



Review

Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis



Peteh Mehdi Nkebiwe^{a,*}, Markus Weinmann^b, Asher Bar-Tal^c, Torsten Müller^a

^a Fertilisation and Soil Matter Dynamics (340 i), Institute of Crop Science, University of Hohenheim, 70593 Stuttgart, Germany

^b Nutritional Crop Physiology (340 h), Institute of Crop Science, University of Hohenheim, 70593 Stuttgart, Germany

^c Institute of Soil, Water and Environmental Sciences, The Agricultural Research Organisation of Israel (ARO)—The Volcani Centre, P.O.B. 6, Bet Dagan 50250, Israel

ARTICLE INFO

Article history:

Received 13 January 2016

Received in revised form 8 July 2016

Accepted 22 July 2016

Available online 7 August 2016

Keywords:

Fertilizer placement

Meta-analysis

Yield

Nutrient mobilization

Nutrient uptake

ABSTRACT

In agricultural soils, plant-available nitrogen (N) and phosphorous (P) may be inadequate for crop production although total N and P concentrations are high. Therefore, N and/or P fertilizer is commonly applied to field soil by broadcast, even though broadcast does not ensure that a considerable proportion of applied fertilizer is available at the right time and place for optimal root uptake. Fertilizer placement in soil, which refers to precise application of specific fertilizer formulations close to seeds or plant roots to ensure high nutrient availability, may be a more effective alternative to broadcast application. The objectives of this paper are: (1) to summarize current techniques for fertilizer placement in soil and to identify fertilizers that are suitable for subsurface placement; and (2) to quantify the relative effects of fertilizer placement to fertilizer broadcast on crop nutrient acquisition and yield. To achieve these aims, we reviewed scientific literature on the dynamics of nutrient movement from soil into roots and studies on fertilizer placement under field conditions. Additionally, we performed three meta-analyses according to the method of *baseline contrasts* on the relative effects of fertilizer placement (Treatment) to fertilizer broadcast (Control) on yield, nutrient concentration and content in above-ground plant parts. In all, we used 1022 datasets from 40 field studies published from 1982 to 2015 (85% of studies from 2000). Results showed that overall, fertilizer placement led to 3.7% higher yield, 3.7% higher nutrient concentration and 11.9% higher nutrient content in above-ground parts than fertilizer broadcast. For $\text{CO}(\text{NH}_2)_2$ and soluble phosphate (PO_4^{3-}), NH_4^+ and PO_4^{3-} , $\text{CO}(\text{NH}_2)_2$, NH_4^+ , and PO_4^{3-} , fertilizer placement led to 27.3%, 14.7%, 11.6%, 3.8% and 0.0% increase in yield in comparison to broadcast respectively. Increase in relative yield and relative nutrient uptake from subsurface placed $\text{CO}(\text{NH}_2)_2$, $\text{CO}(\text{NH}_2)_2$ and PO_4^{3-} , NH_4^+ , NH_4^+ and PO_4^{3-} or K^+ tend to increase with increasing placement depth to more than 10 cm. Results show that deep subsurface placed NH_4^+ ($\pm \text{PO}_4^{3-}$) or $\text{CO}(\text{NH}_2)_2$ ($\pm \text{PO}_4^{3-}$), K^+ , solid or liquid manure is more effective to improve deep rooting, nutrient uptake and yield than broadcast. Thus, deep subsurface fertilizer placement could be one more tool to mitigate negative consequences of increasingly frequent high temperatures and drought that threaten food production globally.

© 2016 Elsevier B.V. All rights reserved.

Contents

1. Introduction	390
2. Literature review	391
2.1. Methodology	391

Abbreviations: ANR, Apparent Nutrient Recovery efficiency; CI95%, Bias-corrected percentile bootstrap confidence intervals (95%) with 999 iterations at the power $\alpha = 0.05$; CULTAN, controlled long-term ammonium nutrition; DMPP, 3,4-dimethylpyrazole phosphate; PGPMs, plant growth-promoting microorganisms; RPE, relative placement effect; STD, standard deviations; USDA, United States department of agriculture.

* Corresponding author.

E-mail addresses: Mehdi.Nkebiwe@uni-hohenheim.de (P.M. Nkebiwe), Markus.Weinmann@uni-hohenheim.de (M. Weinmann), abartal@volcani.agri.gov.il (A. Bar-Tal), Torsten.Mueller@uni-hohenheim.de (T. Müller).

2.2. Techniques for fertilizer placement	391
2.3. Fertilizers suitable for placement as depots.....	391
3. Meta-analyses of relative effects of fertilizer placement to fertilizer broadcast on crop yield and nutrient uptake	393
3.1. Prerequisites for data inclusion.....	393
3.2. Methodology.....	393
3.3. Sensitivity analyses	394
3.4. Results.....	395
3.4.1. Explanation.....	395
3.4.2. Yield	395
3.4.3. Nutrient concentration in above-ground biomass	396
3.4.4. Nutrient content in above-ground biomass	397
4. Discussion	398
5. Conclusion	399
Acknowledgments	399
Appendix A. Supplementary data.....	399
References.....	399

1. Introduction

Intensive agriculture, which requires substantial amounts of soluble fertilizers and other inputs, has considerably increased global food production (Matson et al., 1997; Tilman et al., 2002). However, it has also increased the risk of negative consequences on ecosystems, climate and public health (Delgado and Scallenghe, 2008; Matson et al., 1997; Tilman et al., 2002; Tscharntke et al., 2012). High energy costs for ammonia synthesis (Michalsky and Pfromm, 2012) and increasing scarcity in quality and quantity of rock phosphate reserves (Cordell et al., 2009) suggest that synthetic mineral N and P fertilizers, and agricultural goods produced using them will become more expensive.

Overuse of soluble fertilizers in intensive production systems is often associated with low crop nutrient use efficiency (Fan et al., 2012). In the tropics and sub-tropics, apparent nutrient recovery efficiency (ANR) of applied mineral N, P and K within the first year of application is estimated to be less than 50%, 10% and 40% respectively (Baligar and Bennett, 1986; Baligar et al., 2001; Raun and Johnson, 1999). Excess fertilizer nutrients that cannot be contained in the soil matrix or in soil microbial biomass may be released to the atmosphere (e.g. NH₃, N₂O, NO_x and N₂) and to surface and/or below-ground water bodies (e.g. NO₃⁻, HPO₄²⁻/H₂PO₄⁻) (Fan et al., 2012; Tunney et al., 1997; Weaver et al., 1988).

Compared to other macronutrients, plant-available P is frequently the prime limiting nutrient for plant growth in most agricultural soils (Hinsinger, 2001). Like any other essential nutrient, severe P deficiency, especially during early growth stages in annual plants, may lead to irreversible restrictions in plant growth and development, which may not be corrected even after optimal P supply during later growth stages, thus, limiting crop yield (Colomb et al., 2000; Grant et al., 2001).

After long-term P fertilization, plant-available P levels may become suboptimal for crop production although total P is high (Hinsinger, 2001). A fraction of applied P is taken up by plants and by soil microorganisms, the latter acting as an important sink and source for soil P (Bünemann et al., 2011; Gichangi et al., 2009). The other fraction may be rendered partially or fully unavailable to plants through fixation or occlusion respectively. P fixation may occur by adsorption of PO₄³⁻ and or stabilized organic phosphates (e.g. phosphate monoesters) to sorbent surfaces on soil colloids such as iron and other metal hydroxides (Turner et al., 2005). It may also occur through precipitation of PO₄³⁻ as sparingly soluble Ca-phosphates in calcareous soils with neutral or alkaline pH (up to about 8) (Lu et al., 1987; Moody et al., 1995) or as Fe- or Al-phosphates in acidic soils (pH below 5.5) (Prochnow et al., 2004; Redel et al., 2007).

To optimize N and P availability to crop plants especially in early growth stages, N and P fertilizer can be applied by localized placement at moderate amounts in the seeding zone or in high amounts given sufficient spacing to plants as opposed to conventional fertilizer application by homogenous broadcast over the entire soil surface, with or without subsequent incorporation (Grant et al., 2001; Lu and Miller, 1993; Valluru et al., 2010). In this paper, “fertilizer placement” refers to localized application of fertilizers to small areas on surface or subsurface soil. Early studies on fertilizer placement mainly focused on the effects on crop yields. They reported enhanced plant growth and yield for placement of N and NPK fertilizers and conflicting results for placement of P or K fertilizers (Cooke, 1954; Reith, 1954). Within the last two decades, the significance of fertilizer placement in comparison to broadcast can be appreciated through the wide range of published peer-reviewed articles on the topic. There has been much interest in the effects of fertilizer placement in comparison to fertilizer broadcast on crop performance attributes like root growth and nutrient uptake (Hodge, 2004; Rose et al., 2009; Weligama et al., 2008); crop yield (Jing et al., 2012; Kelley and Sweeney, 2007; Schlegel et al., 2003) and yield quality (Boelcke, 2003; Weber et al., 2008); and on environmental aspects like NO₃⁻ leaching (Baker, 2001; Ruidisch et al., 2013; Zhou et al., 2008); emission of N₂O (Engel et al., 2010; Halvorsen and Del Grosso, 2012; Pfab et al., 2012; Nash et al., 2012); release of CH₄ (Linquist et al., 2012; van Kessel et al., 2012); and volatilization of NH₃ (Hayashi et al., 2009; Ma et al., 2010; Rochette et al., 2009). Fertilizer placement has also gained much interest in weed management where effective fertilizer placement disproportionately favors nutrition of target crop plants and enables them to be more competitive against weeds (Blackshaw et al., 2002; Légeré et al., 2013; Melander et al., 2005; Petersen, 2005). Interest in fertilizer placement can also be appreciated by continuous development of improved placement machinery (Bautista et al., 2001; Nyord et al., 2008).

In more recent decades, many studies on fertilizer placement have also reported conflicting results on its effect on crop performance in comparison to fertilizer broadcast and requirements for effective fertilizer placement remain unclear. Open questions still exist, such as: Which fertilizers and placement techniques have been shown to be consistently effective? Can placement improve the efficiency of alternative recycled N and/or P fertilizers that are usually sparingly soluble (e.g. sewage sludge ash, biogas digestates or P-rich industrial by-products, if levels of heavy metals and other impurities are acceptable)?

The objectives of this paper are: (1) to summarize current techniques for fertilizer placement in the field and to outline properties of fertilizers suitable for placement as a subsurface depot; and (2) to compare the relative effect of fertilizer placement (Treatment)

to fertilizer broadcast (Control) on yield and nutrient concentration and content in above-ground biomass, for various field crops, fertilizers and placement techniques through comprehensive meta-analyses on data published from field studies within the last three decades. Fertilizer placement effect on biomass nutrient concentration is addressed in terms of post-harvest nutritional value of crops (e.g. relation of N concentration to protein content and baking quality of bread wheat) (Boelcke, 2003; Grant et al., 2016) and not regarded as an indicator for crop nutrition or yield potential, given the general inverse allometric relation of nutrient concentration to dry biomass yield per unit area, as clearly illustrated for N concentration in different crop species (Greenwood et al., 1991).

2. Literature review

2.1. Methodology

In order to compile and summarize relevant information on fertilizer placement techniques and fertilizers suitable for placement, and data on yield, nutrient concentration and content in above-ground biomass from fertilizer placement in comparison to fertilizer broadcast, we used published peer-reviewed articles and reviews obtained through recognized literature databases like Scopus and EBSCO EDS-global index as well as free scientific publication servers like Google Scholar. In our comprehensive literature search, we initially employed the following keywords and their combinations: fertilizer application methods, fertilizer application techniques, fertilizer placement, nutrient placement, localized fertilizer, localized nutrient supply, soil fertilizer depot, nitrogen placement, phosphorous placement, potassium placement, manure placement, slurry placement, field soil, field crops. These searches yielded more specific keywords and technical terms that were subsequently used particularly in literature search for data used in the meta-analyses described in Section 3. Further keywords and technical terms included: starter fertilizer; 2 × 2 fertilizer; 5 × 5 fertilizer; pop-up fertilizer; fertilizer band; furrow fertilizer; below-seed fertilizer; deep placement; fertilizer side-dress; fertilizer injection; CULTAN; fertilizer depot placement; N-fertilizer depot; fertilizer nests; knife fertilizer; coulter-knife fertilizer; fertilizer broadcast; broadcast-incorporated; fertilizer topdress; yield; nutrient uptake; yield quality; yield composition; maize; wheat; field experiment; field study. Using defined time ranges; priority was given to scientific papers published from recent years till 2000 before older publications were considered.

