thus, from the perspective of plant physiology or soil availability it is best to optimize N and water management simultaneously.

At a cropping system level most N losses are driven by water. Excessive water inputs, either by rain or irrigation, enhance leaching losses and soil conditions that favor denitrification. In developed countries, the environmental consequences of N losses from agricultural systems to water bodies is a major social concern with special attention to aquifer contamination by nitrate and excessive N availability in estuaries (Rabalais et al., 2002). The relevance of agriculture to N oxides and ammonia emissions is reflected in the various international agreements concerning air quality and global warming (Gothenburg Protocol, 1999; IPCC, 2007). In irrigated agriculture, water application is a management option that the farmers may use to enhance N use efficiency (NUE) and reduce losses. In rainfed cropping systems, adapting N management to water constraints may help to mitigate N losses and therefore increase WUE.

Water and N use efficiency can be described on various scales from the leaf to the field. In general terms, NUE is defined as the ratio between the N removed in harvest products (N outputs or N_{yield}) divided by the sum of all N inputs to a cropland (Zhang et al., 2015; Lassaletta et al., 2014; EUNEP, 2015). It may be further subdivided in several components depending on the purpose of the study. Nitrogen physiological efficiency (N_{yield}/Crop N) allows comparison of species or varieties in their ability to translocate absorbed N to the exported organs. Nitrogen recovery efficiency (Crop N/N input) is used for comparing management practices in

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* Corresponding author.
E-mail address: quemada@upm.es (M. Quemada).

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The analogous water indicator is WUE, defined as the ratio between crop yield or biomass and evapotranspiration (Tanner and Sinclair, 1983; Sadras, 2004). The transpiration efficiency (yield/transpiration) characterizes efficiency at a crop level, whereas WUE is used to compare among management practices. In irrigated cropping systems is common to calculate the efficiency of the water input (WUE_i) as the ratio between yield and incoming water (rainfall + irrigation). The WUE_i, including water loss in different ways (deep percolation, runoff, evaporation), is a valuable metric to compare the bioavailability and the efficient use of water resources.

Enhancement of water and N use efficiency simultaneously will provide advantages over optimization of water and N inputs separately. The benefits conferred by the interaction between NUE and WUE are crucial for increasing productivity in many cropping systems while mitigating environmental problems. The purpose of this paper is to discuss management measures to improve WUE and NUE simultaneously in cropping systems.

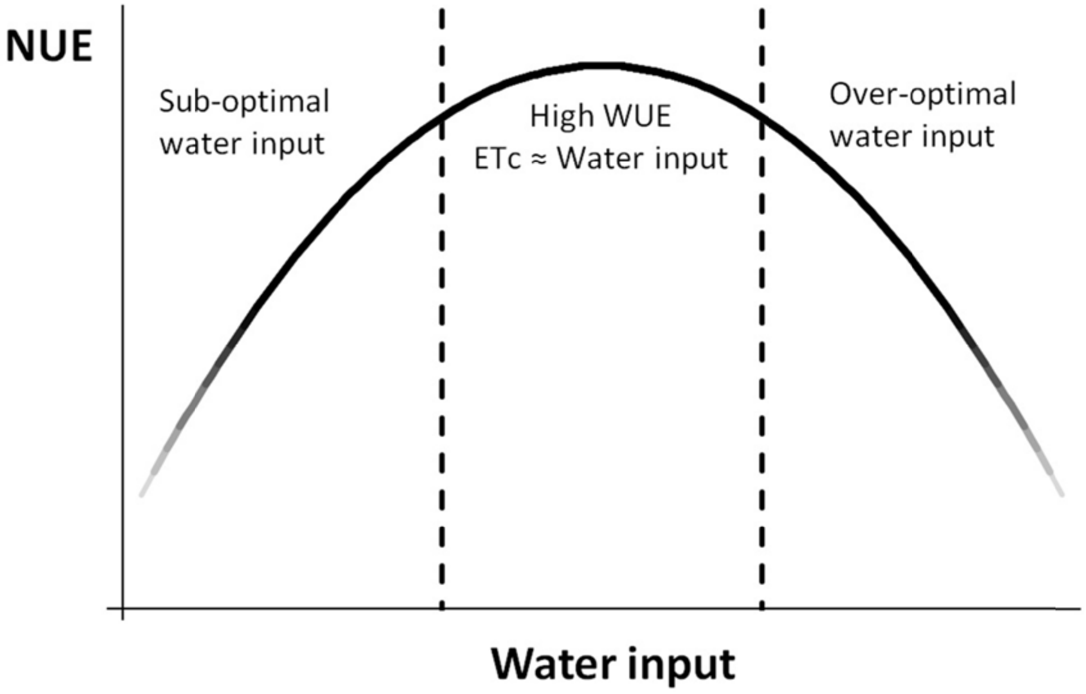

Figure 1. Schematic representation of the effect of water input on nitrogen use efficiency (NUE).

