Agriculture, Ecosystems and Environment 189 (2014) 136–144

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency

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ARTICLE INFO

Article history:
Received 3 January 2014
Received in revised form 17 March 2014
Accepted 19 March 2014
Available online 12 April 2014

Keywords:
DCD
DMPP
NBPT
Crop yield
Nitrogen use efficiency

ABSTRACT

Nitrification and urease inhibitors are proposed as means to reduce nitrogen losses, thereby increasing crop nitrogen use efficiency (NUE). However, their effect on crop yield is variable. A meta-analysis was conducted to evaluate their effectiveness at increasing NUE and crop productivity. Commonly used nitrification inhibitors (dicyandiamide (DCD) and 3,4-dimethylepyrazole phosphate (DMPP)) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) were selected for analysis as they are generally considered the best available options. Our results show that their use can be recommended in order to increase both crop yields and NUE (grand mean increase of 7.5% and 12.9%, respectively). However, their effectiveness was dependent on the environmental and management factors of the studies evaluated. Larger responses were found in coarse-textured soils, irrigated systems and/or crops receiving high nitrogen fertilizer rates. In alkaline soils ($pH \geq 8$), the urease inhibitor NBPT produced the largest effect size. Given that their use represents an additional cost for farmers, understanding the best management practices to maximize their effectiveness is paramount to allow effective comparison with other practices that increase crop productivity and NUE.

1. Introduction

The complex nature of nitrogen (N) transformation in soils, coupled with sub-optimal fertilizer management practices (Cui et al., 2010; Sutton et al., 2013), has led to low N use efficiency (NUE) in many instances (c. 30–50%). These factors have contributed to an increase in N losses such as ammonia (NH_3) volatilization, nitrate (NO_3^-) leaching and nitrous oxide (N_2O) emissions (IPCC, 2007), which are of economic and environmental concern. Enhanced-efficiency fertilizers such as those containing nitrification inhibitors (NIs) and urease inhibitors (UIs) have been developed to increase NUE and reduce N losses by increasing the congruence between N supply and crop N demand. This effect is achieved by delaying the bacterial oxidation of ammonium (NIs) or the hydrolysis of urea (UIs). However, the use of these technologies is under debate because there are studies in which yield increases are not observed despite the additional costs (Akiyama et al., 2010).

Recently, a meta-analysis by Linquist et al. (2013) explored the effect of several enhanced-efficiency N fertilizers (i.e. NIs and UIs but also neem and slow release fertilizers, 17 products in total) on yield and N uptake in rice systems. These authors found that, on average, the use of these fertilizers led to a 5.7% increase in yield and an 8.0% increase in N uptake. It remains to be seen whether results from this specific crop are true for other crop systems. For instance, flooded periods are a singular management practice of rice systems which may have a major impact of N losses and NUE, and therefore on the efficiency of inhibitors. As rice is mainly cultivated in Asia (FAOSTAT, 2013), Thailand, Philippines and India provided 62.5% of the studies used in the meta-analysis, which may also increase bias due to climatic and experimental factors. Further analyses including other crop types are therefore pertinent in order to improve our understanding on the effect of NIs and UIs on crop yield and NUE.

Among the commercial NIs available, 3,4-dimethylepyrazole phosphate (DMPP) and dicyandiamide (DCD) are the most widely used (Liu et al., 2013). N-(n-butyl) thiophosphoric triamide (NBPT) is the most widely used UI (Sanz-Cobena et al., 2012). DCD is more used than DMPP in some countries (e.g. New Zealand) as it is cheaper, less volatile and relatively soluble in water (Giltrap et al., 2010). On the other hand, DMPP can be applied at rates about

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http://dx.doi.org/10.1016/j.agee.2014.03.036
0167-8809/

10 times less than DCD and field studies revealed that it may be more effective lowering NH_3 volatilization, NO_3^- leaching, and N_2O emissions than DCD (Mahmood et al., 2011; Benckiser et al., 2013). This is because DMPP's nitrification inhibition efficacy after heavy rainfall simulations lasts longer and its plant compatibility seems to be better than that of the more mobile DCD (Benckiser et al., 2013). NBPT has been found to reduce N losses at relatively low concentrations under both laboratory and field conditions (Sanz-Cobena et al., 2008; Abalos et al., 2012). However, results are not consistent because the inhibitory activity of NBPT decreases as soil temperature increases (Carmona et al., 1990). The combined use of DCD and NBPT has been promoted as a tool to reduce N losses (Zaman et al., 2013). As DMPP has been recently released, there are currently not enough studies in combination with NBPT to evaluate their effect. Whether a specific product (DMPP, DCD, NBPT or DCD + NBPT) or the type of inhibition (nitrification or urease) leads to lower N losses and a hypothetical correspondingly higher NUE remains unclear. Moreover, a quantitative understanding of their effect on the yield of different crops is necessary in order to evaluate the economic value of these products.

The aim of this study is to integrate available results to quantitatively evaluate the effect of commonly used NIs (DMPP and DCD) and UIs (NBPT) on crop productivity and NUE. Additionally, we investigate the experimental, environmental and management factors which affect each inhibitor's efficiency.