Books were obtained through the library services of the University of Hohenheim, Stuttgart, Germany.

2.2. Techniques for fertilizer placement

Common techniques for fertilizer placement in soil include: indirect placement by pre-treatment of seeds with fertilizers before sowing (Peltonen-Sainio et al., 2006; Sekiya and Yano, 2010); in the seed hole or furrow during seeding (Hocking et al., 2003), on the soil surface as a band with or without incorporation (Kelley and Sweeney, 2007); subsurface as: shallow or deep band (Pfab et al., 2012), in a shallow or deep trench cut in the soil ("knife" or "coulter-knife" application, Kelley and Sweeney, 2007), as shallow or deep point placement ("nest" placement, Engel et al., 2010) or point injection (Sommer, 2005; Weber et al., 2008) (Fig. 1). Fertilizer bands could also be placed on or below the soil surface, on or to the side(s) of the crop row. These techniques can be applied to both inorganic and organic fertilizers (Bittman et al., 2012; Dell et al., 2011) as well as to solid, liquid and gaseous fertilizer formulations, the latter requiring special equipment to minimize gaseous

losses. Effective fertilizer placement requires good timing to crop demand and environmental conditions with low risk of nutrient loss. Split fertilizer placement at key growth stages with high nutrient demand enhances nutrient uptake and crop yield (Saleem et al., 2009), however, it may entail higher labor and energy costs.

Seed placement ensures that as seed nutrient reserves become depleted, nutrients (especially macronutrients N and P) are sufficiently available during susceptible early growth stages when rooting is small. Nevertheless, high seed NH₄⁺ and PO₄³⁻ rates are not advisable to avoid injury on seeds and young plants.

Surface placement without incorporation is not advisable for N fertilizers such as liquid manure, NH₄⁺-fertilizer and CO(NH₂)₂ because it may lead to high gaseous NH₃ losses especially on alkaline or dry soils and under high air temperatures (Adamsen and Sabey, 1987; Dell et al., 2011; Köhler et al., 2003). Surface-placed fertilizers are more prone to wind and water erosion and more likely to emit undesirable odors (especially for manures) than incorporated or subsurface placed fertilizers. Although soil incorporation may reduce NH₃ volatilization from NH₄⁺-fertilizer or CO(NH₂)₂, it increases the surface area of contact with soil microorganisms, thereby promoting biological oxidation with high risk for NO₃⁻ leaching and gaseous N₂O, NO_x and N₂ losses (Malhi et al., 2001; Nash et al., 2012).

Subsurface fertilizer placement may be shallow (often 5–10 cm) or deep (>10 cm). Similarly to seed placement, fertilizer application rates should be kept low if they are placed below ground and close to the seed row (Zhang and Rengel, 2002). If placed close to seeds, granulated fertilizers may be less harmful to seeds than fine and/or highly soluble ones due to slower nutrient release (Olson and Dreier, 1956). "Starter fertilizer" usually refers to macronutrient(s) especially NH₄⁺ and PO₄³⁻ (e.g. (NH₄)₂HPO₄) banded only about 5 cm sideways and 5 cm below seeds, in the seeding hole or on/in the sowing row to ensure high nutrient availability during early crop development stages (Grant et al., 2001; Kristoffersen et al., 2005; Qin et al., 2005; Niehues et al., 2004). Unlike even broadcast with or without incorporation, banding reduces the surface area of contact with soil and soil microorganisms, thereby reducing PO₄³⁻ immobilization by fixation to various cations (Grant et al., 2001) and NH₄⁺ nitrification by soil microorganisms (Malhi et al., 2001). NH₄⁺-fertilizers containing nitrification inhibitors may be suitable for placement (For chemical structures and inhibited reactions of nitrification and urease inhibitors tested in the field studies used in the meta-analyses described in Section 3, see Table A.1, Appendix).

Whereas fertilizers placed deep in soil with high moisture content may be more plant-available than those placed at shallow depths with less moisture (Ma et al., 2009; Singh et al., 2005), nutrients placed too deep may be less plant-available during early stages of plant growth when root density is still low at high depths.

2.3. Fertilizers suitable for placement as depots

To effectively place fertilizer to form a subsurface nutrient depot, we propose the following prerequisites. Fertilizer ions should:

- a.) Be taken up by plants in relevant quantities (macronutrients).
- b.) Considerably stimulate root-growth and attract roots at the site of contact.
- c.) Have limited mobility from the depot. This is feasible for nutrients that have low effective diffusion coefficients in soil due to their adsorption properties (Table 1) although being water-soluble.
- d.) Be relatively stable in chemical form and plant-availability especially at depot borders accessible to roots.

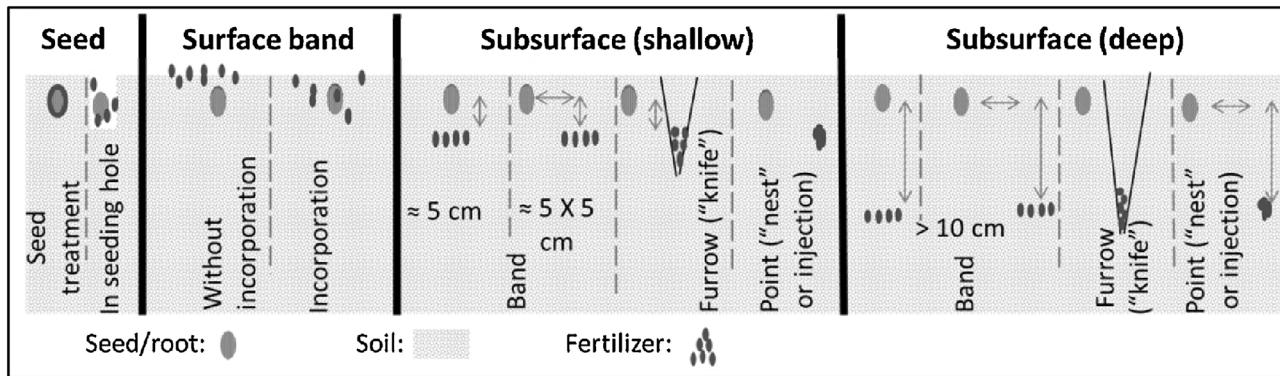


Fig. 1. Fertilizer placement techniques.

Table 1
Effective Diffusion Coefficient

Nutrient	Effective diffusion coefficient in soil ($\times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$)	Soil texture	Volumetric moisture content (%)	Bulk density (g cm^{-3})	Subgroup (USDA soil taxonomy)	Source
H_2PO_4^-	0.00001–0.01					Marschner and Rengel (2012), Neumann and Römhild (2012)
H_2PO_4^-	0.0023	Silt loam				Barber (1984)
H_2PO_4^-	0.007–0.025	Sandy loam				Bhat and Nye (1973)
H_2PO_4^-	0.0042	Loamy sand	20	1.5	Typic Udipsamment	Schenk and Barber (1979)
H_2PO_4^-	0.0062	Loam	24	1.2	Typic Argiaquoll	Schenk and Barber (1979)
H_2PO_4^-	0.0097	Silt loam	24	1.2	Ultic Hapludalf	Schenk and Barber (1979)
H_2PO_4^-	0.0131	Silt loam	24	1.2	Typic Halplaquoll	Schenk and Barber (1979)
H_2PO_4^-	0.0152	Silt loam	24	1.2	Aeric Ochraqualf	Schenk and Barber (1979)
H_2PO_4^-	0.0893	Silt loam	20	1.2	Aquic Argiudoll	Schenk and Barber (1979)
K^+	0.01–0.1					Marschner and Rengel (2012), Neumann and Römhild (2012)
K^+	0.019	Silt loam				Barber (1984)
K^+	0.066	Silt loam				Barber (1984)
K^+	0.075	Silt loam				Barber (1984)
NH_4^+	0.157 ^a	Loam	20	1.14–1.23		Clarke and Barley (1968)
NH_4^+	0.319 ^a	Sand	20	1.48–1.55		Clarke and Barley (1968)
NH_4^+	0.73	Clay loam	32			Pang et al. (1973)
NH_4^+	0.82	Silty clay loam	42			Pang et al. (1973)
NH_4^+	1.24	Fine sandy loam	17			Pang et al. (1973)
$\text{CO}(\text{NH}_2)_2$	0.62	Sandy clay	52	1.22	Typic Hapludults	Sadeghi et al. (1989)
$\text{CO}(\text{NH}_2)_2$	0.805	Silt loam	58.6	1.37	Cumulic Hapludolls	Sadeghi et al. (1989)
NO_3^-	0.1–1.0					Marschner and Rengel (2012), Neumann and Römhild (2012)
NO_3^-	1.99 ^a	Loam	20	1.14–1.23		Clarke and Barley (1968)
NO_3^-	2.5	Silt loam				Barber (1984)
NO_3^-	4.76 ^a	Sand	20	1.48–1.55		Clarke and Barley (1968)

USDA, United States Department of Agriculture.

^a Effective diffusion coefficient derived from equations of effective diffusion as a function of volumetric water content (Clarke and Barley, 1968).

e.) Be placed at an appropriate distance from the seeding zone to avoid injury to plants.

The effective diffusion coefficient of a nutrient in soil (D_e) is given by:

$$D_e = \frac{(D_1 \theta f_1 dC_1)}{dC_s}$$

D_l , diffusion coefficient of the nutrient in water; θ , volumetric moisture content of soil; f_l , tortuosity, the capacity of the soil to impede diffusion of non-adsorbed ions; dC_l/dC_s ; the reciprocal of the soil buffer capacity for the nutrient (Barber, 1984).

An effective approach is to place fertilizers at a high dose and concentration in a limited soil volume to form a nutrient depot providing high and persistent nutrient-availability during the growing season. For placement of NH_4^+ (with or without PO_4^{3-}) as a rich subsurface depot, Sommer (2005) proposed the term Controlled

Long-Term Ammonium Nutrition (CULTAN), which describes a single application of a high phytotoxic concentration of fertilizer solution or granules at a safe distance from plant roots or seeds (Deppe et al., 2016). Toxic NH₄⁺ concentrations inhibit NH₄⁺ oxidation by soil microorganisms (Müller et al., 2006; Shaviv, 1988). Nutrient concentration in such a rich depot could be in the order of 1000 mg N or P kg⁻¹ dry soil and even higher (Lu and Miller, 1993; Pfab et al., 2012).

Based on the suggested criteria, fertilizers containing the macronutrient N in the form of NH_4^+ and/or P normally in the oxidized form of PO_4^{3-} (e.g. $(\text{NH}_4)_2\text{SO}_4$, $\text{Ca}(\text{H}_2\text{PO}_4)_2$, $\text{NH}_4\text{H}_2\text{PO}_4$, $(\text{NH}_4)_2\text{HPO}_4$ and ammonium polyphosphate – $[\text{NH}_4\text{PO}_3]_n$) are the best candidates to be recommended for placement as a subsurface depot. NH_4^+ and PO_4^{3-} ions are both macronutrients that strongly stimulate initiation and elongation of lateral roots on the part of the root system that is within or close to their respective nutrient depots (Anghinoni and Barber, 1990; Chassot et al., 2001; Drew,

1975; Jing et al., 2012), also with a potential to contribute to root growth in soil zones distant from the nutrient patch (Zhang et al., 2000). NH_4^+ and PO_4^{3-} generally have low effective diffusion coefficients in soils (Barber, 1984; Neumann and Römhild, 2012). NH_4^+ readily binds to negative charges on the surface of clay minerals and becomes fixed, especially in 2:1 type clay-rich soils, when it penetrates the clay mineral interlayers and becomes trapped between its silicate sheets (Nieder et al., 2011). As previously indicated, PO_4^{3-} is readily fixed by adsorption to iron and other metal hydroxides or is precipitated depending on pH as Fe-, Al- and Ca-phosphates. PO_4^{3-} sorption capacity of soil can be measured from the concentration of Fe, Al and Ca cations upon extraction with Mehlich-3 solution (Zhang et al., 2005). According to Sommer (2005), high concentrations of NH_4^+ inhibit nitrification in subsurface NH_4^+ -depots, thereby lowering the potential for NO_3^- -related N losses. As a further step, the stability of NH_4^+ in a subsurface depot may be increased by using NH_4^+ treated with nitrification inhibitors e.g. 3, 4-Dimethylpyrazole phosphate (DMPP) (Zerulla et al., 2001). Through localized placement of NH_4^+ and/or PO_4^{3-} in small soil volumes, the surface area for contact to soil microorganisms (biological transformation or immobilization) or to soil minerals (for chemical transformation, adsorption, fixation or occlusion) is greatly reduced, thus, promoting nutrient stability in soil.