2.- Adjust N application to crop demand when limited by water availability

Low water availability occurs in many rainfed cropping systems. Rainfall greatly affects N outputs and is an important factor in the N response of rainfed crops. The result is that water limitation tends to decrease NUE drastically if N input is not reduced to match actual crop demand. As a general approach, the maximum NUE is expected when water inputs are close to crop water demand, whereas over- or suboptimal water inputs lead to a decrease in NUE (Fig. 1). We used a dataset of field experiments with wheat (*Triticum aestivum* L.) conducted during several years in Navarra (North Spain) to elaborate some relevant issues of rainfed crops (Arregui et al., 2006; Arregui and Quemada, 2008). It is a region with a large range of precipitation during the wheat grow season (from 300 to 700 mm). For each experiment we calculated the N response curve (N output versus N applied) and the optimal N rate was calculated by adjusting a quadratic-plateau model to the N output. Experiments in which no response was found due to high soil mineral N at planting were removed from the dataset. The optimal N rate increased parabolically with rainfall (Fig. 2a) and NUE and WUE were linearly related (Fig. 2b). The optimal N rate and the maximum N output increased with rainfall up to 500-600 mm, resulting in NUE values from 0.5 to 0.9. Further increases in rainfall led to increases in the optimal N rate with only small increases in N output, so NUE values occasionally fell below 0.5. Data with a very low optimal N rate, sometimes even zero, correspond to low rainfall areas with a low yield potential. In these data, soil mining (NUE >1) is common when evaluating the wheat season, however, including a fallow year or a legume in the crop rotation may be sufficient to balance N supply and crop demand (López-Bellido et al., 2012). In these systems, common in Mediterranean and semi-arid areas, N deposition and biological N fixation may be relevant contributions. Application of low fertilizers rates may enhance WUE but care should be taken as N rates larger than the optimal may decrease NUE drastically because of the low N output (Passioura and Angus, 2010). Similar results may occur in rainfed vineyards and olive orchards when growth is limited by low water availability: low input systems can attain a high NUE if N from natural sources is optimized, but with a high risk of decreasing NUE drastically if N inputs exceed crop requirements that are governed by natural water inputs.

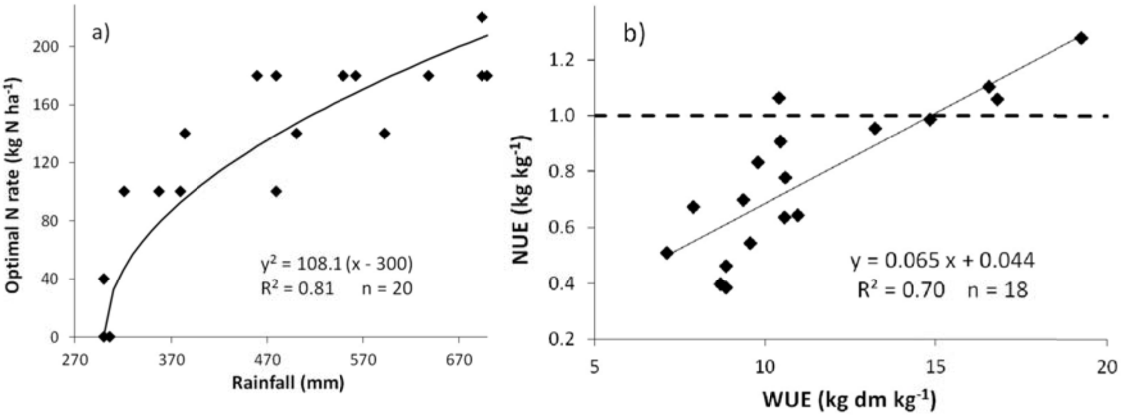

Figure 2. (a) Optimal nitrogen (N) rate versus rainfall during the growing season and (b) nitrogen use efficiency (NUE) versus water use efficiency (WUE) for wheat fertilization trials carry out in Spain. More detail about the experiments can be found in Arregui et al. (2006) and Arregui and Quemada (2008). NUE was not calculated when optimal N rate = 0.

