Estimating and Reducing Nitrate Leaching in Vegetable Production

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Measuring nitrate leaching under vegetable crops with lysimeters. (Photo: Ernst Spiess, Agroscope)

Summary

Although more nitrogen (N) is leached under field vegetable cultivation than under arable and grassland, it is unknown which vegetable crops contribute particularly strongly to nitrate leaching. For this reason, an attempt was made to classify the leaching potential of 40 vegetable species based on literature values for the N fertiliser requirement, the N quantities in the crop residues and the rooting depth. While cabbage species showed a high potential, the risk of leaching was considered low for most leafy vegetable species. Leaching could be reduced in particular by controlling irrigation as well as by a more precise determination of the N fertiliser requirement, an increased integration of catch crops in the rotation and an optimised crop-residue management. In terms of farming practices, there is a considerable need for research, particularly when it comes to fertiliser use and tillage.

Key words: crop residues, fertilisation, nitrate leaching, rooting depth, vegetables.

Introduction

Initial Situation

Nitrate leaching into the groundwater adversely affects drinking-water quality (Di and Cameron, 2002). Several spring catchments and groundwater pumping stations in Switzerland measure nitrate (NO_3^-) concentrations (FOEN 2019) that exceed the numerical requirement of 25 mg NO_3^- L^{-1} for groundwater used as drinking water or designated for this purpose (Water Protection Ordinance 1998), or are even above the chemical requirement for drinking water of 40 mg NO_3^- L^{-1} (TBDV 2016), which if exceeded causes water to be considered unsuitable for human consumption. Leached nitrate can also reach the Rhine and thus the North Sea via groundwater and rivers, where it contributes to the eutrophication of coastal waters, because in this environment nitrogen (N) is often the limiting nutrient for algae growth (Kivi *et al.* 1993).

Objectives

Since more nitrate is leached under field vegetable cultivation than under arable and grassland (Di und Cameron 2002), a literature study was conducted in order to classify vegetable species according to their nitrate leaching potential and to evaluate farming practices for reducing nitrate leaching. The most important findings of this work (Zemek *et al.* 2020) are summarised below.

Method

The literature study included all vegetable species grown outdoors in Switzerland which had an average cultivation area of at least 5 ha in the years 2012–2016. Quantitative data on (i) N leaching load, (ii) N fertiliser requirement, (iii) the amounts of N in the crop residues and (iv) rooting depth were compiled. Using the last three parameters, the nitrate leaching potential was then assessed by dividing the vegetable species into one of four classes for each parameter. Each class was assigned a score from 1 (low) to 4 (very high contribution to the nitrate leaching potential). Four points were awarded for a high N fertiliser requirement, a large quantity of N in the crop residues or a shallow rooting depth. The sum of the points of the three parameters, ranging from a minimum of three to a maximum of 12, then determines the nitrate leaching potential for a vegetable species.

