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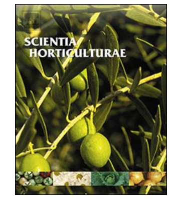

Can optimum yield and quality of vegetables be reconciled with low residual soil mineral nitrogen at harvest?

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ABSTRACT

Despite massive efforts over the past twenty-five years to reduce nitrogen (N) losses, too high nitrate (NO_3^-) concentrations in surface and groundwater from agricultural sources remain a major environmental concern, especially in field grown vegetable production areas. A strict restriction of the N fertiliser application rates is accepted to be the best N management strategy to minimise NO_3^- leaching losses to surface and groundwater.

We analysed Flemish field experiments on lettuce, spinach, leek, carrots, cauliflower and Brussels sprouts with various N fertiliser application rates (2009–2016) with a view to fine-tune the N fertiliser application rates where possible. To find an economic and ecological optimum we considered both yield quantity, quality (leaf colour and uniformity for all vegetables, and nitrate concentration for leafy vegetables) and residual soil mineral N (RSMN) to rooting depth at harvest in function of crop available N. Even at relatively high crop available N, NO_3^- concentrations in lettuce and spinach remained below the legal maximum concentration. Contrary to some farmers' perception, low RSMN can be obtained without a low score for quality parameters leaf colour and uniformity, except for the un- and underfertilised plots. When crop available N exceeds the optimum, RSMN increased steeply (i.e. a breakpoint) for all considered vegetables, except carrots, implying an increased risk of NO_3^- leaching. The results indicate that N fertilisation advices and maximum allowed N fertiliser application rates can be reduced, at least for some vegetables, without a risk of decreasing the marketable yield quantity and quality. As N uptake continues to increase, to a variable extent, after the maximum marketable yield has been obtained, N fertiliser application rates obviously should be based on marketable yield rather than total yield.

1. Introduction

In 2015, vegetable production in Europe (EU) amounted to 2178×10^3 ha on a total of 178779×10^3 ha utilised agricultural land. Despite the relatively small area, vegetable production represented 13.1% of EU's agricultural economic output in 2015, due to the high added value of vegetables compared to arable crops (Forti and Henrard, 2016).

These positive economic figures, however, strongly contrast with observed negative effects. The risk of possibly high nitrogen (N) losses is a consequence of vegetables receiving large N inputs from both mineral and organic N fertilisers, in combination with short growing cycles, shallow rooting depths and the need of high available N till harvest for vegetables harvested in vegetative stage. This results in high residual soil mineral nitrogen (RSMN) and as a consequence high risks of NO_3^- losses. Furthermore, the current N fertiliser cost is low and is not an incentive for horticulturists to reduce N fertiliser application rates (de Haan et al., 2015). Without an adequate management adaptation (e.g. band instead of broadcasted fertilisation) only small amounts of N fertiliser can be reduced without risking a trade-off with yield potential and vegetable quality, at least to some farmers' perception.

To counteract ill-considered N fertilisation strategies and hence to protect ground- and surface waters against pollution caused by NO_3^-

Abbreviations: DM, dry matter; FM, fresh matter; NUE, nitrogen use efficiency; RSMN, residual soil mineral nitrogen; SMNB, soil mineral nitrogen balance; SOM, soil organic matter

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Table 1
General information on the field experiments.

Crop	Number of experiments	Years	Range of soil organic carbon (%)	Mean rooting depth (cm)	Average sowing or planting date with standard deviation (Julian day)	Range of nitrogen fertilisation advice (kg effective N ha^{-1})	Range of nitrogen fertiliser application rate (kg effective N ha^{-1})
Leaf lettuce*	7	2013–2014	1.1–2.0	30	161 ± 69	70–137	0–197
Lettuce*	6	2013–2016	1.4–2.0	30	116 ± 58	71–155	0–221
Spinach**	10	2013–2016	1.0–2.9	30	105 ± 49	164–233	0–350
Leek	9	2013–2016	1.1–3.6	60	148 ± 38	91–265	0–392
Carrots**	5	2015–2016	0.9–2.9	60	118 ± 40	60–73	0–115
Cauliflower**	11	2009–2016	1.2–3.6	60	90 ± 28	124–295	0–386
Brussels sprouts**	5	2015–2016	0.7–1.3	90	128 ± 11	190–260	0–363

* Leaf lettuce = *Lactuca sativa* L. var *crispa* and lettuce = *Lactuca sativa* L. var *longifolia* or *capitata*.
** Mainly varieties for processing industry.

leaching, the European Nitrates Directive (91/676/EEC) has imposed a maximum concentration in ground- and surface waters of 50 mg NO_3^- L^{-1} (Anonymous, 1991). Despite massive efforts over the past twenty-five years to reduce N losses and to increase N use efficiency (NUE), too high NO_3^- concentrations in ground- and surface waters from agricultural sources remain a major environmental concern, especially in field grown vegetable production areas. Excessive N availability can also negatively influence yield and vegetable quality. It can aggravate disease incidences (Westerveld et al., 2008), have effects on taste components, like bitterness in cabbage (Rahn, 2000; Albornoz, 2016), induce an undesired increase of the NO_3^- concentration, especially in leafy vegetables (Rahn, 2000; Ekart et al., 2013; Albornoz, 2016) and reduce the shelf life (Kodithuwakku and Kirthisinghe, 2009; Hoque et al., 2010; Albornoz, 2016).