3.- Improved water management in irrigated agriculture

In irrigated cropping systems, water application is a management option that interacts with the efficient use of N (Vázquez et al., 2006). When proper practices are used, irrigated agriculture can enhance sustainability of rural areas and is expected to supply much of the additional demand for food in the coming decades (FAO, 2003). However, the N in leachates and return flows may contaminate water bodies when crops are abundantly fertilized and watered to achieve high yield potentials (Isidoro et al., 2006). Improving water and fertilizer management practices should be a priority when designing policies to enhance farmer's profitability and mitigate diffuse pollution.

We calculated WUE and NUE from the dataset of a meta-analysis conducted to compare strategies to control nitrate leaching losses from irrigated cropping systems and their effect on yield (Quemada et al, 2013). All the water management strategies proposed had an effect on WUE_i and NUE. The most efficient strategy was to adjust water applications to match crop needs (Fig. 3). Excessive irrigation is a common practice to compensate for soil variability and avoid soil salt accumulation (Gabriel et al., 2012), but it deprives the soil of available N and reduces NUE. Because N losses are enhanced, overwatering is often accompanied by over fertilization leading to a vicious circle with low WUE_i and NUE. In this analysis, adjusting water application to match crop needs increased WUE_i >40% and NUE > 60%. However, there was high variability and the mean effect attained depended on the degree of excessive application. Improving the irrigation schedule and the technology of the water delivery system were also effective if they help to adjust water application to crop needs. Irrigation frequency is a major management tool to increase water and N efficiency and it may enable yields to be maintained even at reduced total application rates (Vázquez et al., 2006). Use of soil and plant moisture sensors to adapt water application to actual crop demand is one of the most promising techniques to further increase NUE and WUE simultaneously (Zotarelli et al., 2011).

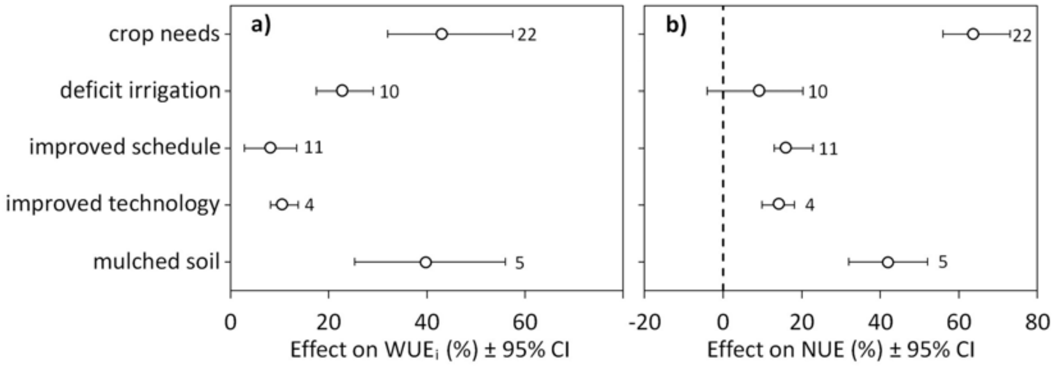

Figure 3. Effect of various management practices on (a) water use efficiency calculated by water input (WUE_i) and (b) nitrogen use efficiency in units of percent change from the control. The control for crop needs is excessive irrigation; the control for all other treatments is crop needs. Mean values and 95% confidence intervals of the back transformed response ratio obtained in a meta-analysis are shown. Sample sizes (i.e. the number of control-management practices pairs) are shown on the right of the confidence intervals. Details on the meta-analysis procedures can be found in Quemada et al. 2013.

In areas with limited water availability, deficit irrigation is a common practice. Deficit irrigation is defined as a reduction in water application with respect to crop needs that usually leads to a significant yield reduction (Fereres and Soriano, 2007). Provided that water scheduling is based on a good knowledge of the critical periods of the crop, the yield impact of decreasing water application can be minimized. As a result, deficit irrigation enhances WUE_i (Fig. 3). A decrease in crop growth is accompanied by lower N uptake, and even if N losses tend to decrease because of lower percolation, the effect on NUE is variable (Quemada et al., 2013). When yield is reduced because of deficit irrigation, N fertilizer application should also be reduced to match crop demand; otherwise a decrease in NUE is expected.

