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Agricultural Water Management

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https://doi.org/10.1016/j.agwat.2020.106316

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Agricultural Water Management 240 (2020) 106316

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Review

Nitrogen management of vegetable crops

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ARTICLE INFO

Keywords:
N balance
Cover crops
Cropping systems
Fertilizers
N fertilization efficiency
N leaching

ABSTRACT

N fertilization is often viewed as a cheap insurance against yield loss in vegetable production because of the generally large added value, resulting in application of fertilizer N often in excess of actual crop demand. In combination with the low fertilizer N recovery by many vegetable crops and the often excessive irrigation, this may lead to both health and environmental risks related to high nitrate concentrations in water leaving the root zone. In this review, we discuss the decisive factors in the overall N balance of field vegetable production systems and the different tools at hand to increase fertilizer use efficiency and consequently reduce N losses to the environment. Based on this, we identify areas of research and technology transfer where further work is required. Only an integration of the different methods and strategies for N management may really mitigate the risk of nitrate leaching and maintain crop yields while enhancing the environmental sustainability of vegetable production systems.

1. Introduction

Many vegetable crop species have a relatively low nutrient use efficiency compared to arable crops, often related to the short growing season and superficial rooting (Greenwood et al., 1989; Thompson et al., 2020). Because of the generally large added value of the vegetable production sector, compared to e.g. arable crops or grassland, fertilization (especially N fertilization) is often viewed as a (cheap) insurance against yield loss, resulting in application of fertilizer N often in excess of actual crop demand (Thompson et al., 2007).

The combination of N application in excess of crop demand, the low N fertilizer recovery by vegetable crops and the often excessive irrigation (Thompson et al., 2007; Thorup-Kristensen et al., 2012) may lead to both health risks (i.e. nitrate accumulation in leafy vegetables; Colla et al., 2018) and environmental risks associated with high nitrate concentrations in water leaving the root zone (Agostini et al., 2010; Cameira and Mota, 2017; Thompson et al., 2020).

Despite the relatively small share in total land area and production, the vegetable sector represents a disproportionately large economic share in Europe (EUROSTAT, 2019). Fresh vegetables production in the EU represented a value of 34.5 billions of Euro in 2017 or 8.3 % of the value of all the agricultural goods and services produced in the EU. In 2016 there were about 823,000 farms in the EU-28 cultivating fresh vegetables, representing just 8.0 % of the total number of farms, and 2.2 million hectares of agricultural land (EUROSTAT, 2019).

In 2014 – 15, vegetables represented 7.4 % of total fertilizer consumption of 103 Mt N at global level (Heffer et al., 2017). In the EU-28 N fertilizers in vegetables represented 2.3 % of the total consumption of about 11 Mt N, while vegetable production is only representing 1.2 % of the area.

In Europe, the protection of natural waters from diffuse pollution by nutrients (N and P) is regulated by the Nitrate Directive (Council of the European Communities, 1991) and the Water Framework Directive (European Commission, 2000), and the main source of this pollution is agriculture. Given the intensive nature of most of the vegetable production in Europe, this sector is contributing much to the problem of nitrate pollution of natural waters. In several regions in Europe, the very existence of intensive vegetable production will depend on its willingness and ability to drastically cut N losses to the environment by implementing a more efficient N management (Quemada et al., 2013). Consequently, research has been focusing increasingly on improving N management in vegetable cropping systems to significantly reduce the environmental and health impacts (Tei et al., 2017; Padilla et al., 2018; Kristensen and Stavridou, 2017). In addition, high nitrate concentrations in soil are associated with the emission of the potent greenhouse gas nitrous oxide (N_2O) (Snyder et al., 2009).

The aim of this review is to discuss the different factors that are decisive in the overall N balance of field vegetable production systems,

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https://doi.org/10.1016/j.agwat.2020.106316
Received 31 January 2020; Received in revised form 1 June 2020; Accepted 2 June 2020

and the different tools at hand to increase fertilizer use efficiency and consequently reduce N losses to the environment, with focus on losses to surface and groundwater, and to identify areas of research and technology transfer where further work is required.

2. Drawing up the N balance for vegetable production systems

An in-depth insight into all processes that govern the N cycling in soil is needed to optimize fertilization and maximize N use efficiency whilst minimizing losses. Therefore, we start by discussing the detailed N balance in the soil-crop-atmosphere continuum (Congreves and Van Eerd, 2015; Thompson et al., 2017), which forms the basis for the so-called balance sheet systems of N fertilization.

The N balance takes into account all possible inputs: soil mineral N available at planting; N mineralized from soil organic matter; N mineralized from organic materials; mineral fertilizer N; N from irrigation and atmospheric deposition, and all possible outputs: crop N uptake; N losses by denitrification; volatilization and leaching and N immobilization in the soil. The individual components of the balance are often difficult to quantify because of the highly dynamic nature of N transformations and the many interactions. Generalizations and simplifications will always have to be made for practical use.

2.1. Soil mineral N at planting

The sum of $NH_4{}^+$-N and $NO_3{}^-$-N at or shortly before planting is a key variable for efficient N fertilizer management. It depends mainly on the previous crop and its management (e.g. applied N fertilizer rate, irrigation and harvest time), the weather conditions (mainly rainfall) and planting time (commonly higher soil mineral N in autumn than in spring due to fall-winter leaching by rainfall) (e.g. Nendel, 2009).

N use efficiency can be improved drastically by including soil mineral N at planting in the calculation of N fertilization (Thompson et al., 2017, 2018; De Pascale et al., 2018).

2.2. N mineralization from soil organic matter and N immobilization

The processes of N mineralization and immobilization occur simultaneously in soil at all times (Mineralization-Immobilization Turnover, MIT; Norton and Schimel, 2012) The result of these two processes is termed net N mineralization, greatly influenced by soil temperature, moisture content and compaction (De Neve, 2017). Soil Organic Matter (SOM) mineralization is the predominant source of N for the crop especially in low-input production systems (Nendel et al., 2019) and crucially needs to be accounted for in N fertilizer calculations.

However, N mineralization from SOM is difficult to measure *in situ* because the mineralized N is rapidly consumed in other processes or transported through the soil profile. A few attempts have been made to measure N mineralization using micro-lysimeters (Nendel et al., 2005) or using buried soil cores in field incubations (Delphin, 2000). Alternatively, *in situ* N mineralization can be derived from measuring all components of the N balance in a field. However, because of the large spatial and temporal variability of soil N processes, and the difficulty in measuring loss processes, this approach is not applicable in practice. Most often, N mineralization is measured in controlled conditions in the laboratory, and there have been many attempts to predict N mineralization in controlled conditions by simple or more complex relationships with soil properties (e.g. SOM C:N, SOM content, pH, texture) and environmental factors (temperature, moisture content, bulk density, general soil structural quality) (De Neve, 2017; Nendel et al., 2019).

Nendel et al. (2019) analyzed 340 data sets extracted from previously published incubation experiments for potential nitrogen mineralization covering a large range of soils and climate conditions. They found that under warm and year-round humid conditions, the potentially mineralizable N as fraction of the soil total N was significantly smaller than in dry or temperate environments. The N mineralization potential, that is the maximum amount of N being released from soil under optimum conditions for mineralization by the microbial biomass (optimum temperature, soil water content, nutrient and oxygen supply) in temperate climates was estimated to be 151 kg N ha^{-1} (as climate zone median). As a coarse first estimate, N mineralization under temperate maritime climates can be very roughly estimated to be 2–3 % of the soil organic N, with the lower limit for heavy soils and the upper limit for sandy soils (De Neve, 2017). Lorenz et al. (1989) suggested a value of 5.5 kg N ha^{-1} week^{-1} of N mineralization from soil organic matter for the Rhineland Palatinate region in Germany. In general, N mineralization from soil organic matter is higher in vegetable cropped soils than in arable soils, because of the intensive nature of vegetable production, with large (historical) applications of mineral and organic fertilizers and the small harvest index with large amounts of crop residues being returned to the soil.

2.3. N mineralization from added organic materials

Incorporation of vegetable crop residues in particular represents a highly important but often neglected source of mineral N. The amount of crop residue can vary from 25 − 30 kg N ha^{-1} (e.g. spinach, lettuce) to as much as 250 − 300 kg N ha^{-1} (e.g. for cabbages) (Chaves et al., 2007; Agneessens et al., 2014; Congreves and Van Eerd, 2015; De Neve, 2017; Tempesta et al., 2019). De Neve and Hofman (1996) found that 60–80 % of the N in vegetable crop residues is mineralized within the 3 weeks following incorporation in summer or early autumn. In a study conducted in Western Europe, under exceptionally good conditions (i.e. a warm, moist and very well aerated soil), over 80 % of the mineral nitrogen present in crop residues was released as early as 9 weeks after incorporation (Tremblay et al., 2001). Failure to properly account for the N contained in crop residues obviously may lead to excessive N fertilization and N losses.

Other added organic materials include cover crops, animal manures (slurries and farmyard manure), composts, by-products from the agricultural industries (e.g. animal by-products such as blood meal, hair meal and bone meal), digestates from manure processing and from bioenergy production, municipal solid wastes, sewage sludge, amongst others. For some of the more common of these materials (green manures, animal slurries) N release is relatively well known, but others are poorly characterized with respect to both the amount and the timing of N release (De Neve, 2017; Sambo and Nicoletto, 2017; Benincasa et al., 2017).

An important aspect of the management of organic materials is the synchronization of N mineralization with crop N demand to avoid yield loss and/or minimize the risk of N losses (Fig.1). For instance, lack of synchrony may occur in early spring in temperate humid climates, when crop N demand can already by high while N mineralization is still

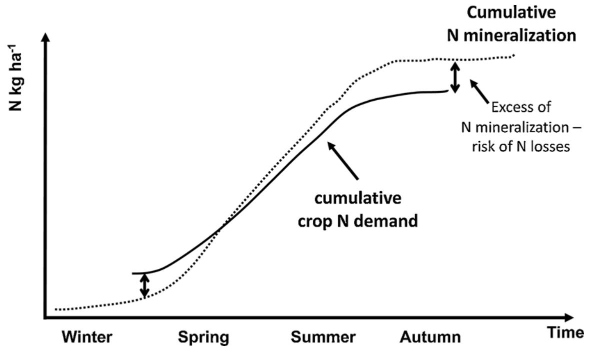

Fig. 1. Lack of synchronization between N mineralization and crop N demand. In spring, mineralization is still limited while crop N demand may already be high, whereas in autumn N mineralization (especially from crop residues) may be very high while there is only limited or no crop N uptake.

limited because of relatively low soil temperatures. In autumn, N mineralization of crop residues rich in N may still proceed at high rates due to high soil temperatures at a time when the soil is bare or the crop N demand is low. The lack of synchronization in spring can easily be remediated by additional fertilization, but excessive N mineralization in autumn is much more difficult to manage and is one of the chief causes for high N losses.

2.4. *N supply from irrigation*

Irrigation water may contain a significant amount of N, particularly in regions with high nitrate levels in groundwater. Reliable estimates of these N inputs can be obtained by frequent analysis of the irrigation water and by keeping good records of irrigation volumes. For example, a typical seasonal irrigation volume for sweet pepper of about 3000 $m^3\ ha^{-1}$ with a nitrate concentration of 50 $mg\ L^{-1}$ corresponds to a total N input from irrigation of 34 kg N ha^{-1}.

2.5. *N from atmospheric deposition*

Both wet (precipitation) and dry (dust) deposition, mainly associated with ammonia (NH_3) emissions related to intensive livestock production and NO_x emissions from industry and traffic, may contribute significantly to the overall N input for agricultural crops. Nitrogen may be transported over long distances before being deposited and thus may have a transboundary component. Vet et al. (2014) found wet deposition of N in Europe to range from < 1 to 25 kg N $ha^{-1}\ yr^{-1}$. While N deposition drastically declined over the past decades as a result of measures to combat air pollution, in some regions of intensive livestock production (Northern part of Belgium, parts of the Netherlands and Denmark), emissions and deposition may still be significant and may represent between 10 and 20 % of the total N requirement of the vegetable crop.

2.6. *Mineral fertilizer N*

In the balance sheet system of N fertilizer advice, the amount of fertilizer to be applied is calculated as the difference between outputs and inputs. Rate, timing, type and application method of mineral fertilizer represent critical issues to optimize crop production and minimize environmental losses (Snyder, 2017) (see section 3.3). Moreover, not only yield, but also produce quality should be considered in calculating optimal N fertilizer rates in vegetables (Burns, 2006). While reduced N availability may negatively affect biomass yield and fruit size, it has been reported to increase the concentration of free radical scavengers with anti-oxidant capacity (Stefanelli et al., 2010). Excessive N fertilization was reported to reduce quality parameters (e.g. fruit size, vitamin C concentration, sugar content…) in different vegetable crops (Albornoz, 2016) and to increase the concentration of harmful compounds such as nitrates in leafy vegetables (Colla et al., 2018). Given the decisive impact of produce quality on price, N management should also be analyzed from an accurate economic analysis of marketable products, in addition to the biomass yield or environmental perspective (Burns, 2006).

2.7. *Crop N uptake*

At optimal N status, mineral N uptake is the product of the total biomass and the critical N concentration (i.e. the minimum N concentration required for maximum plant growth; Greenwood et al., 1990). Total biomass is, in turn, highly correlated with crop yield. Some authors (Greenwood et al., 1990; Lemaire and Gastal, 1997; Lemaire et al., 2008) determined the relationship between the critical N concentration and the above-ground plant dry weight. The relationship is highly different between C3 and C4 plants reflecting the different metabolic pathway but is relatively constant within the same metabolic group. Still, species-specific critical N dilution curves have been determined, for example for potato (Greenwood et al., 1990, 1996), processing tomato (Tei et al., 2002), lettuce (Tei et al., 2003; Di Gioia et al., 2017; Conversa and Elia, 2019), cabbage (Ekbladh and Witter, 2010), broccoli and cauliflower (Riley and Vågen, 2003; Conversa et al., 2019), carrot (Shlevin et al., 2018). From the critical N dilution curve, the relationship can be obtained between crop biomass and crop N uptake at optimal N nutritional status. This allows to quantify the potential N crop demand to be used in the N balance. Crop N demands are often summarized and averaged in look-up tables, based on past agronomic experiments, for use in practice by farmers and technicians.

Despite the high N demand of most vegetable crops (Feller and Fink, 2002; Congreves and Van Eerd, 2015), they can only take up a fraction of the soil mineral N, i.e. the Nitrogen Uptake Efficiency (NUpE) is less than 1 (or less than 100 %). Greenwood et al. (1989) defined the *Apparent Recovery* (REC) of fertilizer-N by the crop as $REC = (U_F - U_0) / N_F$ where N_F = fertilizer-N rate, U_F = N-uptake when N_F is applied, U_0 = N-uptake when no fertilizer is applied (i.e. an estimate of the uptake of mineral N already present into the soil before planting and mineralized during crop growth). The same authors showed that in vegetables the relationship between N-fertilization rates and N-uptake decreased linearly according to the following general equation $REC = REC_0 - b\ N_F$ where REC_0 is the fitted value of REC with an infinitesimally small amount of fertilizer-N and ($-b$) is the gradient of REC against N_F (Fig. 2). Consequently, knowledge of the REC value for a species provides an estimate of the proportion of N fertilizer not taken up by the crop at a given N rate. This approach is useful to achieve a compromise between yield and environmental issues (Burns, 2006).

These relationships are species-specific because they depend on differences in root function and architecture (e.g. Tei et al., 1999); they are also influenced by soil conditions (e.g. water shortage reduces growth and N uptake), weather conditions, agronomic practices (e.g. irrigation) and fertilizer application methods (e.g. broadcast or localized application) (Tremblay et al., 2001; Benincasa et al., 2011).

Given the difficulty of obtaining the REC from specific field experiments, a "*Safety Margin*" practical approach has been proposed by some authors (e.g. Tremblay et al., 2001), defined as an additional amount of mineral N to be present as a kind of "*N buffer*" to allow for maximum N uptake at all times. This N buffer is added to the crop N demand and is higher for crops with small, shallow roots, few root hairs (e.g. leeks and onions), i.e. crops that are inefficient at extracting N, as compared to crops with a better developed root system (e.g. cabbage, Brussels sprouts, carrots) (Tremblay et al., 2001). The KNS system is one example of a N fertilizer advice system (mainly for vegetable crops)

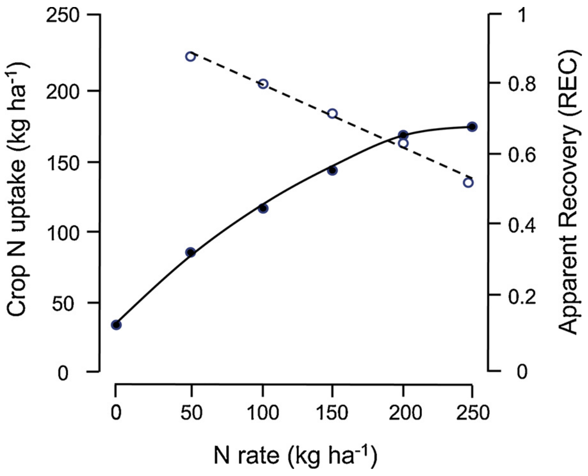

Fig. 2. Example of crop N uptake and apparent recovery of fertilizer-N (REC) as affected by fertilizer-N rate (solid line: N uptake in function of N rate; dashed line: linear relationship between REC and N rate).

that uses such a *N buffer* in the calculation of the N fertilizer requirements (see section 3.1.1).