2. Materials and methods

2.1. Data search and selection criteria

A meta-analysis was conducted to characterize the response of crop productivity and NUE to the application of inhibitors (DMPP, DCD, NBPT and DCD + NBPT). Data were extracted from studies where a fertilizer without inhibitor application (control) could be compared to an equivalent treatment with inhibitor with all other factors unchanged. In order to determine the key drivers (experimental, environmental and management variables) affecting the response of crop productivity and NUE to inhibitors addition, the experiments were grouped in terms of: inhibitor type (UI, NI or both), experiment type (field or pot), crop productivity reporting (grain yield or aboveground biomass production), crop type, N fertilization rate, fertilizer type (organic, mineral or both), method of fertilizer-inhibitor application, irrigated or rainfed system, soil pH, soil texture and climate. NUE (expressed as the percentage of fertilizer N applied that was taken up in the grain or the aboveground biomass of the plant) was calculated as the difference between the total N uptake by crops from fertilized and unfertilized treatments per unit N applied (N difference method).

A survey of literature was conducted using the ISI-Web of Science and Google Scholar for articles published before October 2013. The following search terms and their variations were used: nitrification inhibitor, urease inhibitor, DMPP, DCD, NBPT, biomass, crop productivity, crop yield, nitrogen or nitrogen use efficiency. This search based on keywords was complemented with a search through the literature cited in the articles found. Papers were scrutinized and included if they met the following quality criteria: (i) the experimental design had to be sufficiently detailed to determine all critical aspects of the treatments, plot size and recent history, irrigation systems and fertilizer management; (ii) included treatment replicates (minimum of three); and (iii) only for studies on NUE, the experimental design included a control without fertilizer application. Two exceptions were made to this final criterion (Di and Cameron, 2005; Liu et al., 2013), because the studies were considered to be accurate and representative. To reduce the potential problem of publication bias, we found two available studies from the grey literature (Sanchez-Martin, 2012; Vallejo, 2013) which were also included. For both studies sufficient methodological information was included to demonstrate that the experimental design was sufficiently robust. All the studies included reported crop productivity data in terms of either grain yield or aboveground biomass with the exception of Ding et al. (2011), which contributed with both observations. In order to avoid bias toward short term experiments, studies conducted in different years or growing seasons at the same experimental site were considered independent. Therefore, a total of 27 studies and 160 observations were used for crop productivity, and 21 studies with 94 observations were used for NUE (Table 1). When data was only provided in graphic format, DataThief III (Tummers, 2006), was used to extract needed data from figures. Standard deviation (SD) was used as a measure of variance, which was calculated from the published measure of variance in each study if necessary. When no measures of variance were given, efforts were made to obtain these from the corresponding authors, which in most cases were successful. If not, those studies were also excluded from the analysis. In addition, when no NUE SDs were provided, they were calculated from the N uptake SDs according to the equation proposed by Aguilera et al. (2013) as follows:

$$SD_{NUE} = \frac{\sqrt{(n_F - 1) \times SD_F^2 + (n_C - 1) \times SD_C^2 / (n_F + n_C - 2)}}{\text{kg N fertilizer applied}}$$

where n_F and n_C are the number of observations in the fertilized treatment (with or without inhibitor, depending on the case) and control (without fertilization) treatment, respectively. SD_F and SD_C are the standard deviations of the N uptake with and without fertilizer application, respectively.

2.2. Building the datasets

Data were grouped to maximize in-group homogenization. Crop type was grouped in three categories: cereals (maize, wheat, barley and rice), vegetables/industrial crops (capsicum, amaranth, radish, rapeseed and cotton) and forage (*Lolium perenne*, *Lolium perenne* + *Trifolium repens*, *Lolium perenne* + *Poa pratensis* and *Lolium perenne* + *Holcus lanatus* + *Dactylis glomerata*). Soil texture was grouped into three basic classes (fine, medium and coarse) according to USDA (1999). Climate was grouped in the various thermal climate zones of the world (Tropics, Subtropics-Summer Rainfall, Subtropics-Winter Rainfall, Temperate-Oceanic, Temperate-Subcontinental, Temperate-Continental) defined by FAO and IIASA (2007). Soil pH was divided into three classes (≤6, 6–8 and ≥8) as used by Linquist et al. (2013) for comparative purposes. Fertilizer N rate (kg N ha^{-1}) was grouped into three categories according to low (≤150), medium (150–300) and high (≥300) application rates. For the method of fertilizer-inhibitor application, the fertilizers with and without inhibitor were applied under the same conditions, but the way the inhibitors were supplied varied according to: surface applied-coating the fertilizer, surface applied-in solution, injected-coating the fertilizer and fine particle suspension. Inhibitor types were urease (NBPT), nitrification (DCD and DMPP) and both (DCD + NBPT). Fertilizer types were organic (cow urine and cattle slurry), mineral (urea, ammonium sulphate nitrate (ASN), urea-ammonium nitrate (UAN) and nitrogen-phosphorus-potassium fertilizer (NPK)) and both (urea + cow urine). Other variables analyzed were field vs pot experiments, grain yield vs aboveground biomass production and irrigated vs rainfed systems.