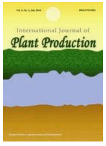

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Influence of nitrification inhibitors on yields of arable crops: A meta-analysis of recent studies in Germany

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Abstract

Nitrification inhibitors (NIs) delay the oxidation of ammonium by soil microorganisms, maintaining a higher proportion of applied nitrogen (N) in the soil by preventing nitrate-N loss from leaching and gaseous N losses from nitrification and denitrification. Thus, a large number of studies have shown N fertilizers with NIs are more environmentally friendly. In contrast, there are only a limited number of studies about effects of the N fertilizers added with NIs on arable crop yields and the conclusions are also divergent. This study presents a meta-analysis of recent research in Germany investigating the effects of NIs on the yields of different agricultural crops (winter wheat, winter barley, winter rapeseed, potato, grain and silage maize) compared to conventional N fertilization without NIs at a given N rate. Crop yields with and without NIs at a reduced number of N fertilizer applications were also compared. Nitrogen fertilizers with NIs did not significantly influence the yields of all investigated crops. For a given N application rate, the number of fertilizer applications could be reduced by at least one without any significant effect on yield when fertilizers with NIs were used. By contrast, the crude protein content of winter wheat was decreased significantly when the number of applications of NI fertilizers was less than that of non-NI-containing fertilizers. These findings may suggest that the key advantages to using N fertilizers with NIs are helping to protect the environment due to reduced N losses and reducing labor costs due to saving at least one fertilizer application, all while maintaining the yields of the investigated crops.

Keywords: Field crops; Nitrification inhibitor (NI); Nitrogen (N); N fertilizers; Crop yield.

Introduction

Nitrogen (N) is an essential element for plant growth and, of all nutrients, is applied in the largest quantities in agriculture. However, a significant amount of the applied N can be lost from the soil-plant system, even under optimized fertilization strategies, through NO_3^- leaching, NO_x and N_2O gaseous emissions from nitrification and denitrification and NH_3 volatilization (Trenkel, 2010). These losses not only represent an unnecessary economic burden but also have a strong negative impact on the environment. In light of this, Shoji and Gandeza (1992) tried to define an "ideal N fertilizer" as one that at minimum features the following characteristics: i) requires only a single application throughout the entire growing season for optimum plant growth; ii) maximizes percentage recovery (i.e. the losses should be as small as possible) and iii) minimizes detrimental effects on the soil, water and atmosphere. Trenkel (2010) suggested that N fertilizers associated with nitrification or urease inhibitors largely meet these requirements and they have been used for both cash and broad agricultural crops.

Directed searches for specific chemical compounds to act as nitrification inhibitors (NIs) started in the late 1950s (Zerulla et al., 2001). As early as 1962, nitrapyrin (2-chloro-6-(trichloromethyl)-pyridine) was introduced as an NI in the United States (Goring, 1962). In addition to nitrapyrin, three other NIs are routinely added to mineral fertilizers today: dicyandiamide + 1H-1,2,4-triazole (DCD-TZ), 3,4-dimethylpyrazole phosphate (DMPP) (Trenkel, 2010; Zerulla et al., 2001) and currently, the only NI available for liquid organic fertilizers on the German market is 1H-1,2,4-triazole and 3-methylpyrazole (TZ-MP). Of these four NIs, three are produced by German companies. For mineral fertilizers, DMPP is usually added to ammonium sulfate nitrate (ENTEC®, BASF, Ludwigshafen, Germany), whereas DCD-TZ is added to urea (ALZON 46®) and TZ-MP is available for liquid organic fertilizers (PIADIN®) (SKW Stickstoffwerke Piesteritz GmbH, Lutherstadt Wittenberg, Germany).

Nitrification is a key process of N transformation and is mediated by Nitrosomonas bacteria and nitrobacter in the soil. The former class of bacteria is responsible for the first step of nitrification, where ammonia (NH_3) is oxidized into nitrite (NO_2^-). Nitrification inhibitors act by depressing the activity of the principal exponent of this first step (*Nitrosomonas* spp.), thereby delaying the oxidation process. Given that nitrate (NO_3^-) is a source of major N loss by leaching and denitrification, the use of NIs can minimize these losses. Indeed, a large number of studies have shown that the leaching of NO_3^- following the application of mineral N fertilizers can be significantly reduced by the addition of either DCD (Ball-Coelho and Roy, 1999; Gutser, 1999; Serma et al., 2000; Di and Cameron, 2002; Di and Cameron, 2004; Sanz-Cobena et al., 2012) or DMPP (Arregui and Quemada, 2006; Arregui and Quemada, 2008; Roco and Blu, 2006; Yu et al., 2007a; Yu et al., 2007b). For instance, treatment of urine patches on a fine sandy loam in New Zealand with DCD reduced NO_3^- leaching losses from 85 to 20-22 kg N ha^{-1} $year^{-1}$ (Di and Cameron, 2002; Di and Cameron, 2004).

