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Influence of co-application of nitrogen with phosphorus, potassium and sulphur on the apparent efficiency of nitrogen fertiliser use, grain yield and protein content of wheat: Review

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ABSTRACT

The efficient capture and utilisation of fertiliser nitrogen (N) by cereals has implications for crop growth, grain yield, farm profits, the environment and human nutrition. Extensive research has evaluated many innovative ways to improve the efficiency of fertiliser N recovery (N use efficiency; NUE) by wheat (*Triticum aestivum*). This review paper, prepared as an outcome of a workshop by the Nutrient Use Efficiency in Wheat Expert Working Group of the Wheat Initiative held in Harpenden, UK in May 2017, is specifically focused on the effects of the co-application of fertiliser N with fertiliser phosphorus (P), potassium (K) and/or sulphur (S) on the efficiencies of capture and utilisation of fertiliser N and its accumulation in wheat grain, as this specific aspect of wheat nutrition was identified by the meeting as a major gap in knowledge. The contribution of P, K and S individually to grain yield has been reasonably well studied, and it is generally assumed that interactions between N and P, K and S will improve crop performance. However, a total of 32 field studies only have been published since 1963 that examine the effects of multiple nutrients on wheat yield and NUE, or changes in the apparent recovery of fertiliser N (% applied) in grain and its impact on grain protein content. The published data showed that NxP, NxK and NxS interactions led to improvements in NUE and the apparent grain recovery of fertiliser N, with the strongest effects generally coming from co-applications of N + P, followed by N + K then N + S treatments. Only five studies explored the combined or interactive effects of NxPxK, and just one considered either NxPxS or NxPxKxS. Grain yields were usually improved by applications of three (N + P + K) or four (N + P + K + S) nutrients in combination, but it was difficult to draw conclusions about effects on fertiliser N recovery and NUE because of the small number of studies, the variability in responses, and the lack of a N fertiliser alone comparative treatment. Grain protein content did not appear to be strongly increased by nutrient interactions, but it did not decrease with higher yields under N, P, K, S fertilisation suggesting that balanced nutrition may provide some protection against protein dilution as yields increase. The available literature suggested that ensuring balanced availability of P, K and S has the potential to reduce the rates of fertiliser N required by wheat because N appears to be accumulated in grain with greater efficiency. This would have both positive agronomic and environmental benefits.

1. Introduction, background and aims of review

Nitrogen (N) is a key component of plant amino and nucleic acids, and chlorophyll, and provides the basis for the dietary N (protein) of all animals, including humans. After carbon (~40% of plant dry matter) and oxygen (~45%), N is the next most abundant element in plants. Concentrations of N in plant tissues change during crop development and growth, and are typically higher in young tissues and lower in mature or senesced materials (Rueter and Robinson, 1986). However, under adequate levels of nutrition, the N contents of shoots of a cereal crop such as wheat (*Triticum aestivum*) are commonly between 1.5 and 3% of the plant dry weight before senescence (Table 1), equivalent to between 15 and 30 kg N per tonne (Mg; 10^6 g) of crop biomass. Therefore, it is not surprising that N tends to be one of the most important factors regulating crop growth and yield, and controlling the nutritional quality of plant products (Fageria and Baligar, 2005). The

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Table 1
Examples of the range of concentrations (% dry weight) of N, P, K and S typically detected in the shoots and grain of wheat (*Triticum aestivum*) under deficient and adequate nutritional regimes. Data collated from Reuter and Robinson (1986) and Peleg et al. (2009). nd indicates no data available.