4.- Fertigation

Fertigation is a particular case of scheduled irrigation combined with nutrient applications. In conventional fertilization the fertilizer is split in one, two or three applications and usually broadcast or incorporated into the soil (Fig. 4a). After each fertilizer application there is an accumulation of soil available N that will be partially taken up by the crop. During a certain period there is N in excess of plant uptake that is prone to be lost, either by leaching or gaseous emission, and the losses cause a decrease in NUE. In fertigation the fertilizers are injected into the irrigation system and delivered with the irrigation water (Fig. 4b). Applications can be numerous and adapted to the crop demand, therefore, accumulation of soil N is reduced and so too the potential N lost. The final result should be a reduction on the N applied and an enhancement of NUE. In addition, fertigation associated with high-frequency drip irrigation causes a concentration of roots within wet bulbs in which nutrient application is localized. Moisture conditions of the wet bulbs favors the movement of nutrients to roots through mass flow or diffusion and the high root density enhances nutrient uptake, contributing to a better NUE.

The potential of fertigation to increase NUE and WUE simultaneously has been showed in several studies. As an example, Zotarelli et al. (2011) compare combinations of three N levels and three water treatments using high-frequency drip irrigation with bell pepper (*Capsicum annuum* L.) in Florida. There was a strong linear relationship between N uptake efficiency and WUE. The main reason for the low efficiency at high irrigation rates was the increase in drainage and nitrate leaching caused by excessive water application. Fertigation became a common practice in greenhouse production during the last decades of the 20th century, then it moved to open-field vegetable and fruit production, and now there are large fields of arable crops that are fertigated.

Despite the potential of fertigation for effective water and N saving, in practice there is a need for improvement in the management of this technology to make it effective. In a meta-analysis, fertigation did not have a significant effect on NUE or yield compared with side-dressing granular N fertilizer (Quemada et al., 2013). The over-optimal supply of N and water in fertigated systems was found to be a common practice in citrus orchards in the most important producing countries (Qin et al., 2016). Thus, there is significant room for improvement N fertigation technology to ensure optimal N and water supply to the crop.