In addition, numerous experiments have demonstrated that the addition of an NI also reduces N losses as gaseous emissions, either as N oxides (NO_x) and/or nitrous oxide (N_2O). A recent review by Akiyama et al. (2010) demonstrated that NIs significantly reduce N_2O emissions by about 38% and NO emissions by about 46%. Skiba et al. (1993) showed that the addition of DCD reduces N_2O emissions by 40%. DMPP is likewise effective in decreasing N_2O emissions from mineral (Linzmeier et al., 2001a; Weiske et al., 2001; Khalil et al., 2009; Akiyama et al., 2010; Kim et al., 2012; Pfad et al., 2012; Sanz-Cobena et al., 2012) and organic fertilizers (Dittert et al., 2001; MacAdam et al., 2003; Hatch et al., 2005; Merino et al., 2005; Menendez et al., 2006; Menendez et al., 2009; Zaman et al., 2009). Similar significant reductions have also been reported for DCD-treated pig slurry (Vallejo et al., 2005) and DCD-treated animal urine patches in pastures (Di and Cameron, 2003; Di and Cameron, 2012; Zaman and Nguyen, 2012). Merino et al. (2005) and Dittert et al. (2001) similarly showed that DMPP is efficient in reducing N_2O emissions from injected slurry applied to grassland and similar results have been reported for TZ-MP (Weber et al., 2004; Khalil et al., 2009).

Beyond reducing N losses, Linzmeier et al. (2001b) and Grant (2005) have suggested that the use of NIs can also simplify the task of fertilization in intensive crop production to save labor and machinery costs, mainly by reducing the number of required applications or by facilitating a greater flexibility in the timing of fertilizer application. Plot experiments with ammonium nitrate containing DMPP supported this statement, showing both increased N use efficiency and a reduced number of fertilizer applications (Roco and Blu, 2006). In addition, the slower N release from the fertilizer caused by the addition of an NI allows for greater flexibility in the timing of fertilizer applications (Grant, 2005). This benefit is of increasing importance in the face of climate change, where greater flexibility offers the potential to reduce the risk associated with either extended drought or extended rainy periods. In the former case, the option exists to apply N fertilizers earlier in the growing season to preempt possible drought periods that inhibit fertilizer dissolution as well as uptake of N, whereas in the latter, the use of NIs helps to protect from possible leaching losses from the fertilized N after extreme precipitation events.

Although the effects of the addition of NIs to N fertilizers on crop yields and quality are important considerations, only a limited number of field studies have been reported in peer-reviewed journals. Those studies have also shown contrasting effects of the addition of NIs to N fertilizers on crop yields. For example, Pasda et al. (2001) reported that the results under various soil-climatic conditions in western and southern Europe demonstrated increased yields of crops like winter wheat, paddy rice, maize, potato, sugar beet and vegetables by fertilizers amended with DMPP compared to those without DMPP. Similarly, a study of major agricultural crops in Germany by Wozniak et al. (1999) showed increased yields of winter cereals, rapeseed, maize, potato and sugar beet by 1% to 6%. Studies throughout the United States have demonstrated that maize yields were often increased by the application of NIs (Nelson and Huber, 1992). The literature also shows positive effects on the yields of wheat (Sharma and Kumar, 1998; Villar et al., 2010), potato (Mohammad et al., 1998; Kelling et al., 2011), maize with irrigation (Halvorson and Del Grosso, 2013) and cotton (Freney et al., 1993). However, Martin et al. (1993) reported that tuber yields of potato were not affected by NIs in four of five tests but were increased by 14% in one test. For potato, Munzert (1984) observed no change in its yield in response to DCD application.

To have a better understanding of the effects of NIs on grain and tuber yields under field conditions, there is clearly a need for a larger number of field studies under different climate and soil conditions. In this work, we used meta-analysis to integrate the results from numerous field studies with different crops have been most recently conducted by several extension agronomists of different federal states of Germany, which, until now, have been published mostly in German professional journals or presented at German meetings. In particular, we tested the following hypotheses:

i) Can N-containing fertilizers with NIs also increase the yield and improve the quality of agricultural crops?
ii) Can the number of applications of N fertilizer containing NIs with the same N rate without NIs be reduced without affecting yield and quality of agricultural crops in order to simplify the task of N application?

