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Influence of nitrogen supply on macro- and micronutrient accumulation during growth of winter wheat

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ABSTRACT

The understanding of the dynamics of nutrient accumulation in crops is essential to obtain optimal yield and high quality food products. Modern crop production is characterized by high nitrogen (N) rates, which can influence the uptake and concentrations of other nutrients. The aim of this study was to investigate the influence of N fertilization on the temporal accumulation pattern and concentrations of nutrients during the life cycle of a winter wheat crop grown in a cool temperate climate. Seven field trials involving four N treatments (0–240 kg N ha^{-1}) in southern and central Sweden were sampled over one growing cycle. Above-ground plant parts were sampled at tillering, stem elongation, flowering and full maturity; and the samples were analyzed for macronutrients (N, S, P, K, Ca, and Mg) and micronutrients (Fe, Zn, Mn, Cu, and B). Temporal accumulation pattern of some elements (P, Mg, Zn, Cu, Mn and B) followed biomass accumulation, while other elements (K, Ca, N, S and Fe) accumulated faster than biomass, especially at the early developmental stages and at high N fertilization rates. Low uptake early in the growing season could, at least partly, be compensated by late season uptake with possible implications for nutrient management. In vegetative tissues, the total amounts and concentrations of most macro- and micronutrients (except P, Mn and B) increased with N uptake. In grains, high N rate resulted in increased concentrations of S and Fe, but decreased concentration of K. Enhanced N supply did not generally result in the dilution of other elements in the grain. Results suggest that the high N accumulation rates in high-yielding crops (here winter wheat) are associated with increased demands also of other nutrients, in terms of both increased amounts and tissue concentrations. Nutrient management plans for these crops should accommodate not only the enhanced demand for N, but also other nutrients. Critical threshold concentrations for the avoidance of nutrient deficiencies should be considered in relation to the crop N concentrations.

1. Introduction

Plant nutrients are of major importance for crop growth and 16 elements are known to be essential for all higher plants (Mengel and Kirkby, 2001). Nitrogen (N) is often the most limiting nutrient in crop production, and N accumulation dynamics in crops therefore often closely follow biomass growth patterns (Drinkwater and Snapp, 2007). High N fertilization, in concert with plant breeding and pest control, has enabled a large increase in biomass production and grain yields in recent decades. However, modern crop management has raised concerns about the potential risk of increasing micronutrient deficiencies in crops and a decline in essential minerals in food and feed products (Ekholm et al., 2007; Kirchmann et al., 2009). The production of cereal grain with sufficiently high concentrations of mineral nutrients is of great importance for the nutrition of humans and livestock.

Nutrient accumulation during crop growth may differ between nutrients, as shown for maize (Bender et al., 2013; Ciampitti et al., 2013; Ciampitti and Vyn, 2013; Xue et al., 2014). Results from those studies suggest that even though major nutrient accumulation occurs before flowering, some nutrients such as phosphorus (P) and micronutrients often accumulate to a larger extent later during crop growth. Nutrient accumulation studies with wheat and other cereal crops have typically investigated only macronutrients (Malhi et al., 2006). Investigations including micronutrients in cereals date back more than 20 years and involved older varieties that may differ considerably from modern varieties in terms of nutrient metabolism (Hocking, 1994; Lasztity et al., 1984). Up-to-date knowledge on accumulation of macro- and micronutrients in wheat during growth, particularly under N fertilized conditions, is important and may have implications for crop nutrient management. It has been known for a long time that plants need a balanced mix of essential nutrients for optimal growth (Sprengel, 1828; Liebig, 1855), and general recommendations for

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Table 1
Soil properties (clay content, organic matter (OM) content and pH) and soil nutrient status (ammonium acetate-lactate (AL) extractable P, K and Mg) at the experimental sites.

Experimental site	Clay (g kg^{-1})	OM (g kg^{-1})	pH-H_2O	P-AL (g kg^{-1})	K-AL (g kg^{-1})	Mg-AL (g kg^{-1})
Falkenberg	140	32	7.3	0.083	0.089	0.102
Grillby	380	58	6.4	0.088	0.187	0.397
Grästorp	330	43	6.5	0.081	0.087	0.021
Karlsfält	230	105	6.1	0.160	0.190	0.010
Nybble	320	31	6.6	0.131	0.178	0.161
Skultuna	200	21	6.7	0.178	0.118	0.112
Strömsholm	490	50	6.0	0.049	0.268	0.375