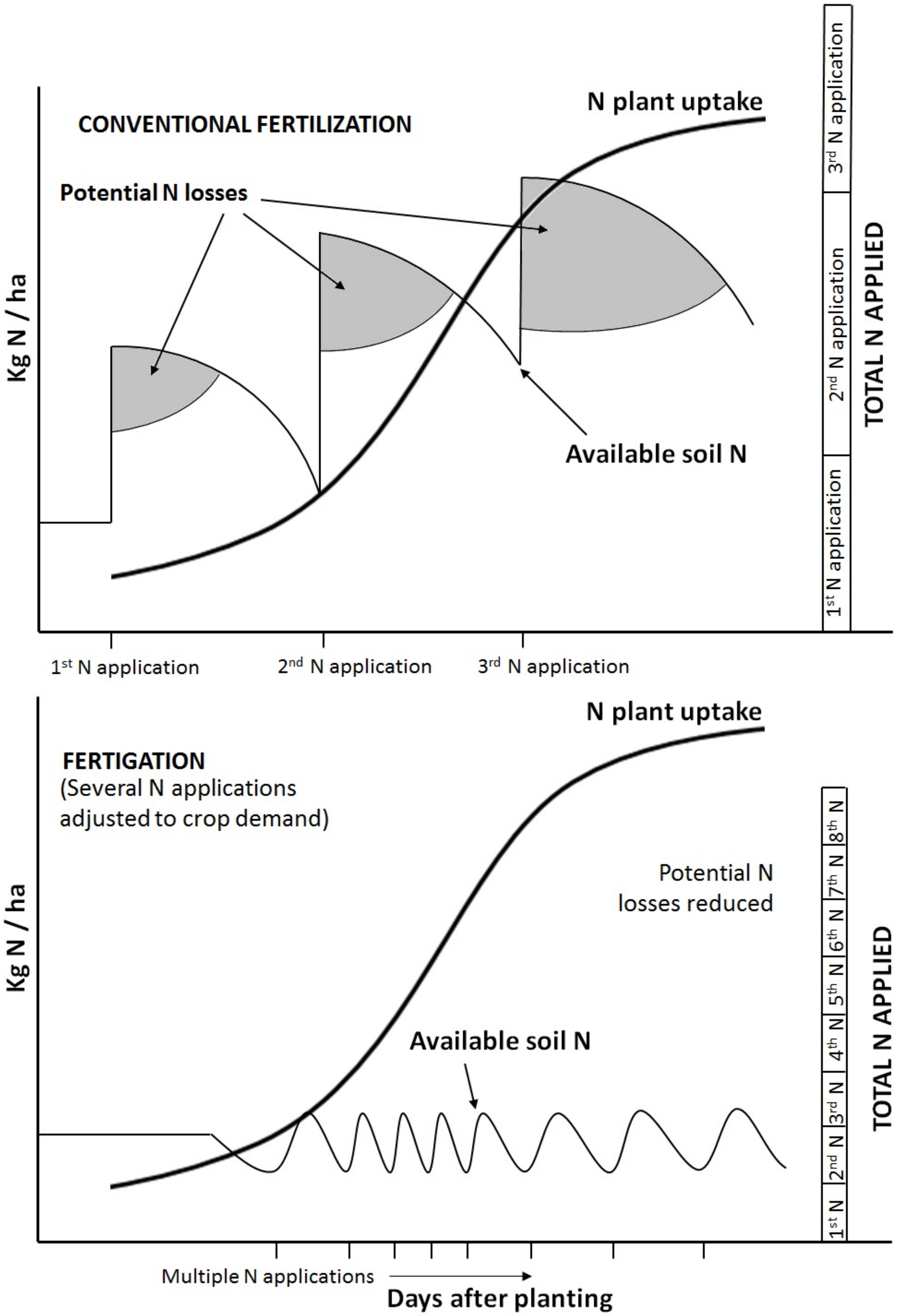

Figure 4. Schematic representation of plant N uptake, available soil N, N application via fertilizers and potential N losses in conventional fertilization and in fertigation.

5.- Soil mulching

Few studies on the combined effect of soil mulching on N and water use were included on the meta-analysis by Quemada et al. (2013) but all of them were consistent and showed a beneficial effect (Fig. 3). Compared to bare soil, the mean effect on NUE and WUE enhancement was ≈40%. Mulching, apart from other agronomic advantages, reduces direct soil evaporation and preserves water for crop transpiration, increasing WUE. At the same time, plastic mulching increased soil temperature and therefore N mineralization and root uptake, enhancing NUE. When combined with drip fertigation, plastic mulching protects the wet bulb from direct infiltration of rain that may cause nitrate leaching and reduce N availability (Romic et al., 2003).

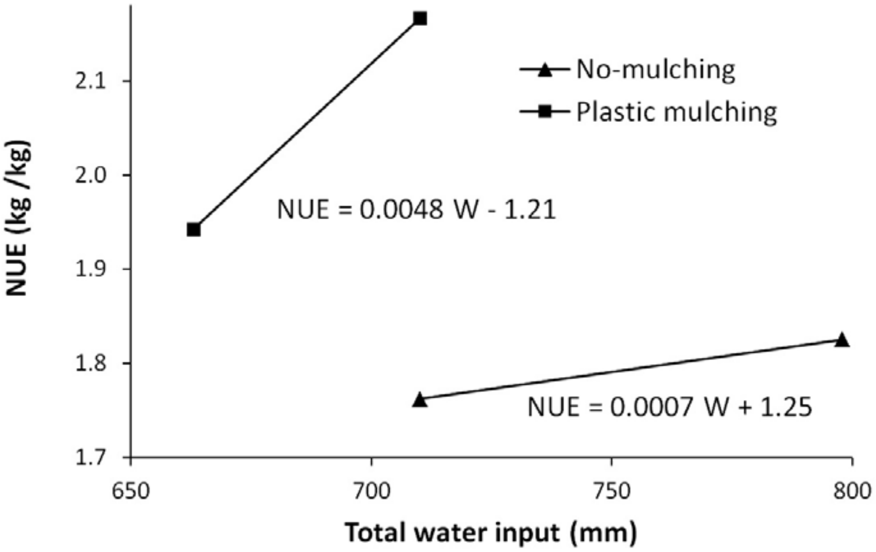

Figure 5. Nitrogen use efficiency (NUE) response to total water input (W) for processing tomato grow under black plastic mulched or bare soil (no-mulched) in an experiment conducted in the Ebro Valley (Spain).