Materials and Methods

Data sources

To select appropriate studies for our meta-analysis, we obtained data from research reports and publications from German agricultural research and extension centers in the Federal States (e.g. Bavaria, Baden-Wuerttemberg, North Rhine-Westphalia, Saxony-Anhalt, Saxonia, Mecklenburg-Western Pomerania, Rhineland Palatinate) and German universities such as the Technische Universität München and the Bingen University of Applied Sciences. These reports and publications contained data from approximately 30 experimental sites on which experiments were conducted from 1997 to 2008 and on which five major agricultural crops (winter wheat, winter barley, winter rapeseed, grain and silage maize and potato) were examined. General information and growth conditions are presented in Table 1. The performance of N fertilizers without NI (-NI) (calcium ammonium nitrate (CAN), ammonium sulfate + ammonium nitrate (ASN), ammonium sulfate (AS), urea, ammonium sulfate + urea (AS/urea) and slurry derived from cattle or pig was compared to that of the following fertilizers containing NIs (+NI): ASN + DMPP, urea + DCD-TZ, AS/urea + DCD-TZ, slurry + TZ-MP. Depending on the specific purpose of the experiment and on the agricultural crop, N rates ranged from 80 to 220 kg N ha^{-1} for mineral N and from 60 to 140 kg N ha^{-1} for slurry (Table 1). The number of split applications varied according to the agricultural crops, the N rates and the use of fertilizers with NIs or without NIs. In general, in conventional N fertilizer systems 2-3 split applications are done, whereas for N fertilizers with NIs, only 1-2 applications were done. Grain yield was determined as dry matter content 86% according to Guidelines for performing agricultural value tests and variety trials by the German Federal of Federal Ministry of Food, Agriculture and Consumer Protection and tuber yield as FM. Standard methods have been used to determine crude protein of grains of cereals and starch of potatoes based on the Methodenbuch by the Association of German Agricultural Analytic and Research Institutes, agricultural analysis and research institutions (VDLUFA, 1993). Dry mass (DM) of grain yield of crops and fresh mass of tuber yield of potato were used for further statistical analysis.

Table 1. Trial sites, number of observations, crops, N rates, trial years, soil texture, soil pH, available soil N_{min} (0-30 cm), annual temperature and annual precipitation.