2.8. N losses

Nitrogen loss processes including denitrification, volatilization and leaching will lead to reduced N availability. Given the often high N fertilization rates and the high concentrations of soil mineral N, the risk of these N losses and the extent to which they occur is particularly high in N-intensive horticultural systems (Cameira and Mota, 2017).

2.8.1. Denitrification and volatilization losses

Denitrification [i.e. conversion of nitrate (NO_3^-) to molecular nitrogen (N_2), with possible formation of nitrous oxide (N_2O) and nitric oxide (NO)] occurs within the soil wherever there is sufficient nitrate, labile organic carbon, and low oxygen concentrations and oxygen diffusion rates. These losses are low in most dryland cropping soils but may be significant in slowly draining and waterlogged soils (Myrold and Bottomley, 2008). Hence normally N losses by denitrification are small in vegetable fields. However, they can be appreciable in specific circumstances, e.g. when large amounts of vegetable crop residues are incorporated, and this is followed by heavy rain.

Ammonia volatilization occurs when ammonium from ammonium-containing or urea containing fertilizers or from organic fertilizers (e.g. cattle manure, castor bean cake, legume fertilizers) is converted to ammonia. The risk of such losses is low when these fertilizers are incorporated immediately or injected, but can be very high when they are surface-applied (Engel et al., 2011; Ramanantenasoa et al., 2019). The potential risk of ammonia volatilization from urea fertilizer can represent up to 65 % of the N applied, depending on soil and climatic conditions (Sutton and Grinsven, 2011). Ammonia volatilization can also occur during mineralization of vegetable crop residues: De Ruijter et al. (2010a) found that about 5–16 % of the N in vegetable crop residues could be lost as NH_3.

2.8.2. Nitrate leaching

Vegetable crops are often grown on coarse textured soils that have low water holding capacity, and a high hydraulic conductivity. So excess nitrate not taken up by the crop has high probability to be leached out below the root zone in case of excess precipitation or not well-managed irrigation. The risk of leaching depends on: i) the soil nitrate concentration at a given time, that depends, in turn, on the history of N management in the specific field; ii) the intensity and frequency of water inputs (i.e. rainfall or irrigation); iii) the soil hydraulic characteristics. Nitrate leaching losses (and the associated potential risk of groundwater contamination) from intensive vegetable production has been studied extensively in a wide variety of pedo-climatic conditions and cropping systems (e.g., Thompson et al., 2007; Xie et al., 2017; Farneselli et al., 2018; Tosti et al., 2019; Rakotovololona et al., 2019; de Haan et al., 2019; Hefner et al., 2019).

2.9. Final considerations on the N balance

As illustrated in this section, the N balance takes into account all possible inputs and outputs of N to and from the field, and is therefore a potentially very accurate basis for calculation of N fertilization, that should allow to minimize N losses, notably by leaching. However, the efficiency of this approach critically depends on the quality of the available data (e.g. crop N uptake, expected mineralization) and the experience of the persons drawing up the balance. It should be pointed out that there are some minor variations in the way that the N balance is calculated by different daughters and recommendation schemes, as discussed by Thompson et al. (2017).

3. Strategies for improved sustainability of N fertilization

3.1. Tools to assist with crop N management

Often growers and advisors make decisions on the amount of N fertilizer to be applied based on *experience* or *look-up tables* adapted to the local pedo-climatic and cropping conditions. For fine tuning of fertilizer recommendations, look-up tables can take into account some crucial characteristics of a specific field and its history (e.g. soil texture, previous crop, crop residues management) but generally lack precision, advising on the safe side to minimize risks of yield reductions, thus potentially leading to high N losses.

