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Approaches for increasing nitrogen and water use efficiency simultaneously

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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 NUE.

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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their success to enhance crop N uptake (Ladha et al., 2005).

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.

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 sub-optimal 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

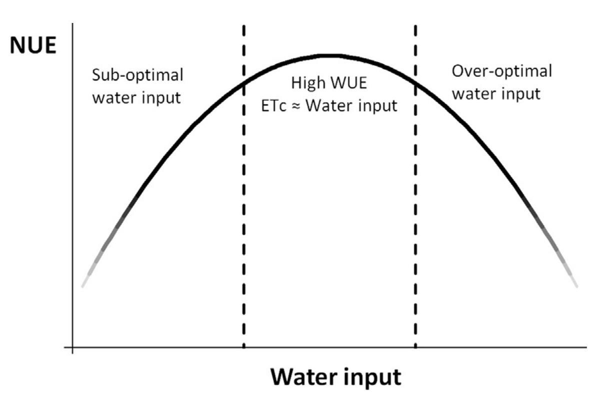

Fig. 1. Schematic representation of the effect of water input on nitrogen use efficiency (NUE). WUE: water use efficiency; ETc: Crop evapotranspiration.

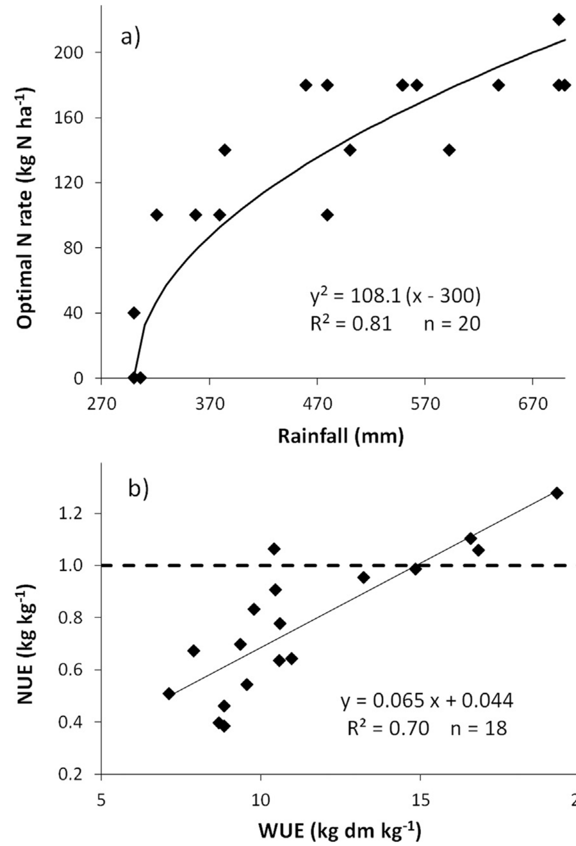

Fig. 2. (a) Optimal nitrogen (N) rate versus rainfall during the growing season and (b) nitrogen use efficiency (NUE) versus water use efficiency (WUE) for wheat fertilization trials carry out in Spain. More detail about the experiments can be found in Arregui et al. (2006) and Arregui and Quemada (2008).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

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.

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.