In an experiment conducted in the Ebro Valley (Spain) comparing black plastic mulching and no-mulching in processing tomato (*Solanum lycopersicon* L.), NUE showed a clear positive interaction with water input (Vázquez et al., 2005). The NUE response to the water input increment was larger for the mulched than for the non-mulched treatment (Fig. 5). This positive effect of black plastic mulching was also observed on yield and WUE, and was related to a significant increase in soil temperature under the plastic mulch that stimulated crop growth. The tomato benefitted from the soil N supply (NUE > 1), a common occurrence in open-air vegetable production, where high valuable crops are grown after crops or conditions that build-up the soil fertility level. Plastic mulching is a widespread practice in horticultural crops all around the world and in arable crops in semi-arid areas (Deng et al., 2006). A field experiment with maize in China showed that plastic mulching enhanced WUE and NUE simultaneously under rainfed conditions by preserving moisture for crop transpiration (Li et al., 2009). The larger water availability under the mulch allowed a more vigorous growth in fertilized treatments and enhanced yield response to N fertilization. Extensive use of plastic requires also proper management and recovery technology to avoid the detrimental effects of residual mulch pollution (Liu et al., 2014).

Minimum and no-tillage systems are characterized by a crop residue mulch protecting the soil surface. Crop residue and straw mulch can be easily implemented by local farmers as materials are easily accessible, low cost and contribute to soil quality (Mupangwa, 2015). Originally developed for soil and water conservation, the crop residue mulch reduces evaporation losses increasing WUE (Unger, 1978). The effect on NUE is not so clear as several processes in the soil N cycle are affected. Crop residues retain water and reduce soil temperature (Quemada and Cabrera, 2002). Decomposition rates of crop residues covering the soil are lower than incorporated residues, the risk of ammonia volatilization increases when stubble and fertilizers remain on the soil surface, and larger N immobilization is expected in conservation tillage (Quemada et al., 1997). Because of these factors, optimum fertilization is even more important with conservation than with conventional tillage (Wang et al., 2011). As a whole, conservation tillage increases crop N uptake in semi-arid areas mainly because of the higher soil water content, and this synergetic effect on NUE and WUE is particularly significant in dry years (Morell et al., 2011; Wang et al., 2011).

6.- Nitrogen mineralization from soils and organic amendments

The N supply by organic matter mineralization depends greatly on moisture conditions (Quemada, 2004). Microorganisms release extracellular hydrolytic enzymes that carry out the decomposition process and require moisture to be active. If the soil is too wet, anaerobic processes are enhanced and the mineralization rate slows down. Cycles of dry and wet conditions are known to promote mineralization and the best scenario for organic matter mineralization is a moist and well drained soil (Jarvis et al., 1996).

In many cropping systems mineralization is limited by a lack of moisture during the dry season. If water is supplied either by rain or irrigation, the mineralization rate increases greatly when thermal conditions are favorable. The effect of moisture on N mineralization is emphasized by comparing the potential mineralization rates determined in laboratory aerobic incubations (k) with the apparent mineralization rates calculated from the field experiments (k*) (Table 1). In the laboratory, soils were incubated under equal and controlled temperature and moisture conditions, whereas in the field k* was calculated based on the N supply by the soil under variable environmental conditions. The potential mineralization rates from the laboratory were similar for soils from rainfed and irrigated fields and variability was largely related to organic C content. In contrast, the apparent N mineralization rate obtained in field experiments was almost four times greater under irrigated than under rainfed conditions, due to the optimal soil moisture in the irrigated fields. This is particularly relevant when rainfed fields are transformed into irrigated fields, as organic matter mineralization may be greatly enhanced (Vázquez et al., 2006). During a transition period, soil may supply large amounts of N until the soil organic matter content eventually stabilizes after several years. Accounting for nutrients supplied by mineralization could provide appreciable savings to farmers and enhance NUE. If this N supply is not accounted for, large quantities of NO_3^- may accumulate in the soil profile increasing the risk of water pollution in the area. In general, organic amendments oriented to enhance soil quality may increase soil water retention capacity and N supply, therefore, they could be considered as a practice to enhance NUE and WUE.

Table 1. Relationship between the N potential mineralization rate (k) determined from aerobic laboratory incubation, and the apparent soil N mineralization rate (k*) observed in field experiments for various soils from either irrigated or rainfed cropping systems at different locations in Spain. Data obtained from Quemada (2006), and Quemada and Díez (2007).

Location	Soil classification	g C kg^{-1}	k	k*
			mg N kg^{-1} d^{-1}	
		Irrigated systems		
Valdegón	*Typic Xerofluvent*	11.3	0.39	0.24
Montañana	*Typic Xerofluvent*	5.9	0.29	0.14
Gimenells	*Petrocalcic Calcixerept*	9.5	0.40	0.14
Tallada-2	*Oxyaquic Xerofluvent*	9.9	0.47	0.20
Average			**0.39±0.07**	**0.18±0.05**
		Rain fed systems		
Gauna	*Vertic Endoaquol*	14.9	0.48	0.08
Aranguiz	*Vertic Endoaquol*	10.6	0.43	0.03
Beriain	*Typic Calcixerept*	11.6	0.41	0.06
Tajonar	*Fluventic Haploxerept*	14.0	0.38	0.01
Average			**0.42±0.04**	**0.05±0.03**

7.- Cropping system strategies

At the cropping system level, there are practices specifically developed to increase NUE and WUE simultaneously, but many practices implemented for other purposes may affect N and water use efficiency. Among these practices are the rotation of crops with shallow and deep root systems, the use of fallows and cover crops, or even weeding to control resource competition with the cash crop.