For the aforementioned reasons, there is an urgent need to significantly improve NUE in intensive vegetable production. Fractionation of N fertilisation, smart crop rotations and crop residue management can all contribute to improving the NUE (Neeteson and Whitmore, 1999; Hartz, 2006; Thompson et al., 2013), but a strict limitation of the N fertiliser application rates is considered one of the best N management strategies to increase NUE (D'Haene et al., 2014). Optimisation of N management in intensive vegetable production requires accurate quantitative information on (i) the expected crop N demand, (ii) the expected crop available N, and (iii) whether the crop available N matches the N demand (Rahn, 2000; Thompson et al., 2013).

The optimum N fertiliser application rates can be calculated based on the various N inputs and outputs of the "soil mineral N balance method" (SMNB method) (Hofman et al., 1981; Neeteson, 1995), combined with the RSMN to rooting depth at harvest. The objective of the SMNB method is to match available inorganic N with the crop N demand, so as to minimise the N surplus and therefore the risks of N losses. For most crops, in the range from low to optimum N availability, RSMN in the root zone at harvest remains constant or increases only slightly with increasing N fertiliser application rates. This relatively constant RSMN has been considered to be the minimum mineral N (N_{min}) buffer necessary for optimal growth. When crop available N exceeds the optimum, the RSMN shows a steep increase for most crops, indicating an increased risk of NO_3^- leaching (Hofman et al., 1981; De Waele et al., 2017). This is a so-called breakpoint in the relation between the crop available N and RSMN.

In this study, we analysed a comprehensive dataset from N fertiliser experiments of vegetable crops with a range in rooting depth and N uptake patterns: lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), leek (*Allium porrum* L.), carrots (*Daucus carota* L. subsp. *sativus*), cauliflower (*Brassica oleracea* L. var. *botrytis*) and Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*). We calculated the effect of crop N availability on yield and N uptake, quality parameters leaf colour and uniformity, RSMN and N surplus, with a view to fine-tune the N fertiliser advices where possible, combining optimum yield and quality and minimising RSMN in the root zone at harvest. We hypothesised that i) a significant reduction in current amounts of N fertiliser application rates is possible without impact on marketable yield and quality if N fertiliser advice is based on timely soil sampling and ii) that the maximum allowed effective N rates in the current nutrient legislation in Western Europe, and Flanders in particular, allow optimal yield of vegetables even with a low amount of N_{min} at planting or sowing and a low N supply from N mineralisation.

2. Materials and methods

2.1. Introduction

Field experiments with different levels of N fertiliser were carried out in the period 2009–2016 at different locations in the three vegetable growing regions in Flanders (Northern part of Belgium) (Fig. S.1) for vegetable crops with varying rooting depth and length of growing period. These experiments included lettuce and spinach (rooting depth appr. 30 cm), leek, carrots and cauliflower (rooting depth appr. 60 cm) and Brussels sprouts (rooting depth appr. 90 cm). In the lettuce field experiments a distinction was made between experiments with leaf lettuce (*Lactuca sativa* L. var *crispa*, here varieties Lollo Rosa and Lollo Bionda) with a non-heading rosette of round fringed, crisp leaves and experiments with Romaine lettuce (*Lactuca sativa* L. var *longifolia*) with long, broad-stemmed leaves that form loose heads, and Batavia lettuce (*Lactuca sativa* L. var *capitata*) with broad curled leaves. Lettuce, spinach and cauliflower start to take up significant amounts of N 3–4 weeks after sowing or planting up to harvest, while significant N uptake starts much later for leek, carrots and Brussels sprouts, and strongly diminishes towards harvesting time for carrots and Brussels sprouts. The set-up of the experiments was comparable to those in D'Haene et al. (2014) and we refer to that paper for more detailed information. Here only a brief overview of materials and methods will be given.

Soil, crop and fertilisation data from the field experiments are given in Table 1. According to the Belgian textural triangle (Tavernier, 1949) the soil textures are sand and sandy loam. There was a wide range in soil organic matter (SOM) content to assure that the N dose response curves and hence the optimum N fertiliser application rates would be generally applicable.

For each vegetable crop studied, we calculated an N dose response curve for yield (marketable as well as total) and N uptake, RSMN and N surplus with the pooled data of the different experiments (see also D'Haene et al., 2014).

2.2. The soil mineral nitrogen balance

2.2.1. In- and outputs

Nitrogen in- and outputs as described in the SMNB method were quantified (Hofman et al., 1981; Neeteson, 1995;D'Haene et al., 2014) and the crop N surplus calculated as follows: