Agricultural Water Management 178 (2016) 225–238

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Review

Influence of the irrigation technique and strategies on the nitrogen cycle and budget: A review

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ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form
28 September 2016
Accepted 28 September 2016

ABSTRACT

The objective of this review is to remedy the lack of knowledge about the expected relationship between the irrigation techniques (flood irrigation, sprinkler irrigation, surface and subsurface drip irrigation) and the nitrogen transformations (fixation, mineralization, immobilization and nitrification) or fluxes (denitrification, runoff, volatilization and lixiviation) in agricultural contexts. This study investigates thus the various controls on the nitrogen cycle and budget, either site-specific (soil C/N ratio, pH, salinity, texture and temperature) or corresponding to deliberate strategies in water and nitrogen management. The comprehensive view gained from the gathered literature elements identifies the local variations (in space and time) of soil water content profile as both the strongest control and the control most directly related to the irrigation technique and to the practitioner's decisions. In the overall picture, flood irrigation and sprinkler irrigation are the techniques in which most transformations or fluxes may be enhanced or reduced, also with the risks associated with non-optimal practices. By contrast, subsurface drip irrigation seems the technique with the least unwanted impacts. Besides the academic aspects (bringing together scattered literature elements) an outcome of this review is thus to facilitate decision-making regarding the choice and/or use of irrigation-fertilization techniques and strategies (doses and scheduling) for given agro-pedoclimatic contexts, also for combined agricultural production, economic and site preservation objectives.

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http://dx.doi.org/10.1016/j.agwat.2016.09.027

1. Introduction

Increased anthropic pressure and growing food demands exerted on cultivated areas have lead to the intensification of agriculture (Galloway et al., 2008; Keys and McConnell, 2005; Konstantinou et al., 2006; Lambin et al., 2001; Vitousek et al., 1997) at the fear of pending runaway Earth contaminations, with the necessity to identify and promote sustainable practices (Alexandratos and Bruinsma, 2012; Tilman et al., 2011). Excessive nutrient and pesticides applications represent one of the most common causes of degradation in surface water and groundwater quality, which makes risk assessment a crucial part of any agricultural management at the plot, catchment and basin scale (Flury, 1993; Long and Sun, 2012; Reichenberger et al., 2007; Rivett et al., 2008). In particular, a comprehensive view of the merits and drawbacks of irrigation and fertilization strategies requires modelling techniques as well as knowledge of the technological and legal angles (Sutton et al., 2011; Van Grinsven et al., 2012). The site-specific optimisation of practices is a wide concern for stakeholders, farmers, agronomists, soil physicists and biogeochemists, in which the first degrees of freedom are the choice of the irrigation technology and technique (FI: flood irrigation, SI: sprinkler irrigation, DI: drip irrigation, SDI: subsurface drip irrigation).

To start from well-established knowledge, soil nitrogen availability has been long known to influence crop and root growth thus to have a direct impact on crop yield, attributing increased death rates for young individuals and leaf yellowing to insufficient nitrogen uptake (Lloyd, 1993; Niste et al., 2013). Conversely, an over-supply of nitrogen into the root zone may also decrease crop yield by stimulating stem growth to the detriment of root growth, grain filling or sugar content, leaving the non-absorbed nitrogen available for lixiviation (Thorburn et al., 2003a; Zahran, 1999). Excessive nitrogen applications are also prone to inhibit the action of the nitrogenase enzyme responsible for the biological fixation of nitrogen (Muthukumarasamy et al., 1999). In complement, any purposive fertigation strategy should also limit, if not suppress, the nitrogen losses towards the atmosphere through denitrification (i.e. the multi-stage conversion of nitrates to nitrogen gas) and ammonia volatilization (Kroeze et al., 2003). The decisions on how, when and where to apply nitrogen should thus arise from a fine understanding of the nitrogen cycle, including the estimation of mineralization rates (Cabrera, 1993; Fierer and Schimel, 2002; Jackson et al., 2008) and that of plant needs at best (Mmolawa and Or, 2000; Soussi et al., 1998; Valé et al., 2007). In all genericity, both crop productivity and the nitrogen budget also depend on the timing of fertigation (or fertilization) within irrigation events (Ebrahimian et al., 2013), the type of molecules used (Hanson et al., 2006), soil properties (Zotarelli et al., 2007), the location of the fertilizer (Siyal et al., 2012), the splitting of nitrogen doses (Yoseftabar, 2012) and the frequency of nitrogen inputs (Gheysari et al., 2009).

In a schematic overview, Fig. 1 shows the quantities of interest for the current study, especially the nine forms under which nitrogen appears in the nitrogen cycle (Robertson and Groffman, 2007), sorted here by decreasing oxidation states: nitrate (NO_3^-, +5), nitrogen dioxide (NO_2, +4), nitrite (NO_2^-, +3), nitric oxide (NO, +2), nitrous oxide (N_2O, +1), dinitrogen gas (N_2, 0), ammonia (NH_3, −3), ammonium (NH_4^+, −3) and organic nitrogen (R-NH_2, −3). The dinitrogen gas represents about 90% of the total nitrogen but the molecule must be split by lightning (into ammonium) or by symbiotic fixation to become available for plants, and the activity of the nitrogen fixing bacteria depend on the local soil conditions: organic matter, water content and temperature (Zahran, 1999). The organic nitrogen also necessitates the action of soil microorganisms (mineralization into ammonium) prior to its absorption by plant roots (Jackson et al., 2008). In addition to ammonium or direct symbiotic fixation, nitrates are the last source of nitrogen for the plant, through root uptake. Finally, fertilization consists in the input of ammonium or nitrates, while lixiviation designates the loss of nitrates by drainage.

Quite surprisingly, there is still a need for the literature to investigate how several elements of the nitrogen cycle may be influenced by the chosen irrigation and fertilization technique but also strategy (e.g. dates of application, doses applied, formulation of the fertilizer) with an expected impact on the nitrogen budget, thus on the environmental footprint, as well as on several key performance indicators: crop yield, water and nitrogen use efficiency and operating profitability. To our knowledge, these issues have not been explicitly addressed so far, even when discussing the global agricultural or environmental perspectives associated with the nitrogen cycle, as affected by human activities (Bassirirad, 2000; Galloway et al., 2004; Gruber and Galloway, 2008; van Groenigen et al., 2015; Ward, 2012). The purpose of the current study is to remedy this lack by collecting results, controversies, recommendations and open questions, from existing but dispersed information. This review aims at eventually outlining the influence of the irrigation techniques and associated fertilization strategies on the nitrogen transformations (cycle) and fluxes (budget) through the direct or indirect effects of irrigation techniques on the controlling factors for nitrogen availability for plant roots (soil C/N ratio, pH, salinity, temperature, texture, water content) and nitrogen fate (fertilizer location and scheduling of applications, soil texture, types of molecules used, water content).

This review leans on 177 literature sources to suggest or establish the existence of a correlation between the irrigation techniques and soil nitrogen transformations or fluxes, focusing on these described in Fig. 1. Prior to more detailed investigations in the manuscript, several popular clues of this correlation may be sought in that (i) nitrogen losses by lixiviation occur when irrigation reaches its peak in intensity (Kroeze et al., 2003), (ii) even a slight increase in soil water content may drastically enhance denitrification (Davidson, 1992), (iii) the use of new fertigation techniques makes nitrogen application far more efficient (Valé et al., 2007), (iv) irrigation water is the driving force for nitrogen movements, availability and transformation (Sánchez-Martín et al., 2008) and (v) nitrogen mineralization is stronger in regularly irrigated soils than in non-irrigated or irregularly irrigated soils (Valé et al., 2007).