NO_3^- , $\text{CO}(\text{NH}_2)_2$ and K^+ do not substantially stimulate initiation and growth of lateral roots upon contact and are highly mobile in soil due to rapid diffusion and movement by mass flow. Therefore, they are less suitable candidates for placement to form a localized subsurface depot. Nevertheless, $\text{CO}(\text{NH}_2)_2$ may be placed as a depot if conditions are optimal for rapid ammonification and reduced NH_3 volatilization.

3. Meta-analyses of relative effects of fertilizer placement to fertilizer broadcast on crop yield and nutrient uptake

3.1. Prerequisites for data inclusion

Studies included in the meta-analysis fulfilled the following conditions:

- Published in an international peer-reviewed journal. Two exceptions were made specific to the fertilizer placement technique termed CULTAN (Sommer, 2005): a Ph.D. Thesis and a publication in a national agricultural research center journal.
- Performed under field conditions.
- Contained at least one fertilizer placement treatment (Treatment) and one fertilizer broadcast (or broadcast/incorporation) treatment (Control).
- Applied the same or comparable fertilizer types and application rates for Treatments and Control.

To compile published peer-reviewed studies that were included in these meta-analyses, we used specific keywords to search in recognized scientific literature databases as already described in Section 2.1. For yield, nutrient concentration in plant parts and nutrient uptake combined, there were 1022 datasets collected from 40 studies: six from 1982 to 1999 and 34 from 2000 to 2015. The term “dataset” refers to a pair of means (\bar{X}), standard deviations (S) and sample sizes (N), one for Treatment and the other for Control derived from the same experiment. Many datasets could be retrieved because several studies were extensive e.g. Borges and Mallarino (2000) which covered 20 field tests in long-term trials and 11 field tests in short-term trials. Additionally, many studies investigated different fertilizer types, application rates, timing and techniques under different systems for cropping, rotation, irrigation and tillage.

Information about crops, soil types, fertilizer types, broadcast and placement techniques, result of fertilizer broadcast and fertilizer placement on yield, nutrient uptake and nutrient concentration in plant parts, relative effects of fertilizer placement to broadcast and source of studies are summarized in Table A.1 (Appendix).

3.2. Methodology

In order to combine treatment effects across several primary independent randomized studies, a suitable method used in most meta-analyses is *baseline contrasts*, which puts the results of these studies in a common framework to enable comparison. This method expresses the effect of an experimental treatment in a study as a contrast or response ratio to the effect of a baseline or control treatment within the same study (Akiyama et al., 2010; Piepho et al., 2012). A *random effects model* with grouping variable was used to analyze the data (data structured in groups e.g. crop species). This model accounted for sampling error between studies and random variation in effect sizes between studies.

The whole data used in each meta-analysis could be arranged according to one of several grouping variables into different subgroups. For relative yield, five grouping variables and their subgroups included: Crop type (15: maize, winter wheat, spring wheat, winter rye, sorghum, rice, soybean, rapeseed, turnip rape, potato, sugar beet, lettuce, cauliflower, Chinese cabbage and mixed grassland grass species); Yield component (6: grain – for cereals, oilseeds and pulses; cob – for maize only; straw – for cereals, oilseeds and pulses; above-ground biomass; tuber – for potato and sugar beet; sucrose – for sugar beet); Fertilizer type (9: ammonium, ammonium and phosphorus, N (no description), urea, urea and phosphorus, phosphorus, potassium, liquid manure and solid manure); Placement technique (11: surface band, seed, below seed, shallow band, shallow knife, shallow point placement, shallow point injection, deep band, deep knife, deep point placement and deep point injection); Placement depth (3: 0 cm, 5–10 cm and >10 cm). For relative nutrient concentration in plant parts, six grouping variables and subgroups were: Crop type (4: maize, winter wheat, soybean and turnip rape); Plant part (3: grain – for cereals, oilseeds and pulses; leaf – youngest or ear-leaf; and above-ground biomass); Nutrient (4: N, P, K and Grain-protein); Fertilizer type (6: ammonium, ammonium and phosphorus, urea, phosphorus, potassium and liquid manure); Placement technique (6: surface band, seed, shallow band, shallow point injection, deep band and deep point injection); Placement depth (3: same as for yield). Finally, for relative nutrient uptake, five grouping variables and subgroups comprised: Crop type (10: maize, winter wheat, winter rye, sorghum, soybean, rapeseed, turnip rape, lettuce, cauliflower and mixed grassland grass species); Nutrient (4: N, P, K and S); Fertilizer type (8: ammonium, ammonium and phosphorus, urea, urea and phosphorus, phosphorus, potassium, liquid manure and solid manure); Placement technique (8: surface band, shallow band, shallow knife, shallow point injection, deep band, deep knife, deep point placement and deep point injection); Placement depth (3: same as for yield).

To perform the meta-analyses, we used the software MetaWin 2.0 (Rosenberg et al., 2000) to calculate effect sizes (response ratios, $\ln R$) of fertilizer placement – experimental Treatment (E) – in relation to fertilizer broadcast – baseline or Control treatment (C).

$$\ln R = \ln \left(\frac{\bar{X}^E}{\bar{X}^C} \right) = \ln (\bar{X}^E) - \ln (\bar{X}^C) \quad (1)$$

The variance of effect sizes ($V_{\ln R}$), was calculated as follows:

$$V_{\ln R} = \frac{(S^E)^2}{N^E(\bar{X}^E)^2} + \frac{(S^C)^2}{N^C(\bar{X}^C)^2} \quad (2)$$

Where mean, standard deviation and sample size are: \bar{X}_E , S_E and N^E for fertilizer placement respectively and \bar{X}_C , S_C and N^C for fertilizer broadcast respectively, (Rosenberg et al., 2000).

Standard deviations (STDs) were not reported in some studies (see details in results). Where applicable, they were calculated from reported variances, standard errors, *p*-values or *t*-values. Where not applicable, we imputed missing STDs with the average of STDs reported in other studies used in the meta-analysis. Imputation of missing STDs for the purpose of including as many data as possible in a meta-analysis has been shown to be safe and accurate (Furukawa et al., 2006; Philbrook et al., 2007). The procedure for STD imputation involved calculating the mean of reported STDs expressed as a fraction of the mean of reported means for a specific variable (e.g. 0.1969 or 19.69% mean for maize grain yield). This number was then multiplied to the reported mean with missing STD to obtain an appropriate STD for it.

The procedure for the weighted random effects model analysis consisted of: (1.) Running a fixed effects model to produce summary statistics (mean effect size and total heterogeneity). (2.) Using the resulting summary statistics to estimate a pooled variance. (3.) Using the pooled variance to calculate random effects-weights for each individual study, which were then used in further calculations (Rosenberg et al., 2000).

For the fixed effects model, weighted mean effect sizes were calculated because individual studies had different sample sizes. The fixed-effects weight of the *i*th study or dataset (w_i), was calculated by inverting the variance of its effect size:

$$w_i = \frac{1}{V \ln R} \quad (3)$$

The overall mean effect size (\bar{E}) for all studies was given as:

$$\bar{E} = \frac{\sum_{i=1}^n w_i E_i}{\sum_{i=1}^n w_i} \quad (4)$$

(n = number of studies or datasets; E_i = effect size of the *i*th study or dataset)

The variance of the overall mean effect size ($S_{\bar{E}}^2$) was given a function of the individual weights.

$$S_{\bar{E}}^2 = \frac{1}{\sum_{i=1}^n w_i} \quad (5)$$

Using $S_{\bar{E}}^2$, the confidence interval (CI) around \bar{E} was calculated as follows:

$$CI = \bar{E} \pm t_{\alpha/2[n-1]} * S_{\bar{E}} \quad (6)$$

(t = two-tailed critical value from the Student's *t*-distribution at the critical level α)

Total heterogeneity (Q_T) was given as:

$$Q_T = \sum_{i=1}^n w_i E_i^2 - \frac{\left(\sum_{i=1}^n w_i E_i\right)^2}{\sum_{i=1}^n w_i} = \sum_{i=1}^n w_i (E_i - \bar{E})^2 \quad (7)$$

Q_T was used for Q statistical test for variability in effect sizes across studies. For this, Q_T was tested against a χ^2 -distribution (Chi-Square) at appropriate degrees of freedom. Presence of significant sample heterogeneity showed that variance among effect sizes was greater than expected by sampling error and therefore, the appropriate weight for each study or dataset should incorporate a pooled study variance.

Total heterogeneity (Q_T) is the sum of model-derived effect size heterogeneity between studies (or effect size heterogeneity between groups for data with grouping structure) (Q_M) and residual error variance (Q_E).

$$Q_T = Q_M + Q_E \quad (8)$$

For the *j*th group of studies or datasets, the mean effect size (\bar{E}_j), its variance ($S_{\bar{E}_j}^2$), confidence intervals ($CI_{\bar{E}_j}$) and heterogeneity (Q_{Wj}) were also calculated as shown by Eqs. (4)–(7) respectively.

The sum of individual group heterogeneity (Q_M) was given by:

$$Q_M = \sum_{j=1}^m \sum_{i=1}^{k_j} w_{ij} (\bar{E}_j - \bar{\bar{E}})^2 \quad (9)$$

(m = number of groups; k_j = number of studies in the *j*th group; w_{ij} = weight for the *i*th study in the *j*th group; \bar{E}_j = mean effect size for the *j*th group; and $\bar{\bar{E}}$ is the overall mean effect size given in Eq. (4).

Residual error heterogeneity (Q_E), the sum of within-group heterogeneity, was given by:

$$Q_E = \sum_{j=1}^m Q_{Wj} = \sum_{j=1}^m \sum_{i=1}^{k_j} w_{ij} (E_{ij} - \bar{E}_j)^2 \quad (10)$$

(Q_{Wj} = individual within-group heterogeneity; m = number of groups; k_j = number of studies in the *j*th group; w_{ij} = weight and E_{ij} = effect size for the *i*th study in the *j*th group; \bar{E}_j = the effect size for the *j*th group).

With Q_E known, the pooled study variance (between-study variance) for data with grouping structure (σ_{pooled}^2), was calculated as follows:

$$\sigma_{\text{pooled}}^2 = \frac{Q_E - (n - m)}{\sum_{j=1}^m \left(\sum_{i=1}^{k_j} w_{ij} - \frac{\sum_{i=1}^{k_j} w_{ij}^2}{\sum_{i=1}^{k_j} w_{ij}} \right)} \quad (11)$$

(Q_E = residual error heterogeneity from the fixed-effects model; n = total number of studies, m = the number of groups; k_j = the number of studies in the *j*th group; w_{ij} = the fixed-effects weight for the *i*th study in the *j*th group)

Using σ_{pooled}^2 , the random-effects weight of the *i*th study or dataset ($w_{i(\text{rand})}$) was then calculated:

$$w_{i(\text{rand})} = \frac{1}{V_i + \sigma_{\text{pooled}}^2} \quad (12)$$

These random-effects weights, which account for pooled variance, were then used for calculation of mean effect sizes according to Eqs. (4)–(6). As a pre-requisite for meta-analysis, normality was checked for bell-shaped distribution in Weighted Histograms (sum of study weights per effect size class plotted against effect size classes) and for location of data points within confidence bands in Normal Quantile Plots (Rosenberg et al., 2000). Finally, the unlogged overall and group mean effect sizes, which show the relative effect of fertilizer placement to fertilizer broadcast, together with their bias-corrected percentile bootstrap confidence intervals with 999 iterations at the power $\alpha = 0.05$, were reported. Any groups with less than two datasets were excluded by default settings from the meta-analysis. We used the software SigmaPlot 12.0 (Systat Software Inc.) to create scatter plots of relative mean effects and their confidence intervals.