Trial site	Crop	N rate kg ha^{-1}	Trial years	Soil texture	pH	Nmin (0-30 cm) kg ha^{-1}	Annual/Average temperature °C	Annual/average precipitation mm	Number of observations
Effects of nitrification inhibitors (NIs) added into mineral fertilizers on crop yields and quality									
Bernburg	Winter wheat[1]	120-200	1998-2003	loam	-	-	9.1	469	12
Wörrstadt	Winter wheat[2]	138-141	2001-2003	-	-	-	10.2-10.5	453-791	2
Donaueschingen	potato[11]	80	1998-2001	silty loam	6.0-7.3	19-50	7.4-8.0	604-911	3
Dürrenmungenau	Potato[4]	120	2002	sand	5.8	17	8.3	627	2
Eckendorf	Potato[4]	80-120	2001-2002	sandy loam	6.4	13	7.6	697	2
Feldkirchen	Potato[4]	80-120	2000-2002	clayey loam	7.2	25	7.6	696	2
Gersthofen	Potato[4]	80-120	2000-2002	sandy loam	6.6	17	7.6	697	2
Köfering	Potato[4]	80-120	2000-2002	silty loam	7.1	24	7.9	643	2
Mussen	Potato[4]	80-120	2001-2002	sandy loam	5.9	28	6.4	927	2
Uttenkofen	Potato[4]	80-120	2000-2001	silty loam	7.0	17	8.4	660	2
Gülzow	Rapeseed[10]	200	2004-2007	sandy loam	-	20-32	9.5	624	4
Hohenlohe	Rapeseed[11]	140	1998, 2000	silty loam	6.7	-	10.4	787	1
Hohenlohe	Rapeseed[11]	170	1998, 2001	clayey loam	7.2	-	10.0	898	1
Hohenlohe	Rapeseed[11]	160	1998, 2002	silty loam	6.8	-	10.2	922	1
Vipperow	Rapeseed[10]	160	2004-2007	sandy loam	-	20-32	8.2	627	3
Augustenberg	Maize[6]	160	2002-2004	silty loam	7.4	-	11.2	670	3
Effects of NIs added into slurry on crop yields and quality									
Düsse	Winter wheat[8]	60	1997, 2008	silty loam	-	-	9.7	827	5
Düsse	Winter wheat8	70-140	2008	sand	-	-	9.7	827	2
Düsse	Winter barley[8]	60-120	1997, 2008	silty loam	-	-	9.7	827	4
Dürnast	Silage maize[9]	140-213	2005, 2007, 2008	silty loam	6.5		8-9.4	876-899	3
Comparison between crop yields and quality without and with NIs at a reduced number of nitrogen fertilizer applications									
Augustenberg	Winter wheat[6]	180	1999-2005	silty loam	7.4	-	11.2	620-695	14
Bernburg	Winter wheat[1]	200	2003	loam	-	-	9.1	469	1
Betzendorf	Winter wheat[3]	80-160	2000-2002	sandy loam	6.3	25	8.3	643	4
Desching	Winter wheat[3]	80	2000-2002	loam	6.9	22	7.8	688	2
Dürnast	Winter wheat[5]	120-160	1997-1999	silty loam	6.5		8.2	736	9
Gersthofen	Winter wheat[3]	80-160	2000-2001	sandy loam	6.8	22	8.0	788	4
Haar	Winter wheat[3]	80-160	2000-2002	sandy loam	7.1	22	7.9	1002	4
Köfering	Winter wheat[3]	80-160	2001-2002	silty loam	7.1	21	7.9	646	4
Osterseeon	Winter wheat[3]	80-160	2000-2002	sandy loam	6.5	17	7.5	994	4
Piering	Winter wheat[3]	80-160	2000-2002	sandy loam	6.9	19	8.0	670	4
Thonstetten	Winter wheat[5]	120-160	1997, 1999	loamy sand	6.8		8.3-8.7	711-750	8
Wolfsdorf	Winter wheat[3]	80-160	2000-2002	sandy loam	6.8	23	8.5	665	4
Hohenlohe	Winter wheat[11]	210-220	1999-2001	silty loam	6.7	-	10.5	822	8
Hohenlohe	Winter wheat[11]	200	1999-2001	clayey loam	7.2	-	10.1-10.8	712-933	2
Hohenlohe	Winter barley[11]	200--220	1999-2003	clayey loam	7.2	-	10.5	875	3
Augustenberg	Winter barley[6]	160	2002-2004	silty loam	7.4	-	11.2	670	1
Donaueschingen	Potato[11]	120	1998-2001	silty loam	6.0-7.3	19-50	7.4-8.0	604-911	3
Hohenlohe	Rapeseed[11]	160	2003	silty loam	6.8	-	10.2	922	1
Bingen	Rapeseed[7]	167-170	2006-2007	clayey loam	6.7-7.36	-	9.9	548	2
Dürnast	Silage maize[9]	140	2005, 2007, 2008	silty loam	6.5		8-9.4	876-899	1
Thonstetten	Silage maize[5]	120-140	1997-1999	loamy sand	6.8		8.3-8.7	711-750	3
Total number of observations:									**144**

[1]Boese 2007; [2]Fritsch 2004; [3]Hege and Offenberger 2010a; [4]Hege and Offenberger 2010b; [5]Linzmeier 2010; [6]Mokry 2008; [7]Pahlmann 2008; [8]Remmersmann 2009; 2010; [9]Schmidhalter et al. 2011; [10]Schulz 2008; [11]Waldorf and Schweiger 2004

Statistical analysis

The meta-analysis was used to examine the two main hypotheses in this study. Each data point in the meta-analysis included two measures with the same amount of N fertilization, i.e. the experimental treatment with the N fertilizers plus NIs and the control treatments with N fertilizers without NIs. We based the meta-analysis on the procedure described by Hedges et al. (1999). Briefly, each data point was summarized by a response ratio (RR), the log of the response ratio (L_{RR}) and the sampling variance (*V*). A positive L_{RR} indicates an increase in yield production or quality by N fertilization with NIs. Concerning the effect of NIs on the yield of agricultural crops, we divided the database into three classes: mineral N fertilizers with NIs at the same number of split applications as that of control without NI; slurry fertilization with NIs at the same number of split applications as that of control without NIs; and mineral N fertilizers with NIs at the reduced number of split applications compared with that of the control without NIs. For the reduced number of split N applications, conventional N fertilizer systems used 2-3 split applications, whereas for N fertilizers with NIs, only 1-2 applications at the same N rate as conventional systems were provided, i.e. one time was reduced for the treatment with NIs. To analyse the effect of NIs on crop quality, the crops of winter wheat and potato at the same number of split applications of mineral N fertilizers with and without NIs and only winter wheat at the reduced number of split applications of mineral N fertilizers with NIs were chosen. Each class was summarized by the weighted mean of L_{RR} (L_{RR}*) and the standard error of L_{RR}* (SE(L_{RR}*)). L_{RR}* was calculated by giving greater weight to data points with a lower standard deviation and higher precision. The use of L_{RR}* increased the precision of the central tendency statistic and L_{RR}* was used in place of the un-weighted mean, because *V* differed between individual data points. SE(L_{RR}*) to determine the standard error of the weighted mean was calculated. Estimates of effect size were considered to be significantly different from zero if their 95% confident intervals around the effect size did not overlap with zero. The effect size was back-transformed as [(EXP(L_{RR})-1]×100% and was reported in the text and the figures as the percentage change from the control.