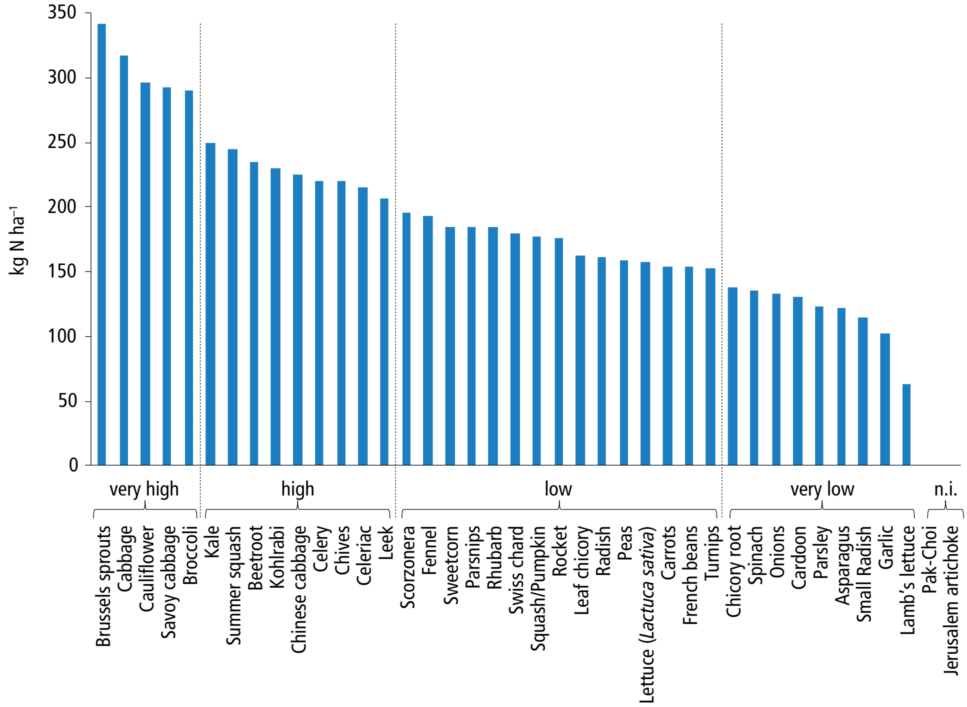

Fig. 1 | SMN target values of vegetable species for determining the N fertiliser requirement in outdoor vegetable production according to the SMN method (average of BMLFUW 2008, Röber and Schacht 2008 and Feller *et al.* 2011; division into the four classes 'very high' (> 250 kg N ha⁻¹), 'high' (200–250 kg N ha⁻¹), 'low' (150–200 kg N ha⁻¹) and 'very low' (< 150 kg N ha⁻¹); n.i. = no information in the literature).

Results

Nitrate leaching potential

Irrespective of the methodology (lysimeters, suction cups, anion exchange resins, soil mineral N (SMN), modelling), the literature on N losses through leaching shows a substantial nitrate leaching potential under and after vegetable crops in the field. However, the published results are unsuitable or only partially suitable for differentiating nitrate leaching according to vegetable species, because trial conditions such as soil and climate, farming practices (e.g. N fertiliser use) and measuring methods differ greatly.

The **N fertiliser requirement** results from the difference between the SMN target value and the measured SMN content before the start of cultivation. The SMN target value represents the SMN supply with which the maximum yield range is just reached on average in various fertilisation trials. In order to achieve maximum yields and avoid quality losses (e.g. inadequate green colouring of the leaves), a minimum SMN stock in the rooted soil depth should be available until harvest, because a large part of the field vegetables are harvested in full vegetative growth when the N requirement of the crops is still high (Scharpf and Weier, 1993). Brassicas (e.g. Brussels sprouts, cabbage) have a high SMN target value compared to leafy vegetables (e.g. lamb's lettuce and spinach) (Fig. 1).

In the course of the harvest, considerable amounts of **crop residues** with correspondingly large quantities of N can accumulate on the field. Taking the average of all crops, 118 kg N ha^{-1} remains with the crop residues in the field, with a range of 5 to 550 kg N ha^{-1} (Fig. 2). The quantities of N in crop residues are high in brassicas such as Brussels sprouts or broccoli and in courgettes, and low in leafy vegetables such as radishes or lamb's lettuce.

Rooting depth is important because nitrate in the deeper soil layers can only be absorbed by deep-rooted species, which then prevent it being leached into the groundwater. The few publications available on the subject suggest that there are large differences in rooting depth between the vegetable species (Fig. 3). The shallow-rooting species include the *Lactuca* sal-