3.3. Sensitivity analyses

We conducted sensitivity analyses to investigate whether non-targeted input factors associated with individual studies affected the outcome of the meta-analysis. In addition to the grouping variables described earlier (Section 3.2), the whole data used for each meta-analysis could be further arranged according to one of the following groupings: Outlier study ± 3 STDs (yes, no), Source

of STD (reported, imputed), Broadcast method (surface, incorporation) and Phenological crop development stage (vegetative, reproductive, maturity). For the first and second sensitivity analyses respectively, mean effect sizes estimated using the whole dataset were compared to values estimated using datasets excluding outliers (limits, ± 3 STDs) or data for which STDs were missing. For the third and fourth, we checked whether (1.) fertilizer broadcast method (surface broadcast and broadcast/incorporation) and (2.) phenological crop development stage (vegetative, reproductive and maturity) affected the outcome of meta-analysis. Additionally, we checked the outcome of the third and fourth sensitivity analyses by running a linear mixed model on *weighted study effect sizes* (using *random-effects* weights) as the dependent variable with broadcast method and crop development stage as independent fixed effects variables, and study as the random effects variable, using SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

To check whether there was a propensity that studies showing statistical significant results were selectively published over those that did not, a condition termed *Publication bias*, we checked for symmetry in *Funnel Plots* of effect size against sample size (widely scattered effect sizes at lowest sample size, bottom; closely placed effect sizes at highest sample size, top) (Rosenberg and Goodnight, 2005). We also looked for linearity and absence of gaps in *Normal Quantile Plots* of standardized effect sizes against normal quantiles (Rosenberg et al., 2000). For a numerical test that is simple to calculate and easy to interpret, we additionally used *fail-safe numbers* (N_R) according to Rosenthal's method ($\alpha = 0.05$) (Rosenberg et al., 2000; Rosenberg and Goodnight, 2005). N_R represents the number of additional non-significant unpublished studies (or datasets), with a mean effect size of zero, that need to be added in order to reduce combined significance of a meta-analysis to non-significant i.e. $P \geq \alpha \cdot 5n + 10$ (n , total number of studies) is given as a reasonable conservative critical lower limit for N_R . Nevertheless, it is recommended to check N_R results with other tests such as symmetry in *Funnel Plots*, because use of N_R only cannot adequately detect presence of publication bias (Rosenberg and Goodnight, 2005).

3.4. Results

3.4.1. Explanation

For the sake of brevity in this subsection, "placement" refers to fertilizer placement in soil using any of the techniques described in Fig. 1 (Section 2.2) and "broadcast" refers to fertilizer application on the soil surface with or without incorporation. All relative mean effects of placement to broadcast are given as percentage (%) differences from broadcast. Directly after each relative mean effect, its 95% confidence interval (CI95%) is given. If CI95% was below zero, there was a negative relative placement effect (RPE) on the measured variable (i.e. Placement < Broadcast); if CI95% included zero, there was no RPE (i.e. Placement = Broadcast); and if CI95% was above zero, there a positive RPE (i.e. Placement > Broadcast). RPE was considered different between groups if their CI95% did not overlap. After the CI95%, the number of datasets in each group (n) is given. In figures, "n" is shown in brackets after the name of each group.

3.4.2. Yield

Overall, 772 datasets from 39 studies were used for this meta-analysis (six from 1982 to 1999 and 33 from 2000 to 2015). Mean effects from all datasets showed that placement resulted in significantly higher yield than broadcast. The RPE on yield was 3.7%, CI95% 3.1–4.3, $n = 772$ ($P < 0.00001$). Symmetrical funnel plot and high N_R (120085) observed suggest absence of significant publication bias. Exclusion of 17 outlier datasets did not change the outcome of the meta-analysis (3.6%, CI95% 3.0–4.3, $n = 755$). Furthermore, there was no difference in RPE on yield between all 772 datasets

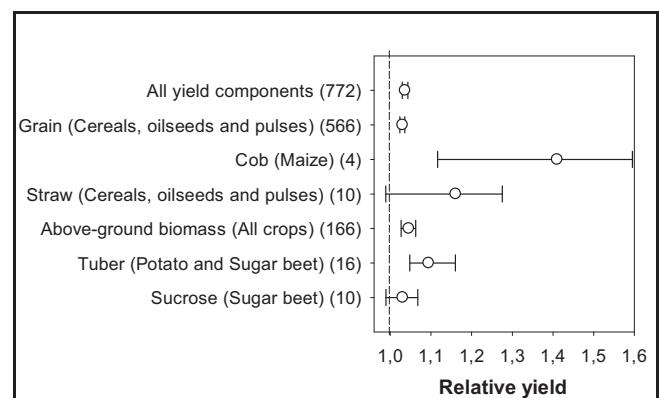


Fig. 2. Relative yield of fertilizer placement by yield component.

Y-axis, categories and number of datasets per category in brackets; **X-axis**, relative value of fertilizer **Placement** to fertilizer **Broadcast**; **Error bars**, 95% confidence intervals; **Placement** ≠ **Broadcast**, if error bars do not include 1.0; Relative values of a pair of categories are different from each other if their 95% confidence intervals do not overlap.

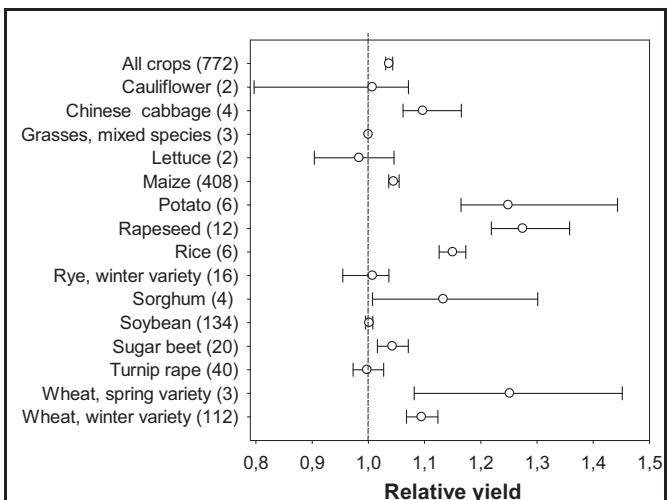


Fig. 3. Relative yield of fertilizer placement by crop type.

Y-axis, categories and number of datasets per category in brackets; **X-axis**, relative value of fertilizer **Placement** to fertilizer **Broadcast**; **Error bars**, 95% confidence intervals; **Placement** ≠ **Broadcast**, if error bars do not include 1.0; Relative values of a pair of categories are different from each other if their 95% confidence intervals do not overlap.

and datasets with reported STDs (3.1%, CI95% 2.3–3.8, $n = 444$) or datasets with imputed STDs (4.6%, CI95% 3.5–6.0, $n = 328$). For broadcast methods, there was also no difference in RPE on yield between Surface broadcast (3.6%, CI95% 2.8–4.2, $n = 719$) and Broadcast/incorporation (5.2%, CI95% 2.2–9.2, $n = 53$). For different crop phenological growth stages, the same RPE was observed: Vegetative (5.7%, CI95% 3.3–8.0, $n = 133$); Reproductive (3.7%, CI95% 1.3–6.7, $n = 13$); Maturity (3.4%, CI95% 2.7–4.1, $n = 626$). The RPE on yield for each broadcast method or phenological growth stage did not differ from the overall RPE on yield. Linear model analysis confirmed that broadcast method ($P = 0.2932$) and crop development stage ($P = 0.9793$) had no effect on weighted study effect sizes.

According to yield components, RPE on yield for Tubers (potato and sugar beet) (9.4%, CI95% 4.8–16.0, $n = 16$) was higher than that for Grains (3.0%, CI95% 2.4–3.6, $n = 566$) (Fig. 2). Among 15 crop species analyzed, yield from placement was higher than yield from broadcast in nine species. The RPE on yield was higher in Winter wheat (9.5%, CI95% 6.8–12.4, $n = 112$) than in Maize (4.5%, CI95% 3.6–5.5, $n = 408$) (Fig. 3). Other crop species for which placement

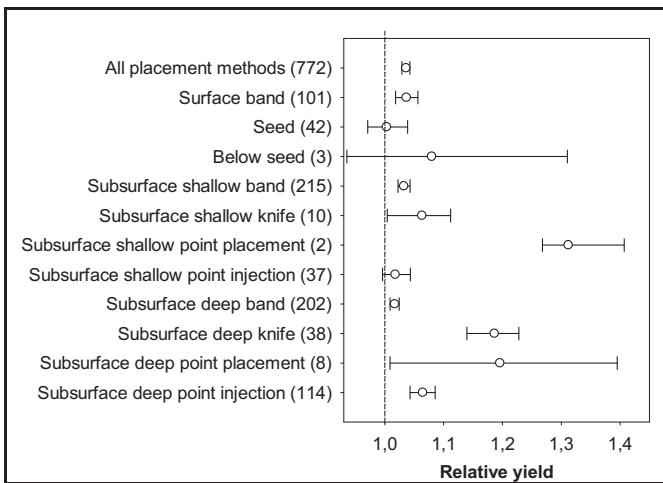


Fig. 4. Relative yield of fertilizer placement by fertilizer placement method. **Y-axis**, categories and number of datasets per category in brackets; **X-axis**, relative value of fertilizer Placement to fertilizer Broadcast; **Error bars**, 95% confidence intervals; **Placement ≠ Broadcast**, if error bars do not include 1.0; Relative values of a pair of categories are different from each other if their 95% confidence intervals do not overlap.

had a positive effect on yield, are shown in Fig. 3. Placement did not have an effect on yield in the following six crop species: Cauliflower, Mixed grassland grass species, Lettuce, Winter rye, Soybean and Turnip rape (Fig. 3).

Sorted by 11 placement techniques involved, yield from placement was higher than yield from broadcast in eight placement techniques. For placement techniques with more than 100 datasets, Subsurface deep point injection showed the highest RPE on yield (6.4%, CI95% 4.3–8.5, n = 114) (Fig. 4). There was no RPE on yield for the following placement methods: Seed, Below-seed and Subsurface shallow point injection (Fig. 4).

Yield from placement for each placement depth was higher than that from broadcast. The RPE on yield was the same across placement depths. Nevertheless, there was a slight tendency for RPE on yield to increase with increasing placement depth: Surface placement (0 cm) (3.9%, CI95% 1.9–5.6, n = 101); 0–5 cm (3.4%, CI95% 2.4–4.6, n = 317); >10 cm (4.1%, CI95% 3.1–5.0, n = 354) (Fig. 5).

According to fertilizer type irrespective of placement depth, there was no RPE on yield for Solid manure (7.9%, CI95% –0.1 to 14.6, n = 6); Soluble P fertilizers (P) (0.0%, CI95% –0.6 to 0.7, n = 136) and Undescribed soluble N fertilizers (1.4%, CI95% –1.5 to 4.4, n = 48). Effective fertilizer types were in the following order of strongest to weakest relative RPE: Urea combined with soluble P (27.3%, CI95% 21.7–34.7, n = 12); Ammonium combined with soluble P (14.7%, CI95% 12.9–17.0, n = 163); Liquid manure (11.6%, CI95% 5.9–18.3, n = 24); Urea (11.0%, CI95% 5.7–17.5, n = 64); Ammonium (3.8%, CI95% 2.2–5.4, n = 134); and soluble Potassium (1.6%, CI95% 0.8–2.4, n = 185). These results showed that placement of combinations of Ammonium and soluble P or Urea and soluble P was more effective to improve yield than placement of ammonium, urea or soluble P uncombined. This occurrence can also be seen in Fig. 5, which also shows that yield from placement of urea or ammonium (each with or without soluble P) or K tends to increase with increasing placement depth from 5 cm to more than 10 cm.