Results

Figures 1-3 summarize the results of yield of agricultural crops (winter wheat, winter barley, winter rapeseed, grain and silage maize and potato) and quality of winter wheat and potato comparing the treatments for mineral fertilizers and slurry with (+NI) and without NI (-NI) on the basis of the same number of applications and at a reduced number of N fertilizer application. Similar mean values of crop yield with the fertilizer applications containing NIs to those without NIs were found in all cases (Figures 1-3). For example, the average grain yield of winter wheat was 9.2 t ha^{-1} for the -NI treatment and 9.1 t ha^{-1} for the +NI treatment at the same number of split fertilizer applications (mineral N fertilizers), 8.7 t ha^{-1} for -NI treatment and 8.9 t $ha^{-1}$for +NI treatment at the same number of split fertilizer applications (slurry) and 7.5 t ha^{-1} for the treatments without NI and with NI at the reduced number of split fertilizer applications (mineral N fertilizers). The average yield of potato tuber was 59.8 t ha^{-1} for the -NI treatment and 59.6 t ha^{-1} for the +NI treatment at the same number of split fertilizer applications (mineral N fertilizers) and 57.6 t ha^{-1} for the treatment without NI and 56.5 t ha^{-1} for the treatment with NI at the reduced number of split fertilizer applications (mineral N fertilizers). The average yield of winter rapeseed was 5.1 t ha^{-1} for both -NI and +NI treatments at the same number of split fertilizer applications (mineral N fertilizers) and 4.0 t ha^{-1} for the treatment without NI and 3.8 t ha^{-1} for the treatment with NI at the reduced number of split mineral N fertilizer applications. The average grain yield of maize was 8.2 t ha^{-1} for the -NI treatment and 8.4 t ha^{-1} for the +NI treatment at the same number of split fertilizer applications (mineral N fertilizers). The average yield of silage maize was 22.6 t ha^{-1} for the -NI treatment and 23.3 t ha^{-1} for the +NI treatment at the same number of split fertilizer applications (slurry) and 19.8 t ha^{-1} for the treatment without NI and with NI at the reduced number of split fertilizer applications (mineral N fertilizers). The average yield of winter barley was 6.5 t ha^{-1} for the -NI treatment and 6.6 t ha^{-1} for the +NI treatment at the same number of split fertilizer applications (slurry) and 5.6 t ha^{-1} for the treatment without NI and 5.8 t ha^{-1} for the treatment with NI at the reduced number of split fertilizer applications (mineral N fertilizers). The average crude protein content of winter wheat was 12.2% for the treatment without NI and the treatment with NI at the same number of split fertilizer applications (mineral N fertilizers), and 12.1% for treatment without NI and 11.5% for the treatment with NI at the reduced number of split fertilizer applications (mineral N fertilizers). The average starch content of potato was 19.3% for the treatment without NI and 19.6% for the treatment with NI at the same number of split fertilizer applications (mineral N fertilizers).

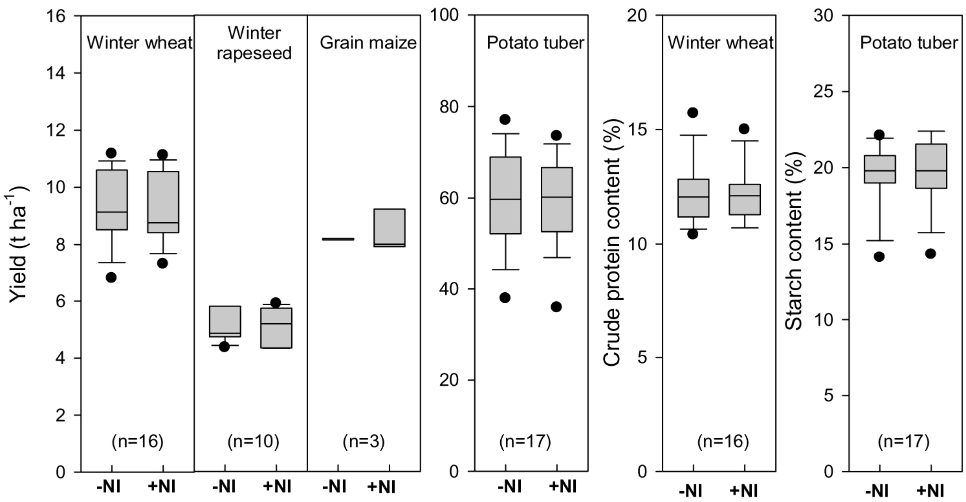

Figure 1. Comparison of yield of agricultural (crops winter wheat, winter rapeseed, potato, grain maize) and of crude protein content of winter wheat or starch content of potato between the N fertilizations with or without nitrification inhibitors NIs at the same number of mineral N fertilizer applications.

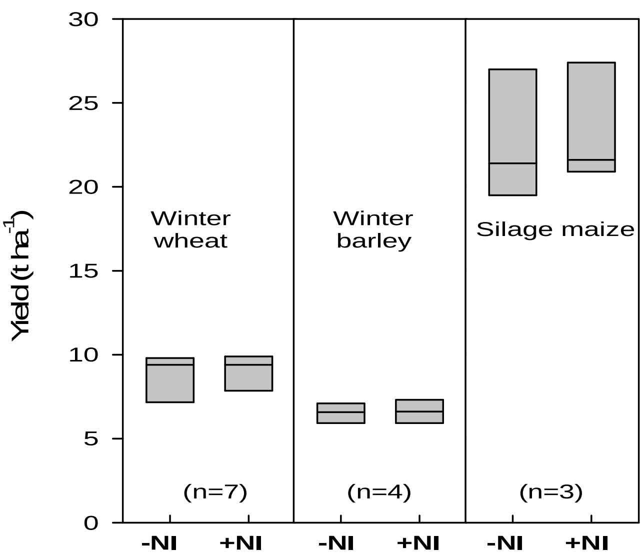

Figure 2. Comparison of yield increases of agricultural (crops winter wheat, winter barley and silage maize) between the slurry N fertilizations with or without nitrification inhibitors NIs at the same number of fertilizer applications.

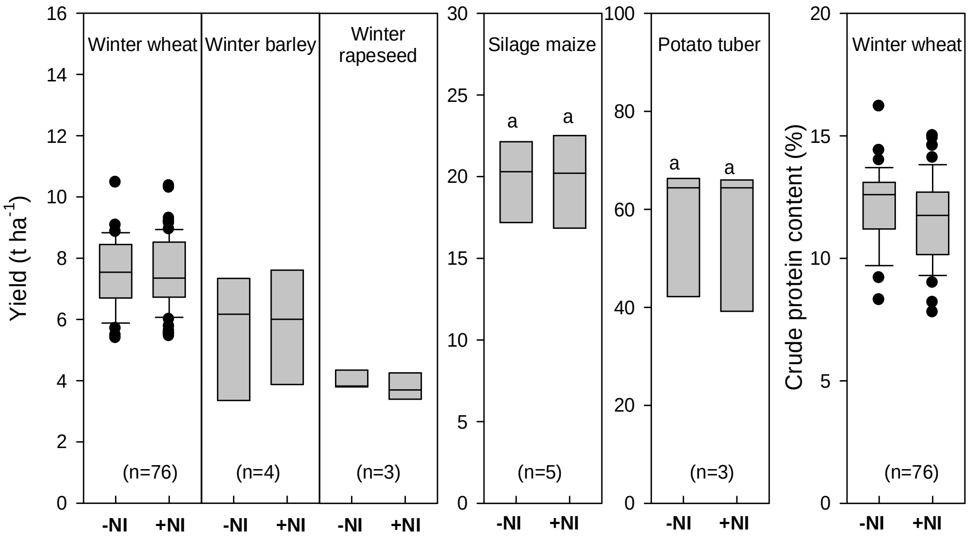

Figure 3. Influence of the reduced number of N fertilizer applications for the +NI treatments on yield of agricultural crops (winter wheat, winter barley, winter rapeseed, silage maize and potato) and on crude protein content of winter wheat.

Results of the meta-analysis are presented in Figures 4-6. Figure 4 shows that for the same number of split N fertilizer applications, yield of all agricultural crops applied with mineral N fertilizers containing NIs was slightly decreased by 0.12% compared with that without NI, while their yield with slurry containing NIs was increased by about 2.1%. For the reduced number of split N fertilizer applications, the yield of all agricultural crops applied with mineral N fertilizers containing NIs was decreased by about 0.99% compared with the control treatment. However, these influences on yield by adding NIs were not significant. Similarly, there was no significant difference in yield and quality of winter wheat and potato between the treatments with and without NIs at the same number of split N applications (Figure 5). In contrast, a significant effect of the NI fertilizers with the reduced application number on the crude protein content was observed for winter wheat (Figure 6), even though there was no significant difference in the yield of winter wheat.

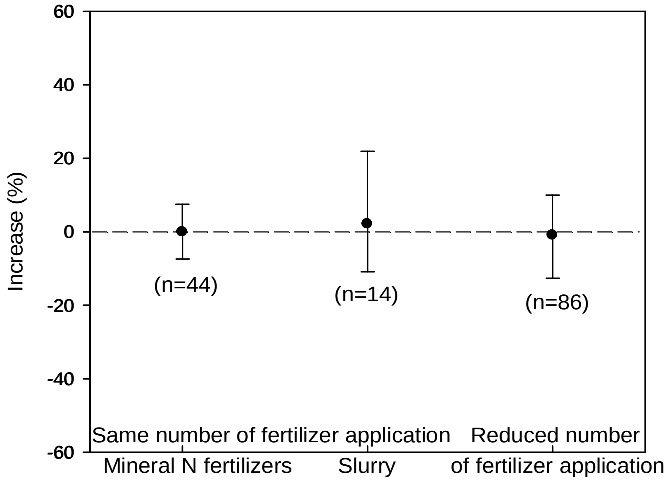

Figure 4. Yield increases of agricultural crops pooled data for winter wheat, winter barley, winter rapeseed, potato, maize due to N fertilization with or without nitrification inhibitors NIs at the same number of N fertilizer applications mineral fertilizers and slurry and at the reduced number of N fertilizer application for the treatments added with NIs. Symbols represent pooled weighted percentage change due to NIs; Bars show 95% confidence intervals CIs; number of observations is in parentheses. Means are significantly different from controls without NIs when their CIs do not overlap with zero.

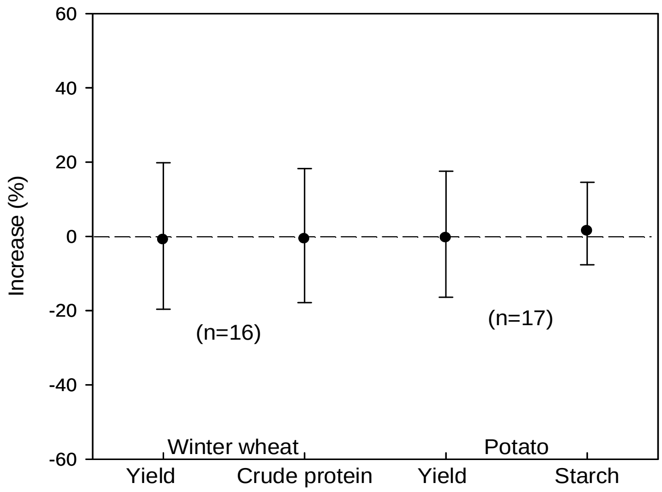

Figure 5. Yield and crude protein or starch increases of winter wheat and potato pooled data for different N levels due to N fertilization with or without nitrification inhibitors NIs at the same number of N fertilizer applications mineral fertilizers for other symbols see the legend of Figure 4.

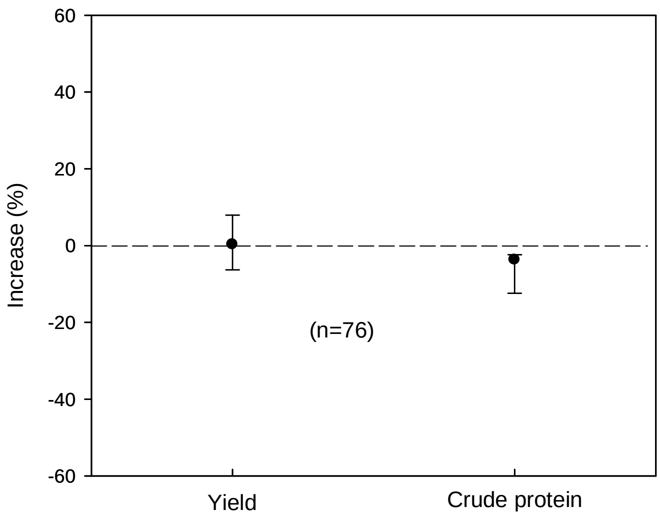

Figure 6. Yield and crude protein increases of winter wheat pooled data for different N levels due to N fertilization with or without nitrification inhibitors NIs at the reduced number of N fertilizer applications mineral fertilizers for other symbols see the legend of Figure 4.