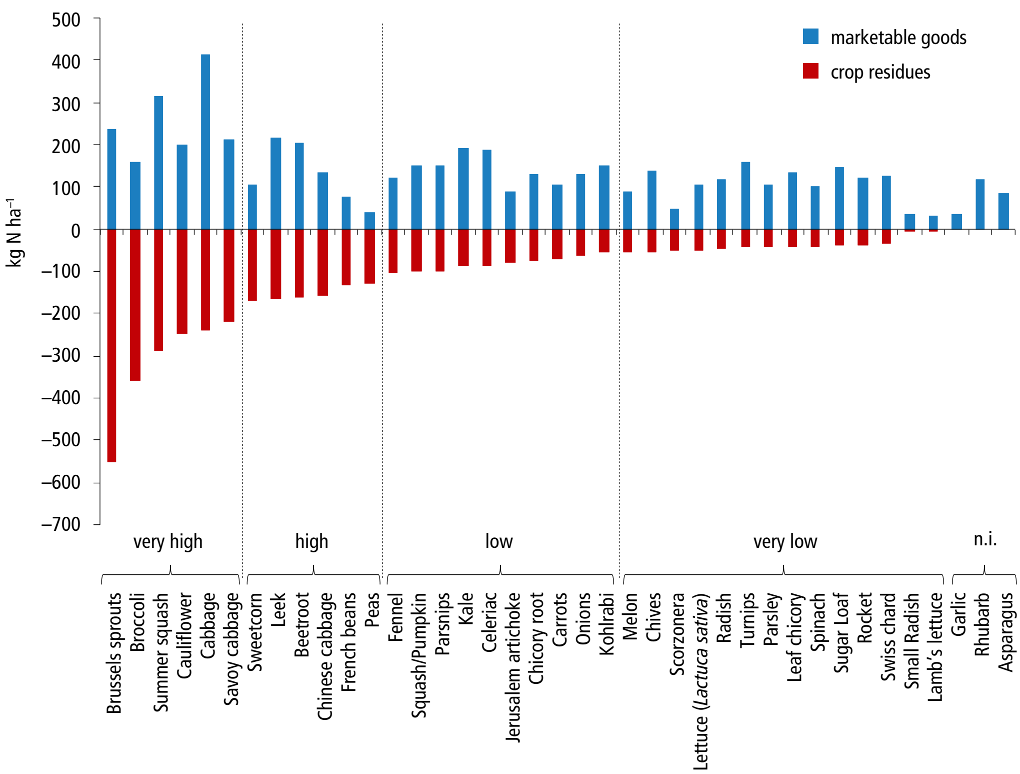

Fig. 2 | Average quantities of N in the above-ground crop residues in field vegetable production. The vegetables are divided into four classes: 'very high' (> 200 kg N ha^{-1}), 'high' (100–200 kg N ha^{-1}), 'low' (50–100 kg N ha^{-1}) and 'very low' (< 50 kg N ha^{-1}); n.i. = no information in the literature. The values for the marketable goods are given for comparison.

ads and lamb's lettuce. Vegetables such as carrots, leaf chicory and cabbage mainly have moderately deep to deep roots. Less-frequently grown vegetables such as scorzonera and the perennial crops of asparagus and rhubarb reach deeper rooting depths.

The cabbage species (e.g. cauliflower, broccoli and Brussels sprouts) in particular have a high **nitrate leaching potential** (score: 10–12), due to the high N fertiliser use and high quantities of N in the crop residues, with the large rooting depth of cabbage highlighted in the literature (score: 9) contributing to the reduction of the potential. By contrast, the leafy vegetables (e.g. lettuces, spinach and rocket), most of which are shallow rooting, show a low (3–6) to medium potential (7–9) due to the lower N fertiliser requirement and the smaller amount of N that remains in the field with the crop residues.

Measures to reduce nitrate loss

The evaluation of the farming practices according to their reduction potential, the state of knowledge and their practical suitability resulted in four measures that are particularly suitable for reducing nitrate leaching:

Irrigation control: Proper irrigation reduces the risk of leaching (Vögeli Albisser and Prasuhn 2013) and ensures a water supply that allows the best possible nutrient uptake, and hence optimal plant growth and high product quality. In order to adapt the irrigation of vegetable crops with high water-use efficiency to the growth stage, it is advisable to control irrigation. Basically, there are four different methods available to aid decision-making (Paschold *et al.* 2009; Marti and Keiser 2019): (i) calculation of the climatic water balance (e.g. Geisenheim irrigation scheduling); (ii) multilayer soil moisture and evapotranspiration models; (iii) soil moisture sensors (e.g. tensiometer, FDR) and (iv) continuous sensor-based monitoring of the crop stand (e.g. stand temperature).