Meaningful RPE regarding the use of nitrification inhibitors; urease inhibitors (or both); toxic concentrations of ammonium depot solutions; urea coating; or palletization of solid manure, methods used to stabilize mineral and/or organic N fertilizers with the aim to optimize N uptake and yield, could not be obtained from this meta-analysis. The reason was that the number of datasets for each

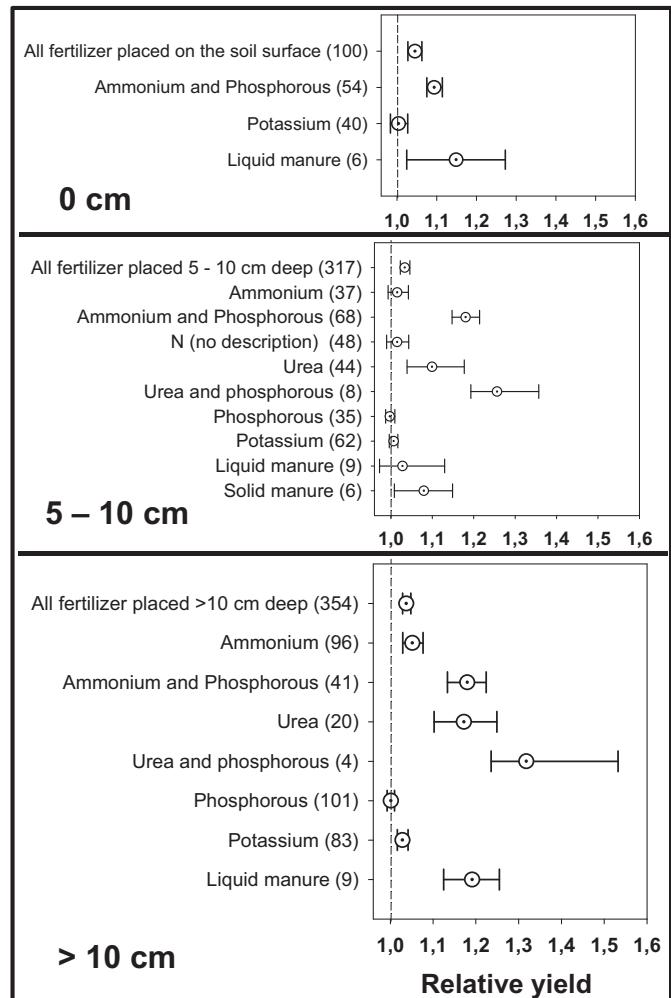


Fig. 5. Relative yield of fertilizer placement by fertilizer type and placement depth. **Y-axis**, categories and number of datasets per category in brackets; **X-axis**, relative value of fertilizer Placement to fertilizer Broadcast; **Error bars**, 95% confidence intervals; **Placement ≠ Broadcast**, if error bars do not include 1.0; Relative values of a pair of categories are different from each other if their 95% confidence intervals do not overlap.

of these modified or stabilized N fertilizer groups was too small in comparison to the number of datasets for unmodified N fertilizers.

3.4.3. Nutrient concentration in above-ground biomass

357 datasets from 11 studies (two studies published in 1982 and nine from 2000 to 2013) were used for this meta-analysis. In all, placement resulted in higher concentrations of N, P, K or grain protein in different above-ground plant parts than broadcast. For all plant parts combined, overall RPE on nutrient concentration in plant parts was 3.7%, CI95% 2.7–4.9, n = 357 ($P < 0.00001$). Exclusion of six outliers or imputation of missing STDs for 190 datasets did not change the outcome of the meta-analysis. Analysis according broadcast methods (Surface broadcast 3.8%, Broadcast/Incorporation 2.1%) or crop development stages (Reproductive 2.3%, Vegetative 3.2%, Maturity 5.03%) did not change the result. Linear model analysis confirmed that broadcast method had no effect on weighted study effect sizes ($P = 0.1093$). However, crop development stage had an effect ($P = 0.0222$) with the same increasing trend from Reproductive, Vegetative to Maturity shown by the meta-analysis. There was no difference between the RPE on nutrient concentration in plant parts between each plant part (Leaf (ear or youngest developed leaf), Total above-ground biomass and Grain) and all parts combined. RPE on nutrient concentration tend to decrease slightly

from Leaf (5.7%, CI95% 3.8–7.7, n = 123) to Total above-ground biomass (2.9%, CI95% 1.4–4.8, n = 154) to Grain (2.0%, CI95% 0.1–3.9, n = 80). According to crop species, RPE on nutrient concentration in different plant parts decreased in the order: Maize (7.0%, CI95% 5.4–8.7, n = 197) > Soybean (1.8%, CI95% 0.6–3.0, n = 126) > Turnip rape (−4.9%, CI95% −8.6 to −2.2, n = 24) = Winter wheat (−8.0%, CI95% −10.7 to −4.4, n = 10). By fertilizer placement technique, the decreasing trend was: Subsurface deep point injection (7.6%, CI95% 5.7–9.7, n = 149); Subsurface deep band (4.4%, CI95% 1.7–7.7, n = 66); Subsurface shallow band (1.8%, CI95% 0.0–3.8, n = 78); Surface band (1.2%, CI95% 0.2–2.3, n = 40); Seed (−3.3%, CI95% −7.6 to 0.3, n = 12); and Subsurface shallow point injection (−6.4%, CI95% −9.7 to −3.2, n = 12).

There was no difference between the overall RPE on nutrient concentration in plant parts for all nutrients combined (3.7%, CI95% 2.7–4.9, n = 357, also shown above) and the RPE for the following individual nutrients: Grain protein (6.3%, CI95% 1.3–10.7, n = 26), K (3.4%, CI95% 2.2–5.0, n = 132), N (3.8%, CI95% 2.0–5.9, n = 141) and P (3.0%, CI95% 0.7–5.8, n = 58). According to fertilizer type and nutrient taken up (except P), there was a tendency of RPE on nutrient concentration in plant parts to increase with increase in the fertilizer placement depth (Fig. 6).

3.4.4. Nutrient content in above-ground biomass

In this study, the term “nutrient content” refers to the quantity of N, P, K and S in kilograms recovered in total or partial above-ground crop biomass per hectare of agricultural land.

The meta-analysis in this section involved 245 datasets from 22 studies (three studies published from 1993 to 1999 and 19 from 2000 to 2015). Overall, nutrient content from placement was higher than nutrient content from broadcast. The overall RPE on nutrient content was 11.9%, CI95% 9.7–14.5, n = 245 ($P < 0.00001$). Removal of two outlier studies did not change the outcome of the meta-analysis. For 148 datasets with reported STDs, RPE was 19.2%, CI95% 15.5–23.0, n = 148. Therefore, imputation of STDs for 97 datasets resulted in an underestimation of the RPE on nutrient content. RPE on nutrient content was the same irrespective of broadcast method. According to phenological growth stage, RPE on nutrient content was higher in the vegetative growth stage than in later growth stages: Vegetative (20.3%, CI95% 15.8–26.1, n = 91) > Maturity (9.2%, CI95% 6.5–12.0, n = 138) = Reproductive (6.5%, CI95% 1.2–11.7, n = 16). Linear model analysis also confirmed that broadcast method had no effect on weighted study effect sizes ($P = 0.1022$) and that crop development stage had an effect ($P = 0.0372$), with the same decreasing trend from Vegetative, Maturity to Reproductive. RPE on nutrient content was higher in the Vegetative than in Generative growth stage (i.e. Reproductive and Maturity stages combined). By crop type only, RPE on nutrient content for different crop species were in the following order: Rapeseed (36.4%, CI95% 30.2–43.3, n = 36); Turnip rape (30.3%, CI95% 28.1–32.9, n = 2); Sorghum (17.7%, CI95% 10.8–26.4, n = 12); Maize (12.2%, CI95% 8.7–16.1, n = 112); Cauliflower (12.2%, CI95% 9.1–15.4, n = 2); Winter wheat (7.2%, CI95% 3.5–11.1, n = 57); Soybean (2.2%, CI95% 0.6–4.1, n = 2); Mixed grass species (0.0%, CI95% 0.0–0.0, n = 3); Lettuce (−2.0%, CI95% −17.4 to 13.2, n = 2); Winter rye (−3.1%, CI95% −9.0 to 0.8, n = 16). According to crop type and development stage the following trend of RPE on nutrient content was observed: Maize-Vegetative (19.6%, CI95% 13.9–26.9, n = 60) > Maize-Generative (7.5%, CI95% 3.4–12.0, n = 52); Rapeseed-Vegetative (52.6%, CI95% 40.9–66.7, n = 18) > Rapeseed-Generative (29.1%, CI95% 23.5–36.7, n = 18); Sorghum-Vegetative (32.7%, CI95% 10.7–56.2, n = 6) > Sorghum-Generative (13.7%, CI95% 6.4–20, n = 6).

In two out of eight fertilizer placement methods (Subsurface shallow point injection and Subsurface deep point injection), nutrient content from placement was the same as that from broadcast.

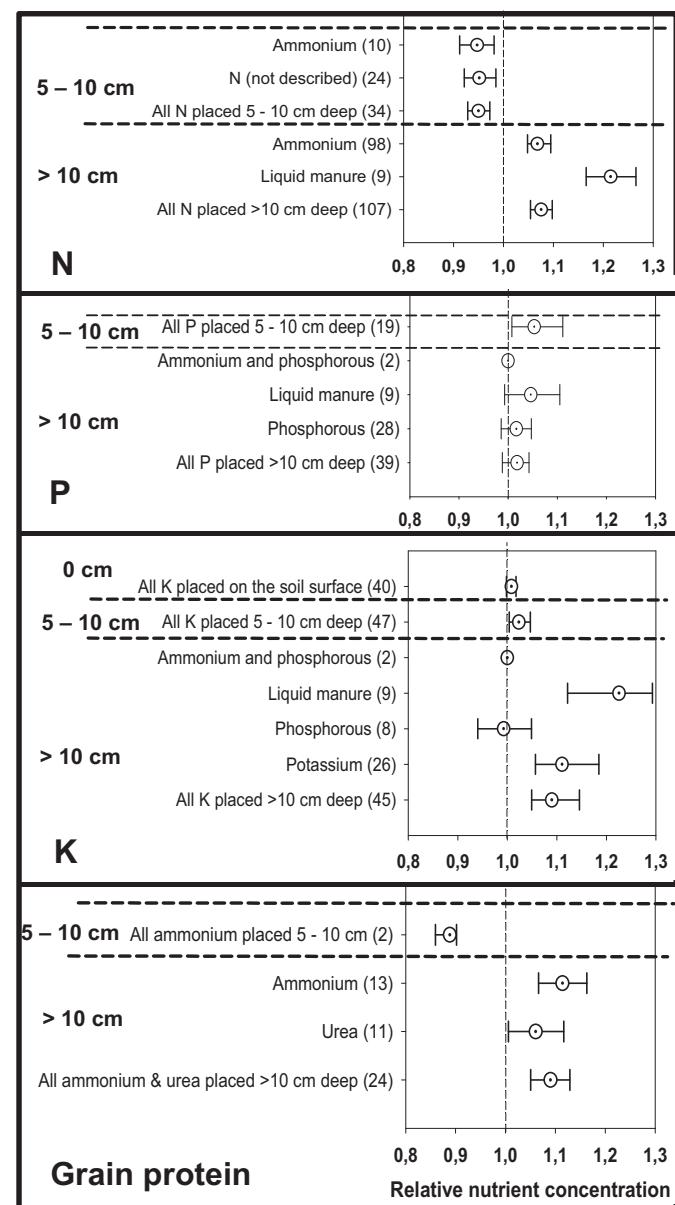


Fig. 6. Relative nutrient concentration of plant parts by nutrient, fertilizer type and placement depth (0, 5–10, and >10 cm).

Y-axis, categories and number of datasets per category in brackets; **X-axis**, relative value of fertilizer **Placement** to fertilizer **Broadcast**; **Error bars**, 95% confidence intervals; **Placement** ≠ **Broadcast**, if error bars do not include 1.0; Relative values of a pair of categories are different from each other if their 95% confidence intervals do not overlap.

In six placement methods, it was higher than that from broadcast. For groups with more than 50 datasets, the trend of RPE on nutrient content was: Subsurface shallow band (15.2%, CI95% 11.8–19.5, n = 98) = Subsurface deep band (14.4%, CI95% 9.8–19.9, n = 60).

During vegetative growth, RPE on nutrient content showed the following decreasing trend according to placement depth: >10 cm (24.9%, CI95% 16.8–33.8, n = 36) = 5–10 cm (23.4%, CI95% 16.2–32.5, n = 51) > Surface (−5.7%, CI95% −15.4 to 6.3, n = 4). For the generative growth stage (Reproductive and Maturity combined), nutrient content for all placement depths combined (8.7%, CI95% 6.3–11.2, n = 154) was higher than that for broadcast. There were no differences in relative nutrient content between placement depths.