Nutrient	Shoot		Grain	
	Deficient (%)	Adequate (%)	Deficient (%)	Adequate (%)
N	< 1.5	1.8-2.6	< 1.6	> 2.0
P	< 0.15	0.21-0.5	< 0.25	0.37-0.53
K	< 1.25	1.5-3.0	nd	0.3-0.6
S	nd	0.15-0.4	nd	> 0.12

total amounts of N taken up by plants are a reflection of ecosystem productivity and N supply. For example, irrigated wheat in highly productive systems may require as much as 450 kg N/ha per year, whereas in low rainfall (< 300 mm per annum) environments, crop N uptake can be < 100 kg N/ha (Hawkesford, 2014). Since every tonne of wheat grain contains ~20 kg N (Ladha et al., 2016), the 640–737 Tg of wheat harvested each year between 2010 and 2015 (FAOstat, 2017) equated to an annual global removal of around 13–15 Tg N (million tonnes; 10^{12} g).

Annual global fertiliser consumption rose from 11 Tg N in 1960 to around 110 Tg N by the year 2015 (FAOstat, 2017), of which > 50% is typically applied to cereals and ~18% is supplied to wheat (Fischer et al., 2014; Ladha et al., 2016). Unfortunately the capture, uptake and utilisation of fertiliser N can be relatively poor with < 50% of the fertiliser N applied commonly recovered in the above-ground biomass of wheat (Peoples et al., 1995; Baligar et al., 2001; Krupnik et al., 2004; Ladha et al., 2005; Sadras and Lawson, 2013; Angus and Grace, 2017).

A recently published life-cycle analysis indicated that up to 40% of the environmental impact of producing a staple food like bread could be associated with the use of fertiliser N in some systems (Goucher et al., 2017). The authors concluded that the most immediate way of addressing this impact would be to improve the N use efficiency (NUE) of wheat while maintaining yields. While average fertiliser N use efficiency is < 50%, there are examples where good fertiliser and crop management techniques combined with favourable environmental conditions can result in N recovery of up to ~70% (Godfrey et al., 2010).

It is known that, while environmental conditions such as weather and soil type lead to significant variability in NUE, it is possible to improve NUE through judicious crop management (Asseng et al., 2001; Semenov et al., 2007). Many researchers have explored prospective ways of improving the use efficiency of fertiliser N applied to cereal crops (e.g. see reviews by Raun and Johnson, 1999; Jenkinson, 2001; Crews and Peoples, 2005; Ladha et al., 2005; Chen et al., 2008; Garnett et al., 2009). This has included advances in plant breeding and our understanding of the genetic control of the acquisition and internal use of N (Le Gouis et al., 2000; Good et al., 2007; Cormier et al., 2016; Hawkesford, 2017), and changes in agronomic management practices such as removing abiotic and biotic constraints to root and crop growth, the timing of fertiliser applications and the forms of N applied, the use of tools to assist farmer decision-making, conservation farming and precision agriculture techniques (Syme et al., 1976; Peoples et al., 1995; Raun and Johnson, 1999; Angus, 2001; Fageria and Baligar, 2005; Dawson et al., 2008).