Improved determination of the N fertiliser requirement: In addition to the choice of fertiliser and its application, the determination of the fertiliser requirement plays a decisive role in fertiliser use. There are different approaches to this determination. Highly promising methods are the SMN method (Neuweiler and Krauss 2017), which is based on the measurement of the quantity of

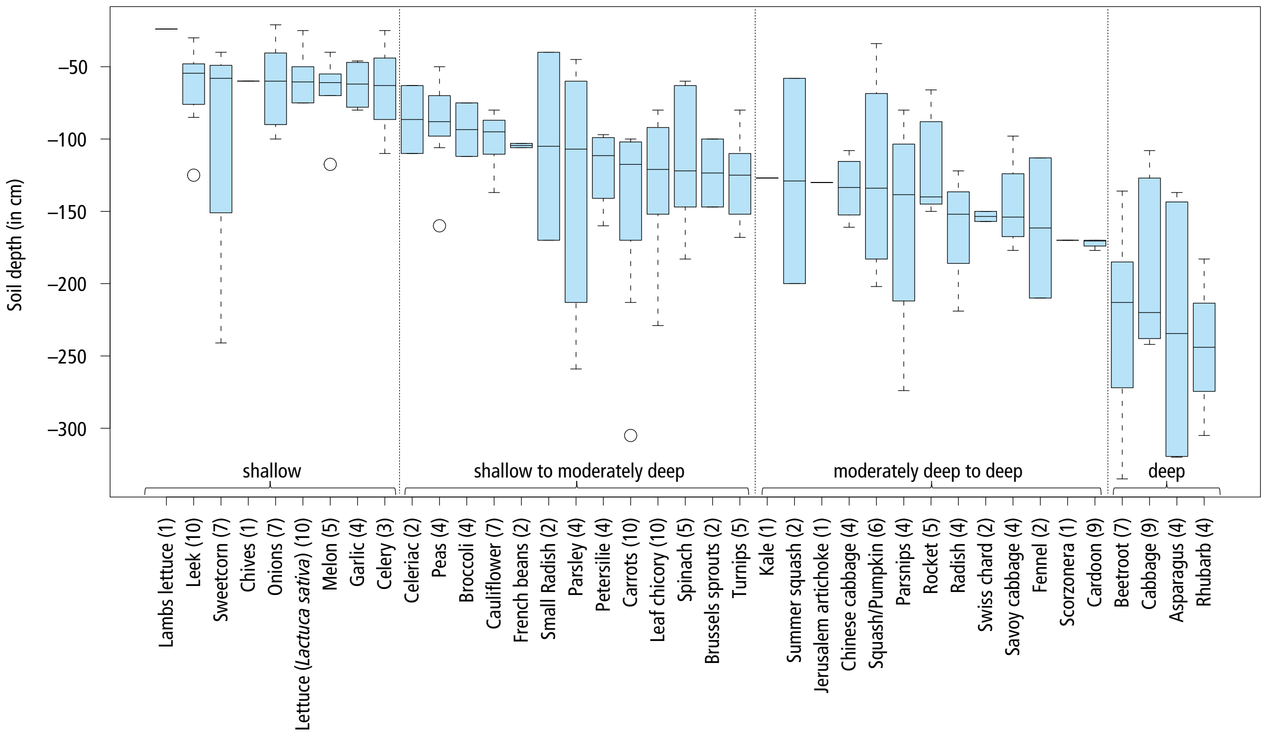

Fig. 3 | Rooting depths of outdoor-grown vegetables measured at the end of the cultivation period. In the boxplot diagram, the box indicates the range in which 50 % of the data is located, and the median is shown in the box as a continuous bold line. 95 % of all values are within the box and the dashed whiskers. Outliers are shown as open circles. The vegetables are divided into four classes based on the median of the measured values: 'shallow' (< 50 cm), 'shallow to moderately deep' (50–100 cm), 'moderately deep to deep' (100–150 cm) and 'deep-rooting' (> 150 cm). Figures in parentheses show the number of measured values.