According to fertilizer type and placement depth, there was also a tendency for the RPE on uptake of N, P and K to increase with

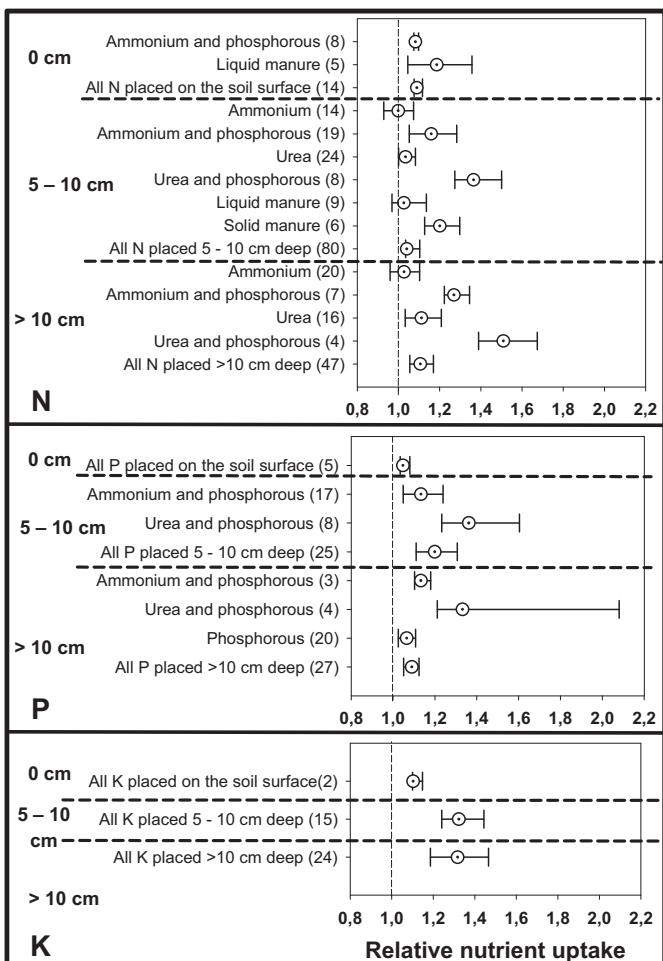


Fig. 7. Relative contents of N, P and K in above-ground biomass by fertilizer type and placement depth (0, 5–10, and >10 cm).

Y-axis, categories and number of datasets per category in brackets; **X-axis**, relative value of fertilizer **Placement** to fertilizer **Broadcast**; **Error bars**, 95% confidence intervals; **Placement ≠ Broadcast**, if error bars do not include 1.0; Relative values of a pair of categories are different from each other if their 95% confidence intervals do not overlap.

increasing placement depth (Fig. 7). Placement of a combination of ammonium or urea with soluble P showed a tendency to lead to stronger RPE on N or P uptake than placement of ammonium, urea or soluble P uncombined (Fig. 7).

4. Discussion

Subsurface placement of fertilizers close to seeds or plant roots has been shown to lead to higher nutrient uptake, higher concentration of nutrients in above-ground biomass and higher yield than homogenous broadcast of fertilizers. Likely modes of occurrence include: (1) persistence of high levels of nutrients in plant-available form close to roots; (2) stimulation of root growth close to and away from fertilizer depots based on NH_4^+ , $\text{CO}(\text{NH}_2)_2$, PO_4^{3-} or their combinations for improved depot exploitation (Arkoun et al., 2012; Forde and Lorenzo, 2001; Zhang et al., 2000); (3) induction of favorable changes in chemical (Jing et al., 2012; Marschner et al., 1986; Neumann and Römhild, 2007) and biological properties of the rhizosphere (Ghorbani et al., 2008; Huber et al., 2012; Marschner, 2012; Murakami et al., 2002); and (4) reduction of nutrient loss to the environment (Dell et al., 2011; Shaviv, 1988; Sommer, 2003).

In accordance with prerequisite *a* formulated in Section 2.3 – fertilizers suitable for placement in soil as a depot should be taken up

by plants in relevant quantities – most published studies on fertilizer placement under field conditions that we found and utilized in our meta-analysis (shown in Table A.1, Appendix) mainly investigated the effect of placing macronutrients N, P or K or their combinations (also organic fertilizers) on crop performance. We found little literature on placement of micronutrients in field soil (Malhi and Karamanos, 2006), given that it is not a common farming practice. Micronutrient application in soil is associated with lower nutrient recovery efficiencies than seed treatment and foliar sprays, which are more effective alternatives (Farooq et al., 2012).

Prerequisite *b* formulated in Section 2.3, – fertilizers considered for placement as a depot should *considerably stimulate root growth and attract roots* – could also be supported. The meta-analyses showed that subsurface placement of NH_4^+ or $\text{CO}(\text{NH}_2)_2$ or both (with or without soluble phosphates, PO_4^{3-}) resulted in statistically higher (or a tendency of higher) relative yield, nutrient concentration and content in above-ground plant parts than subsurface placement of PO_4^{3-} . Under favorable conditions, subsurface placed $\text{CO}(\text{NH}_2)_2$ may be rapidly hydrolyzed to root growth-stimulating NH_4^+ . Subsurface placement of liquid or solid manure, which also contains NH_4^+ and PO_4^{3-} led to higher yield and nutrient content in above-ground biomass than broadcast.

In disagreement to the requirement suggested at *c*, Section 2.3 – suitable fertilizers for depot placement should have *limited mobility* in soil – subsurface placed $\text{CO}(\text{NH}_2)_2$ or $\text{CO}(\text{NH}_2)_2$ and PO_4^{3-} performed better than NH_4^+ or NH_4^+ and PO_4^{3-} at improving yield and biomass N or P contents. Su et al. (2015) observed that deep subsurface placement of $\text{CO}(\text{NH}_2)_2$ and superphosphate in winter rapeseed was associated with increased growth of lateral roots at deep soil layers as well as increased taproot diameter and length, which functioned as an important nutrient storage organ. High moisture availability in deep soil layers may promote rapid hydrolysis of $\text{CO}(\text{NH}_2)_2$ to NH_4^+ with lower mobility and stronger root growth-promotion effects. Furthermore, deep-placed $\text{CO}(\text{NH}_2)_2$ is more protected from NH_3 volatilization than one that is surface-placed or applied by broadcast and incorporated (Ma et al., 2010). In line with *c*, Section 2.3, among all field studies reviewed, NO_3^- was placed in subsurface soil only in combination with NH_4^+ , $\text{CO}(\text{NH}_2)_2$ or PO_4^{3-} or their combinations.

In divergence from the suggested prerequisites: *localized root-growth stimulation* (*b*, Section 2.3) and *limited mobility* in soil (*c*, Section 2.3), subsurface placement of soluble K^+ produced statistically higher yields (>10 cm depth), K concentrations (>10 cm depth) and K content (0, 5–10 and >10 cm depth) in above-ground plant parts than broadcast. This can be explained by high moisture content in deep soil layers than on the surface because K movement to roots is mainly determined mass flow and not by root interception (Barber, 1984). Under drought stress, it is not advisable to place any fertilizer on the soil surface or at shallow depths (Su et al., 2015). Under such conditions, deep subsurface fertilizer placement has been shown to enhance resilience of crop plants to drought stress, thereby increasing yields (Garwood and Williams, 1967; Ma et al., 2009; Randall and Hoeft, 1988; Singh et al., 2005; Su et al., 2015). Nevertheless, to adopt deep subsurface fertilizer placement, cost of additional mechanical power required should be considered (Su et al., 2015).

The effect of placement depth on the effectiveness of fertilizer placement could be confirmed by the meta-analysis. With increasing placement depth from 0 cm to more than 10 cm, fertilizers based on NH_4^+ , NH_4^+ and PO_4^{3-} , $\text{CO}(\text{NH}_2)_2$, $\text{CO}(\text{NH}_2)_2$ and PO_4^{3-} , or K^+ tend to result in an increase in yield, nutrient concentration and content in above-ground plant parts. Contrarily, placement of PO_4^{3-} without combination with NH_4^+ or $\text{CO}(\text{NH}_2)_2$, at 5–10 cm depth or >10 cm resulted in the same yield and nutrient content in above-ground biomass as broadcast. This suggests that PO_4^{3-} depots can be more efficiently exploited by plant roots if NH_4^+ or

$\text{CO}(\text{NH}_2)_2$ is added to the depot to induce stronger root signaling and root-growth.

Seed treatment with fertilizer or subsurface placement of fertilizer in the seeding hole was shown to produce the same yield as broadcast. Niehues et al. (2004) showed that NH_4^+ placed on maize seeds at high rates ($>22 \text{ kg N ha}^{-1}$) led to seed or seedling damage, reduced plant density and grain yield.

Nutrient acquisition by plants from moderately or sparingly available nutrient pools in soil or from placed fertilizers may also be improved by bio-effectors (Weinmann and Römhild, 2012), which refer to plant growth-promoting microorganisms (PGPMs) (Altomare et al., 1999; Grant et al., 2001; Jiang et al., 2012; Lugtenberg and Kamilova, 2009; Richardson et al., 2009; Vassilev et al., 2006) or active natural bio-stimulants like humic acids (Giovannini et al., 2013; Muhammad et al., 2007; Uygur and Karabatak, 2009) and seaweed extracts (Sharma et al., 2012). Such bio-effectors can be applied to seeds, aerial plant parts or soil. First field studies combining fertilizer placement and inoculation of fluorescent *Pseudomonads* as bio-effectors show promising growth-promotion effects on chickpea (*Cicer arietinum*) (Dutta and Bandyopadhyay, 2009) and maize (*Zea mays* L.) (Nkebiwe et al., 2016).

5. Conclusion

Collectively, several field studies showed that fertilizer placement resulted in 3.7% higher yield than broadcast and up to 27.3% for placement of urea and soluble P, and 14.7% for ammonium and soluble P. Fertilizer placement also led to higher nutrient concentrations in different plant parts by 3.7% and nutrient content in above-ground biomass by 11.9% than fertilizer broadcast. Deep subsurface placement of ammonium ($\pm \text{P}$) or urea ($\pm \text{P}$), potassium, solid or liquid manure (10–30 cm) is more effective to improve nutrient uptake and yield of field crops than broadcast with or without incorporation. This suggests that deep subsurface fertilizer placement may be an additional tool for the mitigation of negative consequences of increasingly frequent extreme weather events like high temperatures, droughts or heavy rainfall (Parry et al., 2004), which affect food production for an expanding global population.

Acknowledgments

This study was funded by the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 312117 (BIOFECTOR).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.fcr.2016.07.018>.