Simple *observational methods* that introduce *basic diagnostic tools*, such as plant color, unfertilized windows, indicator plants (Tremblay et al., 2001), for monitoring soil and crop N status allow for a first refinement of N fertilization in data poor conditions. In some countries, legislation demands quite complex N fertilizer planning often guided by extension services. For example, in Denmark, the use of look-up tables is combined with modelling of previous winter leaching at regional scale, taking into account the soil type, pre-crop effect, irrigation and crop N demand at field-level for conventional production; organic production is regulated by a general rule on maximal 100 kg used N ha^{-1} in average across the fields of a farm (Danish Ministry of Environment and Food, 2020).

Given the increasing pressure for improving environmental performance of agriculture in general and vegetable growing in particular, e.g. with respect to the targets in the framework guidelines for water protection (European Commission, 2000), more science-based methods of N management have been developed in the past decades. Extensive reviews of such methods including application, reliability and sensitivity have been published recently (e.g. Thompson et al., 2017; Padilla et al., 2018; De Pascale et al., 2018).

3.1.1. Fertilizer recommendation schemes based on soil analysis or soil N supply

N_{min}, KNS and N-expert systems are methods that use the soil mineral N content to calculate N fertilizer advices through a simplified N balance (Thompson et al., 2017, 2018). *N_{min} system* is the simplest method because it calculates the mineral N fertilizer rate for the entire crop cycle by subtracting the measured soil mineral N in the root zone at crop planting from a tabled “N target value”. *KNS system* refines the approach of the N_{min} system by including a tabled N buffer (i.e. a safety margin) to determine a N target value, an estimate of the expected weekly N mineralization from SOM, and a soil mineral N analysis during the crop growth period to calculate the N top dressing. The *N-expert system* is a further development of KNS by introducing an “apparent recovery” of 80 % of total N supply; the estimated N recovery and the estimated mineralisation from soil organic matter are combined in a component called “apparent N net mineralisation”. These methods are commonly used with field-grown vegetable crops in North-western and Central Europe.

Soil N Supply (SNS) system is an index system used in England and Wales in which the soil N supply is estimated rather than measured (Thompson et al., 2017; AHDB, 2020). The SNS indices estimate available soil mineral N including estimates of N mineralised from organic material during the crop growth period. SNS indices are determined for a specific field by considering average annual rainfall, soil texture and residues from the preceding crop and are used to recommend the N fertilizer rate.

These methods when used as part of improved management systems proved to notably reduce NO_3^- leaching in vegetable cropping systems (Thompson et al., 2017, 2018).

Additionally, the *nitrate concentration of the soil solution in the root zone* can be used to assist with N management of fertigated vegetable crops (Thompson et al., 2017; Padilla et al., 2020): this method, developed in Israel but used in Spain too, is based on analysis of soil solution extracted with ceramic suction samplers and on the use of sufficiency values or tendencies for data interpretation and N management (Peña-Fleitas et al., 2015; Padilla et al., 2020).

3.1.2. Methods based on crop or plant analysis

Destructive (*leaf tissue N analysis, petiole sap test*) and non-destructive (*chlorophyll meters, flavonols meters, canopy reflectance sensors*) crop-based methods are mainly used to detect crop N status and to guide top-dressing N fertilization. *Petiole sap test* is very sensitive to crop N status and is easily used on the farm (Peña-Fleitas et al., 2015) while the other methods are of limited use for different reasons: *leaf tissue N analysis* because of the very time-consuming nature of the measurement (Lemaire et al., 2008), *chlorophyll meters* and *flavonols meters* because they can be influenced by cultivar and environment, and require a thorough calibration and validation, and *canopy reflectance sensors* which, although they are promising tools within a Precision Agriculture context, the high cost of some optical sensors makes them expensive for small-scale farmers.

The use of these methods as a key for efficient N management of vegetable crops with reduced N loss to the environment has been reviewed in detail by Thompson et al. (2017) and Padilla et al. (2020).