As an example, the data from a long-term field experiment in Central Spain were analyzed. In this experiment cover crops were used to replace the traditional winter fallow between irrigated summer crops (Gabriel and Quemada, 2011). Maize was planted in April and harvested in September, and from October to March the soil was fallow, or cover cropped with a grass or a legume. All treatments received the same N fertilizer and water. In the first year, there was no difference in NUE between treatments, but after the second year maize NUE was highest after the vetch cover crop, followed by the barley as a cover crop and the fallow. Differences in WUE appeared in the third year because differences in N uptake did not translate into yield increases until that time. It is interesting that NUE and WUE were highly correlated (Fig. 6). Correlation between these two variables is common (Fig. 2b) and high NUE and WUE values are indicative of good crop management practices (i.e. weed control, crop rotations,...). It is probable that many farmer's practices were consciously or unconsciously developed to improve NUE and WUE simultaneously. Identification of these local practices may enhance learning from farmer experience, and new technology could further improve resource efficiency in specific cropping systems.

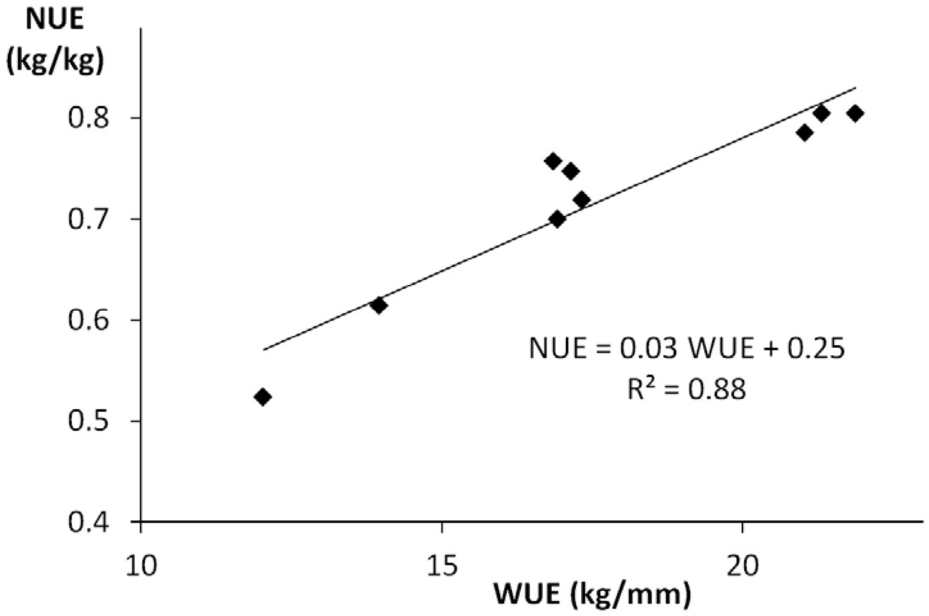

Figure 6. Nitrogen use efficiency (NUE) versus water use efficiency (WUE) for maize in a long-term trial in which cover crops were used to replace the winter fallow between irrigated summer crops carry out in Spain. More detail about the experiment can be found in Gabriel and Quemada (2011).

8.- Monitoring: N and water interactions in remote sensing

Substantial research on new nutrient and water management technologies has been carried out in recent years. Crop monitoring technologies based on optical sensors have been developed to use the crop as an indicator of its requirement for N fertilizer and water. Chlorophyll (Chl) concentration is strongly related to crop N status, so Chl estimation based on the ratio of either the light transmittance or reflectance at various wavelengths has been implemented in leaf-clip and tractor mounted equipment. In addition, field-scale imagery obtained from remote-sensing platforms has been used to estimate physiological crop status. Several indices based on remote sensing have been developed to characterize crop N status and recommend N fertilization (Chen et al., 2010). Indices for identification of water stress based on reflectance sensors or canopy temperature may be used for irrigation scheduling (Zarco-Tejada et al., 2012).