References

- Adamsen, F.J., Sabey, B.R., 1987. Ammonia volatilization from liquid digested sewage sludge as affected by placement in soil. *Soil Sci. Am. J.* 51, 1080–1082.
- Akiyama, H., Yan, X., Yagi, K., 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis. *Global Change Biol.* 16, 1837–1846.
- Altomare, C., Norvell, W.A., Björkman, T., Harman, G.E., 1999. Solubilization of phosphates and micronutrients by the plant-growth-promoting and biocontrol fungus *Trichoderma harzianum* Rifai 1295–22. *Appl. Environ. Microbiol.* 65 (7), 2926–2933.
- Anghinoni, I., Barber, S.A., 1990. Predicting the effect of ammonium placement on nitrogen uptake by corn. *Agron. J.* 82, 135–138.
- Arkoun, M., Sarda, X., Jannin, L., Laîné, P., Etienne, P., Garcia-Mina, J.-M., Yvin, J.-C., Ourry, A., 2012. Hydroporons versus field lysimeter studies of urea, ammonium and nitrate uptake by oilseed rape (*Brassica napus* L.). *J. Exp. Bot.* 63, 5245–5258.
- Bünemann, E.K., Prusisz, B., Ehlers, K., 2011. Characterization of phosphorous forms in soil microorganisms. In: Bünnemann, E.K., Oberson, A., Frossard, E. (Eds.), *Phosphorous in Action, Biological Processes in Soil Phosphorous Cycling*. Springer-Verlag Berlin Heidelberg, Germany, pp. 37–58.
- Baker, J.L., 2001. Limitations of improved nitrogen management to reduce nitrate leaching and increase use efficiency. *Sci. World J.* 1, 10–16.
- Baligar, V.C., Bennett, O.L., 1986. Outlook on fertilizer use efficiency in the tropics. *Fert. Res.* 10, 83–96.
- Baligar, V.C., Fageria, N.K., He, Z.L., 2001. Nutrient use efficiency in plants. *Commun. Soil. Sci. Plant Anal.* 32, 921–950.
- Barber, S.A., 1984. *Soil Nutrient Bioavailability. A Mechanistic Approach*. Wiley, New York, pp. 90–113, 218, 251.
- Bautista, E., Koike, M., Suministrado, D., 2001. PM—power and machinery: mechanical deep placement of nitrogen in wetland rice. *J. Agri. Eng. Res.* 78, 333–346.
- Bhat, K.K.S., Nye, P.H., 1973. Diffusion of phosphate to plant roots in soil. *Plant Soil* 38, 161–175.
- Bittman, S., Liu, A., Hunt, D., Forge, T., Kowalenko, C., Chantigny, M., Buckley, K., 2012. Precision placement of separated dairy sludge improves early phosphorus nutrition and growth in corn (*Zea mays* L.). *J. Environ. Qual.* 41, 582–591.
- Blackshaw, R.E., Semach, G., Janzen, H.H., 2002. Fertilizer application method affects nitrogen uptake in weeds and wheat. *Weed Sci.* 50, 634–641.
- Boelcke, B., 2003. Effekt der N-Injektionsdüngung auf Ertrag und Qualität von Getreide un Raps in Mecklenburg-Vorpommern, In: Kücke, M., (Ed.) Anbauverfahren mit N-injektion (CULTAN), Ergebnisse, Perspektiven, Erfahrungen (Beiträge des Workshops am 29. November 2001 in Braunschweig). Bundesforschungsamt für Landwirtschaft (FAL), Landbauforschung Völkenrode, Sonderheft 245 (FAL Agricultural Research, special issue 245) pp. 45–53.
- Borges, R., Mallarino, A.P., 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. *Agron. J.* 92, 380–388.
- Chassot, A., Stamp, P., Richner, W., 2001. Root distribution and morphology of maize seedlings as affected by tillage and fertilizer placement. *Plant Soil* 231, 123–135.
- Clarke, A.L., Barley, K.P., 1968. The uptake of nitrogen from soils in relation to solute diffusion. *Aust. J. Soil Res.* 6, 75–92.
- Colomb, B., Kiniry, J.R., Debaeke, P., 2000. Effect of soil phosphorus on leaf development and senescence dynamics of field-grown maize. *Agron. J.* 92, 428–435.
- Cooke, G.W., 1954. Recent advances in fertilizer placement. II.—Fertilizer placement in England. *J. Sci. Food Agric.* 5, 429–440.
- Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. *Global Environ. Change* 19, 292–305.
- Delgado, A., Scalenghe, R., 2008. Aspects of phosphorus transfer from soils in Europe. *J. Plant Nutr. Soil Sci.* 171, 552–575.
- Dell, C.J., Meisinger, J.J., Beegle, D.B., 2011. Subsurface application of manures slurries for conservation tillage and pasture soils and their impact on the nitrogen balance. *J. Environ. Qual.* 40, 352–361.
- Deppe, M., Well, R., Kücke, M., Fuß, R., Giesemann, A., Flessa, H., 2016. Impact of CULTAN fertilization with ammonium sulfate on field emissions of nitrous oxide. *Agric. Ecosyst. Environ.* 219, 138–151.
- Drew, M.C., 1975. Comparison of the effects of a localised supply of phosphate, nitrate, ammonium and potassium on the growth of the seminal root system, and the shoot, in barley. *New Phytol.* 75, 479–490.
- Dutta, D., Bandyopadhyay, P., 2009. Performance of chickpea (*Cicer arietinum* L.) to application of phosphorus and bio-fertilizer in laterite soil. *Arch. Agron. Soil Sci.* 55, 147–155.
- Engel, R., Liang, D.L., Wallander, R., Bembenek, A., 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. *J. Environ. Qual.* 39, 115–125.
- Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W.J., Zhang, F., 2012. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *J. Exp. Bot.* 63 (1), 13–24.
- Farooq, M., Wahid, A., Siddique, K.H.M., 2012. Micronutrient application through seed treatments: a review. *J. Soil Sci. Plant Nutr.* 12, 14–125.
- Forde, B., Lorenzo, H., 2001. The nutritional control of root development. *Plant Soil* 232, 51–68.
- Furukawa, T.A., Barbui, C., Cipriani, A., Brambilla, P., Watanabe, N., 2006. Imputing missing standard deviations in meta-analyses can provide accurate results. *J. Clin. Epidemiol.* 59, 7–10.
- Garwood, E.A., Williams, T.E., 1967. Growth, water use and nutrient uptake from the subsoil by grass swards. *J. Agric. Sci.* 69, 125–130.
- Ghorbani, R., Wilcockson, S., Koocheki, A., Leifert, C., 2008. Soil management for sustainable crop disease control: a review. *Environ. Chem. Lett.* 6, 149–162.
- Gichangi, E.M., Mnkeni, P.N.S., Brookes, P.C., 2009. Effects of goat manure and inorganic phosphate addition on soil inorganic and microbial biomass phosphorus fractions under laboratory incubation conditions. *Soil Sci. Plant Nutr.* 55, 764–771.
- Giovannini, C., Garcia-Mina, J.M., Ciavatta, C., Marzadori, C., 2013. Effect of organic-complexed superphosphates on microbial biomass and microbial activity of soil. *Biol. Fertil. Soils* 49, 395–401.
- Grant, C.A., Flaten, D.N., Tomasiewicz, D.J., Sheppard, S.C., 2001. The importance of early season phosphorus nutrition. *Can. J. Plant Sci.* 81, 211–224.
- Grant, C.A., Moulin, A.P., Tremblay, N., 2016. Nitrogen management effects on spring wheat yield and protein concentration vary with seeding date and slope position. *Agron. J.* 108, 1246–1256.

- Greenwood, D.J., Gastal, F., Lemaire, G., Draycott, A., Millard, P., Neeteson, J.J., 1991. Growth rate and % N of field grown crops: theory and experiments. *Ann. Bot.* 67, 181–190.
- Halvorson, A.D., Del Grosso, S.J., 2012. Nitrogen source and placement effects on soil nitrous oxide emissions from no-till corn. *J. Environ. Qual.* 41, 1349–1360.
- Hayashi, K., Koga, N., Yanai, Y., 2009. Effects of field-applied composted cattle manure and chemical fertilizer on ammonia and particulate ammonium exchanges at an upland field. *Atmos. Environ.* 43, 5702–5707.
- Hinsinger, P., 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil* 237, 173–195.
- Hocking, P.J., Mead, J.A., Good, A.J., Diffey, S.M., 2003. The response of canola (*Brassica napus* L.) to tillage and fertiliser placement in contrasting environments in southern NSW. *Aust. J. Exp. Agric.* 43, 1323–1335.
- Hodge, A., 2004. The plastic plant: root responses to heterogeneous supplies of nutrients. *New Phytol.* 162, 9–24.
- Huber, D., Römhild, V., Weinmann, M., 2012. Relationship between nutrition, plant diseases and pests. In: Marschner, P. (Ed.), Marschner's Mineral Nutrition of Higher Plants, Third Edition. Academic Press, Elsevier, Amsterdam, pp. 283–298.
- Jiang, Y., Wu, Y., Xu, W., Cheng, Y., Chen, J., Xu, L., Hu, F., Li, H., 2012. IAA-producing bacteria and bacterial-feeding nematodes promote *Arabidopsis thaliana* root growth in natural soil. *Eur. J. Soil Biol.* 52, 20–26.
- Jing, J., Zhang, F., Rengel, Z., Shen, J., 2012. Localized fertilization with P plus N elicits an ammonium-dependent enhancement of maize root growth and nutrient uptake. *Field Crop. Res.* 133, 176–185.
- Köhler, S., Bischoff, W.-A., Liebig, H.-P., 2003. Culturdüngung- ein Beitrag zum Grundwasserschutz durch Verringerung des Nitrataustrages, In: Kücke, M., (Ed.), Anbauverfahren mit N-injektion (CULTAN), Ergebnisse, Perspektiven, Erfahrungen (Beiträge des Workshops am 29. November 2001 in Braunschweig). Bundesforschungsamt für Landwirtschaft (FAL), Landbauforschung Völkenrode, Sonderheft 245 (FAL Agricultural Research, special issue 245) pp. 117–127.
- Kelley, K.W., Sweeney, D.W., 2007. Placement of preplant liquid nitrogen and phosphorus fertilizer and nitrogen rate affects no-till wheat following different summer crops. *Agron. J.* 99, 1009–1017.
- Kristoffersen, A.Ø., Riley, H., Sogn, T.A., 2005. Effects of P fertilizer placement and temperature on root hair formation, shoot growth and P content of barley grown on soils with varying P status. *Nutr. Cycl. Agroecosys.* 73, 147–159.
- Légerre, A., Shirtliffe, S.J., Vanasse, A., Gulden, R.H., 2013. Extreme grain-based cropping systems: when herbicide-free weed management meets conservation tillage in northern climates. *Weed Technol.* 27, 204–211.
- Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., van Groenigen, K.J., 2012. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. *Field Crop. Res.* 135, 10–21.
- Lu, S., Miller, M.H., 1993. Determination of the most efficient phosphorus placement for field-grown maize (*Zea mays* L.) in early growth stages. *Can. J. Soil. Sci.* 73, 349–358.
- Lu, D.Q., Chien, H.S., Henao, J., Sompongse, D., 1987. Evaluation of short-term efficiency of diammonium phosphate versus urea plus single superphosphate on a calcareous soil. *Agron. J.* 79, 896–900.
- Lutgenberg, B., Kamilova, F., 2009. Plant-growth-promoting rhizobacteria. *Annu. Rev. Microbiol.* 63, 541–556.
- Müller, T., Walter, B., Wirtz, A., Burkovski, A., 2006. Ammonium toxicity in bacteria. *Curr. Microbiol.* 52, 400–406.
- Ma, Q., Rengel, Z., Rose, T., 2009. The effectiveness of deep placement of fertilisers is determined by crop species and edaphic conditions in Mediterranean-type environments: a review. *Aust. J. Soil Res.* 47, 19–32.
- Ma, B.L., Wu, T.Y., Tremblay, N., Deen, W., McLaughlin, N.B., Morrison, M.J., Stewart, G., 2010. On-farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. *Agron. J.* 102, 134–144.
- Malhi, S.S., Karamanos, R.E., 2006. A review of copper fertilizer management for optimum yield and quality of crops in the Canadian Prairie Provinces. *Can. J. Plant Sci.* 86, 605–619.
- Malhi, S.S., Grant, C.A., Johnston, A.M., Gill, K.S., 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. *Soil Till. Res.* 60, 101–122.
- Marschner, P., Rengel, Z., 2012. Nutrient availability in soils. In: Marschner, P. (Ed.), Marschner's Mineral Nutrition of Higher Plants, Third Edition. Academic Press, Elsevier, Amsterdam, pp. 315–330.
- Marschner, H., Römhild, V., Horst, W.J., Martin, P., 1986. Root-induced changes in the rhizosphere: importance for the mineral nutrition of plants. *Z. Pflanzenernaehr. Bodenk.* 149, 441–456.
- Marschner, P., 2012. Rhizosphere biology. In: Marschner, P. (Ed.), Marschner's Mineral Nutrition of Higher Plants, Third Edition. Academic Press, Elsevier, Amsterdam, pp. 369–388.
- Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural intensification and ecosystem properties. *Science* 277, 504–509.
- Melander, B., Rasmussen, I.A., Bärberi, P., 2005. Integrating physical and cultural methods of weed control—examples from European research. *Weed Sci.* 53, 369–381.
- Michalsky, R., Pfromm, P.H., 2012. Thermodynamics of metal reactants for ammonia synthesis from steam, nitrogen and biomass at atmospheric pressure. *AIChE J.* 58, 3203–3213.
- Moody, P.W., Edwards, D.G., Bell, L.C., 1995. Effect of banded fertilizers on soil solution composition and short-term root growth. II. Mono- and di-ammonium phosphates. *Aust. J. Soil Res.* 33, 689–707.
- Muhammad, S., Müller, T., Joergensen, R.G., 2007. Compost and P amendments for stimulating microorganisms and maize growth in a saline soil from Pakistan in comparison with a nonsaline soil from Germany. *J. Plant Nutr. Soil Sci.* 170, 745–751.
- Murakami, H., Tsushima, S., Shishido, Y., 2002. Factors affecting the pattern of the dose response curve of clubroot disease caused by *Plasmodiophora brassicae*. *Soil Sci. Plant Nut.* 48, 421–427.
- Nash, P.R., Motavalli, P.P., Nelson, K.A., 2012. Nitrous oxide emissions from claypan soils due to nitrogen fertilizer source and tillage/fertilizer placement practices. *Soil Sci. Soc. Am. J.* 76, 983–993.
- Neumann, G., Römhild, V., 2007. The release of root exudates as affected by the plant physiological status. In: Pinton, R., Varanini, Z., Nannipieri, P. (Eds.), The Rhizosphere. Biochemistry and Organic Substances at the Soil-plant Interface, Ed. 2. CRC Press, Boca Raton, Florida, pp. 23–72.
- Neumann, G., Römhild, V., 2012. Rhizosphere chemistry in relation to plant nutrition. In: Marschner, P. (Ed.), Marschner's Mineral Nutrition of Higher Plants, Third Edition. Academic Press, Elsevier, Amsterdam, pp. 347–360.
- Nieder, R., Benbi, D., Scherer, H., 2011. Fixation and defixation of ammonium in soils: a review. *Biol. Fert. Soils* 47, 1–14.
- Niehues, B.J., Lamond, R.E., Godsey, C.B., Olsen, C.J., 2004. Starter nitrogen fertilizer management for continuous no-till corn production contribution no. 04-099-J, K-state research and extension. *Agron. J.* 96, 1412–1418.
- Nkebiwe, P.M., Weinmann, M., Müller, T., 2016. Improving fertilizer-depot exploitation and maize growth by inoculation with plant growth-promoting bacteria: from lab to field. *Chem. Biol. Technol. Agric.* 3, 1–16.
- Nyord, T., Søgaard, H.T., Hansen, M.N., Jensen, L.S., 2008. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. *Biosyst. Eng.* 100, 235–244.
- Olson, R.A., Dreier, A.F., 1956. Fertilizer placement for small grains in relation to crop stand and nutrient efficiency in Nebraska. *Soil Sci. Soc. Am. J.* 20, 19–24.
- Pang, P.C., Hedlin, R.A., Cho, C.M., 1973. Transformation and movement of band-applied urea, ammonium sulfate, and ammonium hydroxide during incubation in several Manitoba soils. *Can. J. Soil. Sci.* 53, 331–341.
- Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Clim. Change* 14, 53–67.
- Peltonen-Sainio, P., Kontturi, M., Peltonen, J., 2006. Phosphorus seed coating enhancement on early growth and yield components in oat. *Agron. J.* 98, 206–211.
- Petersen, J., 2005. Competition between weeds and spring wheat for 15N-labelled nitrogen applied in pig slurry. *Weed Res.* 45, 103–113.
- Pfab, H., Palmer, I., Buegger, F., Fiedler, S., Müller, T., Ruser, R., 2012. Influence of a nitrification inhibitor and of placed N-fertilization on N2O fluxes from a vegetable cropped loamy soil. *Agric. Ecosyst. Environ.* 150, 91–101.
- Philbrook, H.T., Barrowman, N., Garg, A.X., 2007. Imputing variance estimates do not alter the conclusions of a meta-analysis with continuous outcomes: a case study of changes in renal function after living kidney donation. *J. Clin. Epidemiol.* 60, 228–240.
- Piepho, H.P., Williams, E.R., Madden, L.V., 2012. The use of two-way linear mixed models in multitreatment meta-analysis. *Biometrics* 68, 1269–1277.
- Prochnow, L.I., Chien, S.H., Carmona, G., Henao, J., 2004. Greenhouse evaluation of phosphorous sources produced from low-reactive Brazilian phosphate rock. *Agron. J.* 96, 761–768.
- Qin, R., Stamp, P., Richner, W., 2005. Impact of tillage and banded starter fertilizer on maize root growth in the top 25 centimeters of the soil. *Agron. J.* 97, 674–683.
- Randall, G.W., Hoeft, R.G., 1988. Placement methods for improved efficiency of P and K fertilizers: a review. *J. Prod. Agric.* 1, 70–79.
- Raun, W.R., Johnson, G.V., 1999. Improving nitrogen use efficiency for cereal production. *Agron. J.* 91, 357–363.
- Redel, Y.D., Rubio, R., Rouanet, J.L., Borie, F., 2007. Phosphorus bioavailability affected by tillage and crop rotation on a Chilean volcanic derived Ultisol. *Geoderma* 139, 388–396.
- Reith, J.W.S., 1954. Recent advances in fertilizer placement. I. Fertilizer placement for swedes and turnips in Scotland. *J. Sci. Food Agric.* 5, 421–428.
- Richardson, A.E., Barea, J.-M., McNeill, A.M., Prigent-Combaret, C., 2009. Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant Soil* 321, 305–339.
- Rochette, P., Angers, D.A., Chantigny, M.H., MacDonald, J.D., Gasser, M.-O., Bertrand, N., 2009. Reducing ammonia volatilization in a no-till soil by incorporating urea and pig slurry in shallow bands. *Nutr. Cycl. Agroecosys.* 84, 71–80.
- Rose, T.J., Rengel, Z., Ma, Q.F., Bowden, J.W., 2009. Crop species differ in root plasticity response to localised P supply. *J. Plant Nutr. Soil Sci.* 172, 360–368.
- Rosenberg, M.S., Goodnight, C., 2005. The file-drawer problem revisited: a general weighted method for calculating fail-safe numbers in meta-analysis. *Evolution* 59, 464–468.
- Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin. Statistical Software for Meta-analysis. Version 2. Sinauer Associates, Sunderland, MA, USA.
- Ruidisch, M., Bartsch, S., Kettering, J., Huwe, B., Frei, S., 2013. The effect of fertilizer best management practices on nitrate leaching in a plastic mulched ridge cultivation system. *Agric. Ecosyst. Environ.* 169, 21–32.
- Sadeghi, A.M., Kissel, D.E., Cabrera, M.L., 1989. Estimating molecular diffusion coefficients of urea in unsaturated soil. *Soil Sci. Soc. Am. J.* 53, 15–18.
- Saleem, M.F., Randhawa, M.S., Hussain, S., Wahid, M.A., Anjum, S.A., 2009. Nitrogen management studies in autumn planted maize (*Zea Mays* L.) hybrids. *J. Anim. Plant Sci.* 19, 140–143.