A number of definitions of NUE have arisen as a result of these many and diverse approaches (Fageria and Baligar, 2005; Dawson et al., 2008; Cormier et al., 2016), but often NUE is expressed as a measure of grain yield produced per unit (e.g. kg) of fertiliser N applied (Eq. (1); Fischer et al., 2014). This is an important measure in an agronomic sense given that inefficiencies in the use of fertiliser N represent an economic cost to growers (Matson et al., 1998; Jenkinson, 2001; Fageria and Baligar, 2005; Chen et al., 2008; Dawson et al., 2008; Canfield et al., 2010) and are a potential source of environmental pollution (Matson et al., 1998; Jenkinson, 2001; Peoples et al., 2004; Chen et al., 2008; Canfield et al., 2010). When N is applied to soils as fertilisers, such as urea (CH_4N_2O) or ammonium sulphate ($(NH_4)_2SO_4$), various N species including ammonium (NH_4^+), ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-), nitrous oxide (N_2O), nitric oxide (NO), and di-nitrogen gas (N_2) can be produced. Soil pools of NH_4^+ and NO_3- are generally considered to be the main forms of 'available' N assimilated by plant roots (Canfield et al., 2010). However, given the labile (reactive) nature of these forms of N, inorganic N not utilised by crops is susceptible to multiple loss processes (Jenkinson, 2001; Peoples et al., 2004; Sutton et al., 2011). For example, NO_3^- is especially mobile in soil and can move from the original site of fertiliser application during periods when water supplied via precipitation or irrigation exceeds crop demand (Peoples et al., 2004). High rates of application of ammonium-based fertilisers and the runoff and leaching of fertiliser-derived NO_3^- into groundwater, rivers and coastal waters have been implicated as causes of aquifer contamination (Powlson, 1993; Canfield et al., 2010) and the eutrophication of aquatic ecosystems (Jenkinson, 2001; Canfield et al., 2010; Sutton et al., 2011), while the leaching of NO_3^- has been directly linked to soil acidification (Powlson, 1993; Jenkinson, 2001; Crews and Peoples, 2004). Volatile N species such as N_2O, NO and N_2 can be formed from NO_3^- under waterlogged conditions as a result of denitrification (Peoples et al., 1995). Although N_2 gas is environmentally benign, N_2O and NO are directly or indirectly involved in atmospheric warming (Dalal et al., 2003; Peoples et al., 2004) and N_2O and NO emissions following N fertiliser use have been specifically identified as major factors that could accelerate the effects of climate change (Jenkinson, 2001; Canfield et al., 2010). Gaseous losses of NH_3 following the applications of urea or ammonium-based fertilisers can also be substantial from irrigated cropping systems and alkaline soils (Peoples et al., 1995; Crews and Peoples, 2004). The released NH_3 affects aerosol chemistry and acid deposition (Peoples et al., 1995), but since it has a relatively short lifetime in the atmosphere, it can also provide a secondary source of N_2O and NO (Mosier, 2001).

Various research studies have directly quantified leaching and/or gaseous losses of N from many different fertilised cereal cropping systems and under contrasting farming practices around the world (Prakasa Rao and Puttanna, 1987; Smith et al., 1990; Fillery and McInnes, 1992; Poss and Saragoni, 1992; Powlson et al., 1992; Peoples et al., 1995; Dalal et al., 2003; Vagstad et al., 2004; Barton et al., 2008; Oenema et al., 2009; Gallejones et al., 2012). However, other investigations have addressed this issue by calculating crop N recovery (i.e. the % of N accumulated by the plant or in grain relative to the amount of fertiliser N applied), as a surrogate for comparing the relative losses of fertiliser N by different experimental treatments (Peoples et al., 1995; Raun and Johnson, 1999; Fageria and Baligar, 2005) (Eq. (2)).

$$NUE\ \left(\frac{kg\ grain}{kg\ N}\right) = \frac{(yield\ N1 - yield\ N0)}{fert\ N} \tag{1}$$

$$N\ Recovery\ (\%)\ \left(\frac{kg\ grain\ N}{kg\ N}\right) = \frac{(grain\ N\ N1 - grain\ N\ N0)}{fert\ N} \tag{2}$$

Simplified equations to calculate fertiliser N use efficiency (NUE) and apparent N recovery (% fertiliser N applied) by grain. In both equations 'N1' refers to the rate of fertiliser N applied (e.g. 50 kg N ha^{-1}), whilst 'N0' refers to treatments where no fertiliser N was supplied. In these equations 'yield' refers to grain yield per plant (kg ha^{-1}) and 'grain N' refers to the amount of N accumulated in grain (kg N ha^{-1}).

Considerable data exist in the published literature detailing changes in NUE and N recovery by wheat (e.g. Van Sanford and MacKown, 1986; Wuest and Cassman, 1992; Campbell et al., 1993; Fiez et al., 1995; Ortiz-Monasterio et al., 1997; Delogu et al., 1998; Le Gouis et al.,