SMN in the soil layer that can be utilised by the roots at the start of cultivation, and two tools developed for Germany: the 'Culture-accompanying 'SMN-Target-Value System' (abbreviated in German as KNS) (Feller *et al.* 2011), with several SMN analyses during the cultivation period, and the computer program N-Expert (Fink and Scharpf 1993), which models N availability based on soil properties, climate and farming practices data.

Cultivation of catch crops for more-environmentally-friendly crop-rotation sequences: Catch crops absorb water and N from the soil. This reduces leachate formation and the resulting leachate has a lower nitrate concentration (Spiess *et al.* 2011). Consequently, less nitrate is leached from the soil. In addition to a wide range of overwintering and non-overwintering pure stands (e.g. phacelia, winter rye) and mixtures, the renewed growth of certain autumn crops whose roots have not been damaged by harvesting (e.g. spinach), can also serve as winter greening.

Optimisation of crop residue management: While crop residues have so far usually remained in the fields, their removal and subsequent recycling in anaerobic digestion and composting facilities should be considered in the future, especially when growing vegetable species with high quantities of N in the remaining plant material and for the last batch in the growing season. Attention must also be paid to the humus balance.

Need for Research

- The approach presented here for differentiating vegetables according to their nitrate leaching potential can be further developed with the help of modelling. Instead of individual species of vegetables, vegetable crop rotations that are typical for Switzerland should be assessed. The modelled data could be verified by means of measured values obtained from new experiments.
- The standards for fertiliser use – especially for irrigated crops – should be reviewed, taking into account the current yield and quality expectations and variety differences. Moreover, if several sets of crops are grown per year, the yield and fertiliser requirement differ according to the season (Fink and Scharpf 1993). Existing expert systems such as N-Expert should be tested under Swiss conditions.
- Conservation tillage is associated with lower energy and labour costs and reduced erosion due to better soil cover and structure. However, since there are hardly

Tab 1 | Nitrate leaching potential of outdoor-grown vegetable species as a function of the SMN target value, the amount of N in crop residues, and rooting depth

Vegetable	N-Target Value	Amount of N in Crop Residues	Rooting Depth	Total Score	Potential
Cauliflower	4	4	3	11	
Broccoli	4	4	3	11	
Brussels sprouts	4	4	3	11	high
Leeks	3	3	4	10	
Savoy cabbage	4	4	2	10	
Courgettes	3	4	2	9	
Sweetcorn	2	3	4	9	
Cabbage	4	4	1	9	
Celery	3	2	4	9	
French beans	2	3	3	8	
Chinese cabbage	3	3	2	8	
Peas	2	3	3	8	
Kale	4	2	2	8	Moderate
Kohlrabi	3	2	3	8	
Chives	3	1	4	8	
Celeriac	3	2	3	8	
Beetroot	3	3	1	7	
Onions	1	2	4	7	
Carrots	2	2	3	7	
Lettuce (*Lactuca sativa*)	2	1	4	7	
Fennel	2	2	2	6	
Squash, Pumpkins	2	2	2	6	
Parsnips	2	2	2	6	
Lamb's lettuce	1	1	4	6	
Turnips	2	1	3	6	
Leaf chicory (*Cichorium*)	2	1	3	6	
Scorzonera	2	1	2	5	Low
Spinach	1	1	3	5	
Swiss chard	2	1	2	5	
Parsley	1	1	3	5	
Radishes	1	1	3	5	
Mooli	2	1	2	5	
Rocket	2	1	2	5	
Garlic	1	n.i.	4	–	
Chicory root	2	2	n.i.	–	
Rhubarb	3	n.i.	1	–	
Jerusalem artichoke	n.i.	2	2	–	n.a.
Cardoon	1	n.i.	2	–	
Asparagus	1	n.i.	1	–	
Bok choy	n.i.	n.i.	n.i.	–	

n.i. = no information in the literature; n.a. = not applicable any results available showing the extent to which it influences N dynamics in the soil and nitrate leaching in outdoor vegetable production, experiments addressing this topic should be conducted.

- In order to improve crop-residue management, an investigation of how better to preserve N in residual plant material is required.

It appears that the consistent application and further development of the measures described enable the reduction of nitrate leaching under field vegetable cultivation. ■

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