Nevertheless, a major limitation is that the readings may be affected by water stress and nutrient deficiencies simultaneously. Particularly, water stress increases reflectance in the visible and in the NIR region, but these bands are also used for indices of N nutritional. Adapting these technologies based on ground-level and remote sensing to account for water stress interference on the identification of the N nutritional status is a requirement for detecting the water-N co-limitation.

The goal of a field experiment conducted in Central Spain with maize (*Zea mays*, L.) was to evaluate the potential of images taken from an aircraft at 300 m for developing N fertilizer recommendations (Quemada et al., 2014). Airborne campaigns were conducted flying with a hyper-spectral imager and a thermal camera over the experiment at two different dates: when the maize had eight fully unfolded leaves and at flowering. The radiance spectra and the canopy temperature were extracted from the experimental plots and the indices calculated were related to crop N status and yield. The most reliable indices to differentiate between crops with different N status (R750/R710 Chl index and the sun-induced fluorescence) greatly improved their relationship with crop yield when the canopy temperature was accounted for (Fig. 7). Thermal measurements have been shown to be very sensitive to water stress and a combination of thermal and spectral indices has great potential to examine water and N stress in agricultural crops. These results show the need to study crop N status and water stress simultaneously for field application of this technology.

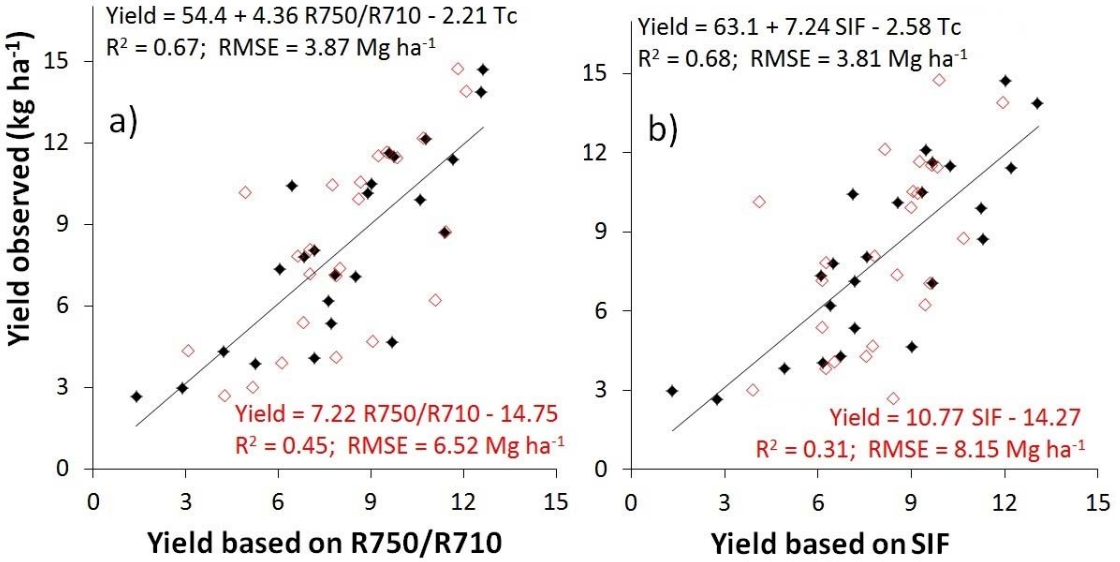

Figure 7. Maize yield observed *versus* the estimated yield based on either a linear correlation of (a) R750/R710 (black) or a combination of R750/R710 and canopy temperature (Tc) (red), and (b) SIF760 (black) or a combination of SIF760 and Tc (red).Yield data obtained from a fertilization experiment with six N levels and optical indices from hyperspectral airborne images taking at flowering (Quemada et al. 2014). R750/R710 is the red edge optical reflectance ratio and SIF760 is the solar-induced fluorescence.

9.- Conclusions

Strong interactions between WUE and NUE are common in many agricultural systems. Management practices that aim to enhance WUE and NUE simultaneously are more successful that those that seek to optimize water or N inputs separately. In addition, environmental problems caused by excessive use of N, such as nitrate contamination of water bodies or increasing atmospheric concentration of greenhouse gasses, are driven by water. Therefore, management practices oriented towards reducing N losses and maintaining farm productivity should optimize N and water use simultaneously. Identifying effective local farmer practices and new technologies to further improve resource efficiency may increase NUE and WUE in specific cropping systems.

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