- Schenk, M.K., Barber, S.A., 1979. Phosphate uptake by corn as affected by soil characteristics and root morphology. *Soil Sci. Soc. Am. J.* 43, 880–883.
- Schlegel, A.J., Dhuyvetter, K.C., Havlin, J.L., 2003. Placement of UAN for dryland winter wheat in the central high plains. *Agron. J.* 95, 1532–1541.
- Sekiya, N., Yano, K., 2010. Seed P-enrichment as an effective P supply to wheat. *Plant Soil* 327, 347–354.
- Sharma, S.H.S., Lyons, G., McRoberts, C., McCall, D., Carmichael, E., Andrews, F., Swan, R., McCormack, R., Mellon, R., 2012. Biostimulant activity of brown seaweed species from Strangford Lough: compositional analyses of polysaccharides and bioassay of extracts using mung bean (*Vigna mungo* L.) and pak choi (*Brassica rapa chinensis* L.). *J. Appl. Phycol.* 24, 1081–1091.
- Shaviv, A., 1988. Control of nitrification rate by increasing ammonium concentration. *Fert. Res.* 17, 177–188.
- Singh, D.K., Sale, P.W.G., Routley, R.R., 2005. Increasing phosphorus supply in subsurface soil in northern Australia: rationale for deep placement and the effects with various crops. *Plant Soil* 269, 35–44.
- Sommer, K., 2003. Grundlagen des CULTAN-Verfahrens, In: Kücke, M., (Ed.) Anbauverfahren mit N-injektion (CULTAN), Ergebnisse, Perspektiven, Erfahrungen (Beiträge des Workshops am 29. November 2001 in Braunschweig). Bundesforschungsanstalt für Landwirtschaft (FAL), Landbauforschung Völkenrode, Sonderheft 245 (FAL Agricultural Research, special issue 245), pp. 1–22.
- Sommer, K., 2005. CULTAN-Düngung: Physiologisch, ökologisch, ökonomisch Optimiertes Düngungsverfahren für Ackerkulturen, Grünland, Gemüse, Zierpflanzen Und Obstgehölze. Verlag Th. Mann, Gelsenkirchen-Buer, Germany.
- Su, W., Liu, B., Liu, X., Li, X., Ren, T., Cong, R., Lu, J., 2015. Effect of depth of fertilizer banded-placement on growth, nutrient uptake and yield of oilseed rape (*Brassica napus* L.). *Eur. J. Agron.* 62, 38–45.
- Tilman, D., Cassman, G.K., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418, 671–677.
- Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biol. Conserv.* 151, 53–59.
- Tunney, H., Carton, O.T., Brookes, P.C., Johnston, A.E.I., 1997. Phosphorous Loss from Soil to Water. CAB International, Wellingford, UK (pp. 3, 138, 185, 273 and 276).
- Turner, B.L., Frossard, E., Baldwin, D.S.I., 2005. Organic Phosphorous in the Environment. CAB International, Wellingford, UK, pp. 1–2, 75, 92–96, 113, 133, 165 and 175.
- Uygur, V., Karabatak, I., 2009. The effect of organic amendments on mineral phosphate fractions in calcareous soils. *J. Plant Nutr. Soil Sci.* 172, 336–345.
- Valluru, R., Vadez, V., Hash, C.T., Karanam, P., 2010. A minute P application contributes to a better establishment of pearl millet (*Pennisetum glaucum* (L.) R.Br.) seedling in P deficient soils. *Soil Use Manag.* 26, 36–43.
- Vassilev, N., Vassileva, M., Nikolaeva, I., 2006. Simultaneous P-solubilizing and biocontrol activity of microorganisms: potentials and future trends. *Appl. Microbiol. Biot.* 71, 137–144.
- Weaver, D.M., Ritchie, G.S., Anderson, G.C., Deeley, D.M., 1988. Phosphorus leaching in sandy soils. I. Short-term effects of fertilizer applications and environmental conditions. *Aust. J. Soil Res.* 26, 177–190.
- Weber, E.A., Koller, W.-D., Graeff, S., Hermann, W., Merkt, N., Claupein, W., 2008. Impact of different nitrogen fertilizers and an additional sulfur supply on grain yield, quality, and the potential of acrylamide formation in winter wheat. *J. Plant Nutr. Soil Sci.* 171, 643–655.
- Weinmann, M., Römhild, V., 2012. Resource preservation by application of BIOeffECTORs in European crop production (research proposal). European Community's Seventh Framework Programme (FP7/2007–2013) Under Grant Agreement No. 312117 (BIOFECTOR) <http://www.biofector.info/>.
- Weligama, C., Tang, C., Sale, P.W.G., Conyers, M.K., Liu, D.L., 2008. Localised nitrate and phosphate application enhances root proliferation by wheat and maximises rhizosphere alkalisation in acid subsoil. *Plant Soil* 312, 101–115.
- Zerulla, W., Barth, T., Dressel, J., Erhardt, K., Horchler von Locquenghien, K., Pasda, G., Rädle, M., Wissemeier, A., 2001. 3,4-Dimethylpyrazole phosphate (DMPP)—a new nitrification inhibitor for agriculture and horticulture. *Biol. Fert. Soils* 34, 79–84.
- Zhang, X.K., Rengel, Z., 2002. Temporal dynamics of gradients of phosphorus, ammonium, pH, and electrical conductivity between a di-ammonium phosphate band and wheat roots. *Aust. J. Agric. Res.* 53, 985–992.
- Zhang, M., Nyborg, M., Malhi, S.S., Solberg, E.D., 2000. Localized root growth in soil induced by controlled-release urea granule and barley nitrogen uptake. *J. Plant Nutr.* 23, 413–422.
- Zhang, H., Schroder, J.L., Fuhrman, J.K., Basta, N.T., Storm, D.E., Payton, M.E., 2005. Path and multiple regression analyses of phosphorus sorption capacity. *Soil Sci. Soc. Am. J.* 69, 96–106.
- van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J., 2012. Climate, duration, and N placement determine N₂O emissions in reduced tillage systems: a meta-analysis. *Glob. Change Biol.* 19, 33–44.
- Zhou, S.-L., Wu, Y.-C., Wang, Z.-M., Lu, L.-Q., Wang, R.-Z., 2008. The nitrate leached below maize root zone is available for deep-rooted wheat in winter wheat–summer maize rotation in the North China Plain. *Environ. Pollut.* 152, 723–730.