Discussion

The meta-analysis for the studies carried out by extension agronomists and scientists from German federal states and universities showed that the application of N fertilizers with NIs did not significantly influence the yields of a variety of agricultural crops (including winter wheat, winter barley, winter rapeseed, grain and silage maize and potato) (Figures 4-6). However, numerous studies in literature have shown that NIs can significantly reduce N losses through NO_3^- leaching and N_2O emissions. For example, Gutser (1999), Serma et al. (2000), Di and Cameron (2004), Arregui and Quemada (2008) reported that the leaching of NO_3^- following the application of mineral fertilizers can be significantly reduced by adding the NIs. The NIs can reduce N_2O emissions by 30-80% (e.g., Linzmeier et al., 2001a; Di et al., 2007; Khalil et al., 2009; Zaman et al., 2009; Akiyama et al., 2010). Because the environmental benefits to society are currently not ascribed an economic value, life cycle analysis is needed to more clearly define the costs and benefits throughout the system associated with adoption of NI fertilizers, including manufacturing, emissions on and off farms, transport and the total potential off-site impacts (Grant, 2005). Furthermore, agricultural systems globally contribute nearly 70% of N_2O emissions to the atmosphere and the global N_2O emissions are projected by 2100 to be four times greater than the current emissions, due largely to an increase in the use of N-fertilizers (Hofstra and Bouwman, 2005). Therefore, potential future increases in the use of NI fertilizers will depend on future energy costs and fertilizer prices as well as on the continued strengthening of efforts to reduce gaseous N emissions and NO_3 losses through leaching by directives and regulations from both the EU and climate change organizations.

Figure 4 shows that, although there was no significant difference in crop yield between -NIs and +NIs treatments for the slurry application, the yield increase was about 2%, which may indicate a potential increase in crop yield by adding NIs into slurry. Schmidhalter et al. (2011) reported that the maize yield in Germany was improved when slurry with NIs was applied compared with that without NIs and N uptake was increased in the +NI treatment. Similarly, the positively affected yield for adding NIs into slurry or animal urine-patches was also found for herbage production in Ireland (O´Connor et al., 2012) and for pasture and forage dry matter in New Zealand (Carey et al., 2012; Moir et al., 2012). In contrast to our study, positive effects of NIs on vegetable and cereal crop yield were shown by other authors in Europe (Pasda et al., 2001; Villar et al., 2010) and in America, Australia, India and Pakistan (Nelson and Huber, 1992; Freney et al., 1993; Sharma and Kumar, 1998; Mohammad et al., 1998). Since the benefit to the crop is dependent upon the existence of environmental conditions conducive to N losses prior to when the N is taken up by the crop, the following two reasons may explain why there was no effect of NIs on agricultural crop yield in the German studies cited above. First, it may be that the experimental sites have low N losses during the growing seasons. For instance, some of the experimental sites are characterized by loamy soils and an annual precipitation of around 700 mm (Table 1), which may also reduce the risk of N leaching during the growing season. Field experiments and long-term lysimeter experiments with NI fertilizers compared to fertilizers without NIs showed that NI fertilizers increased crop yields of winter wheat and winter barley and decreased nitrate leaching under the higher annual precipitation of Bavarian sites in Germany (Gutser, 1999; Linzmeier et al., 2001b). Second, it is known that the application of N fertilizers in Germany is rather above optimum or presumably optimized as in the current studies. Under optimal conditions, the use of NIs reduced N losses (e.g., NO_3 leaching or N_2O emissions) by 10-20 kg N ha^{-1}, which would not necessarily influence crop yield. Supporting this hypothesis is the study of Frye (2005), which examined the effects of NIs on crop yield under different N level. He found that the yield increase was more pronounced under conditions of sub-optimal N supply. Fourth, the increase in the retention ability of NH_4^+ -N in soils may also contribute to no change in the yield of plants by adding NIs.

Furthermore, the meta-study indicates that the number of fertilizer applications can be reduced without significant effects on crop yield when an NI fertilizer is used (Figure 6), which is in agreement with other studies in Germany (Linzmeier et al., 2001b) and in Canada and Chile (Grant, 2005; Roco and Blu, 2006). For the given amount of N mineral fertilizers without NIs, the common recommendations in German conditions are 3 split applications for winter wheat and winter barley and 2 split applications for winter rapeseed, maize and potato. For the given amount of N mineral fertilizers with NIs, it is recommended that one split application can be reduced for the above crops, i.e. the recommendations are 2 split applications for winter wheat and winter barley and 1 single application for winter rapeseed, maize and potato.

In conclusion, although the increased yield has not been found by adding NIs to N fertilizers, the findings from German studies suggest that the use of NIs simplifies the task of N application and allows for greater flexibility in the timing of N applications without influencing the agricultural crop yield. These benefits, in turn, translate into reduced costs for the farmers and reduced soil compaction by tractor traffic. However, caution must be taken because, despite enabling a reduced number of split applications compared to conventional fertilizers with no effect on crop yield, the application of NI fertilizers with a reduced number of split applications did reduce the crude protein content of winter wheat.

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