optimal nutrient element proportions (or element stoichiometry) in plants have been developed (e.g. Knecht and Göransson, 2004). However, these recommendations need to be tested and further developed for the specific case of high-yielding agricultural crops. In plant physiology, the concept of plant nutrient stoichiometry is frequently used to describe the relationships between elements in plants and how these are influenced by plant type and environmental factors (Sterner and Elser, 2002). For example, the growth rate hypothesis proposes that the P:N ratio increases at enhanced N levels, and support for this hypothesis has been found for microorganisms and higher plants (Ågren, 2004). In cereals, most stoichiometry studies have focused on carbon (C):N or C:N:P ratio only (Sadras, 2006; Ågren, 2008). Nutrient stoichiometry studies that have looked at a wider range of nutrients than C, N and P have been performed for Salix () and maize (Ciampitti et al., 2013; Ciampitti and Vyn, 2013; Riedell, 2010). The results showed that the concentrations of some nutrients increase at higher N rates whereas other nutrients are negatively correlated to N concentration. While the application of N fertilizer is often controlled by crop demand, the input of other nutrients is less well regulated. Thus, there is a need to further investigate how N rate and increased biomass production influence the uptake and concentrations of other nutrients in cereal crops, and how the ratio between N and other nutrients may differ depending on the crop N concentration. Moreover, several studies indicate that crop demand for nutrients (in terms of amount per unit biomass) increases with biomass production, as shown for copper (Cu) (Krähmer and Sattelmacher, 1997; Loneragan et al., 1981).

Detailed knowledge about nutrient translocation from vegetative crop parts to grain (nutrient harvest index) and about the influence of crop N concentration on element translocation is currently lacking. An important question is whether modern crop production with high-yielding varieties and large N application rates can negatively affect food and feed quality through lower mineral content. This so-called "dilution" effect could possibly be attributed to decreased grain nutrient concentration in high-yielding crops, due to an over-proportional increase in biomass production in relation to nutrient uptake (Jarrell and Beverly, 1981). Evidence for the dilution effect has been reported in several studies on different crops, although the results are inconsistent (Davis, 2009; Gooding et al., 2012). While some studies report a decline in nutrient concentrations in high-yielding crops (e.g. Fan et al., 2008), others report that N fertilization increased concentrations of zinc (Zn) and iron (Fe); a mechanism that has been suggested to biofortify cereal grain (e.g. Cakmak et al., 2010; Kutman et al., 2010; Shi et al., 2010). In this context, grain size is a potentially interesting characteristic. From a plant physiology point of view, minimum amounts of nutrients in the seed are needed to support the embryo and ensure high germination success and viable seedlings. From the embryo perspective, the total amount of nutrients per seed are expected to be of greater importance than the relative nutrient concentrations per seed. As a consequence, larger grains could potentially be associated with lower nutrient concentrations, even though the total amount per seed is unaffected. Furthermore, grain nutrient concentrations could also be affected by the nutrient mobility in the phloem, where immobile nutrients like Ca, B, and Mn, would lead to a smaller proportion translocated to the grain than nutrients with a high mobility.

The aim of this study was to investigate: (1) the temporal uptake patterns of macro- and micronutrients during the life cycle of a wheat crop; and (2) the effect of N fertilization rate on the concentrations of other nutrients and their translocation to the grain.

The following specific hypotheses were explored:

1) The accumulation of both macro- and micronutrients occurs predominantly during the main growth period of the vegetative crop, i.e. before anthesis.
2) Increased N fertilization results in increased concentrations of all other nutrients in the crop, provided that the supply of other nutrients from soil is not limited. High N fertilization results in high biomass production and thereby a higher demand of other nutrients.
3) The nutrient harvest index is low for calcium (Ca), manganese (Mn) and boron (B) and high for N, P and sulphur (S) due to differing phloem mobility.
4) Grain nutrient concentrations are influenced by grain size, being lower in larger grains. Nutrient amounts per grain are similar irrespective of grain size.

2. Material and methods

2.1. Experimental design

Field trials at seven sites in southern and central Sweden were sampled across one growth cycle of a winter wheat crop (*Triticum aestivum* L.) in 2014. Soil properties for the experimental sites are shown in Table 1. All field sites consisted of mineral soils with a clay content of 14–49% and an organic matter (OM) content of 2.1–10.5%. All soils had weakly acid or neutral pH (6.1–7.3). The study included sites over a reasonably large geographical area representing a variation in climate factors such as soil type and amount of rainfall (Fig. 1).

The experiments had a randomized-block design with four blocks, where each block contained one replicate of each treatment and each plot measured 3 × 12 m. The experimental design was the same for all sites. Four sites were cropped with winter wheat cultivar *Ellvis* and three sites with cv. *Julius*, both of which are frequently used for flour production. Sowing density was similar for the different sites (180 to210 kg ha^{-1}) and no correlation was detected between sowing density and grain yield. The preceding crop consisted of cereals at all sites (see Table 2 for details). Treatments used in the study were: 1) No N fertilization (N0), 2) 80 kg N ha^{-1} (N80), 3) 160 kg N ha^{-1} (N160) and 4) 240 kg N ha^{-1} (N240). All N applications (treatments 2–4) were split, with a starter dose of 40 kg N and the remaining amount in a second dose. For N240 there was also a third dose of 40 kg N (see Table 2 for details). All N fertilizations were broadcasted and applied to the soil. The mineral N fertilizer consisted of NH_4NO_3 with S supplementation corresponding to addition of 11, 22 and 33 kg S ha^{-1} in the N80, N160 and N240 treatments, respectively. The fertilizer was applied with a machine specially designed for field experiments to avoid drift of the fertilizers between plots. At some sites there was also addition of P and K at sowing, which followed farmers' practice for the field (Table 2). Time of sowing and fertilizations are shown in Table 2. Weed and pest control was performed according to farmers' practice