3.1.3. Simulation models and decision support systems (DSSs)

Dynamic computer simulation models are very useful for demonstration purposes but many are too complex for steering crop management decisions at farm level. A considerable number of *DSSs*, based on mechanistic simulation models, have been developed in Europe to calculate N fertilization rates for vegetable crops. Examples include N-Expert in Germany, Azofert® in France, VegSyst-DSS and FertiliCalc in Mediterranean countries (notably Spain), GeCoN and CAL-FERT in Italy, PLANET and RB209 in the United Kingdom, and EU-Rotate in several European countries (Thompson et al., 2017; Gallardo et al., 2020). The use of DSS proved to significantly reduce N leaching losses in intensive vegetable rotations as compared to the management used by growers (Gallardo et al., 2020). It is difficult to measure the extent to which DSSs are being used for nutrient management in commercial farming. Nevertheless, Azofert®, N-Expert, CropManage, GesCoN, and PLANET were used to provide nutrient recommendations for numerous commercial farms, and smartphone versions of RB209 were downloaded thousands of times since the release in 2017. Gallardo et al. (2020) provided an in-depth discussion of these issues.

Use of all these tools has been demonstrated to appreciably reduce fertilizer N application and N losses while maintaining production levels, but the selection of tools to be used by a grower will be influenced by factors such as availability, the grower's technical level, and economic considerations (Thompson et al., 2017; Padilla et al., 2020; Gallardo et al., 2020).

3.2. Agronomic cropping practices

3.2.1. Crop rotation

Nitrogen management is usually focused on a single crop, but it is only by integrating available techniques of soil fertility management at the level of the *crop rotation* that effective environmental sustainability can be achieved, including efficient N management (Agneessens et al., 2014; Benincasa et al., 2017).

Some basic principles for a well-designed crop rotation include:

- legume crops - as cash crops or cover crops - can supply significant amounts of N to the succeeding crops, possibly eliminating the need for additional N fertilization (Thorup-Kristensen et al., 1999; Thorup-Kristensen and Dresbøll, 2010; Farneselli et al., 2018; Tosti et al., 2019; Hefner et al., 2020);
- catch crops to minimize nitrate leaching during the fall-winter season when there is no cash crop in temperate climates (Thorup-Kristensen et al., 2003; Gabriel et al., 2012);
- alternation of shallow and deep rooting crops (vegetable crops, catch crops, living mulches) in time (Thorup-Kristensen, 2006; Kristensen and Thorup-Kristensen, 2004a, 2004b; Christiansen et al., 2006) and in space to recycle soil NO_3^- from deep soil layers by growing deep-rooted crops (Xie and Kristensen, 2016; Xie et al., 2017). In addition, some crops - such as several crucifers and summer squash, but not leek, potato or beetroot - increase rooting depth and N exploitation at deep N placement or high sowing density (Kristensen and Thorup-Kristensen, 2007; Kristensen and Stavridou, 2017).

Large reductions of nitrate leaching losses were shown by Thorup-Kristensen (2006) by a simple change in crop sequence after winter fallow in crop rotation. The deep-rooted white cabbage (2.4 m root depth) reduced soil mineral N in deep soil layers of 1–2.5 m depth by more than 100 kg N ha^{-1} compared to the shallow-rooted leek (0.5 m root depth). Therefore, 100 kg N ha^{-1} less of mineral N was present in the deep soil layers after the harvest of this long-seasoned crop, where it was too late to establish a winter catch crop.

When growing a winter catch crop prior to vegetables, the leaching of mineral N was decreased for leek and medium deep-rooted beetroot (1.9 m root depth) by 60 kg N ha^{-1} the following winter. The effect was much lower for white cabbage because of its own deep N uptake (Thorup-Kristensen et al., 2012). The catch crop grown prior to the vegetables had kept or transferred the soil mineral N to the shallow soil layers within the reach of the shallow-rooted crop, resulting in 34 % higher N uptake in leek at harvest (Kristensen and Thorup-Kristensen, 2007).

Adapting crop rotations may have large economic consequences as it often means that high value vegetable crops are replaced by other low value crops or cover crops as was shown for two examples by de Haan and Garcia Diaz (2002). However, adapting rotations in this way can also improve the growing conditions of the vegetable crop, resulting in higher yields or better quality and even positive economic results.

3.2.2. Cover crops

Cover crops - including catch crops, intercrops, living mulches and green manures (legumes) - replace bare fallow or a cash crop and are either incorporated or left on the soil surface, before the succeeding cash crop. The terminology is not settled, but cover crops are first of all grown for soil-cover, which may have other purposes than to close the N cycle (e.g. N fixation, weed suppression, C-storage). Catch crops are grown to scavenge (residual) soil mineral N and are defined in some countries as non-legumes (e.g. Denmark). Legumes are often grown as cover crops to bring N into the system through biological fixation. Common cover crops include grasses (e.g. barley, rye, ryegrass, wheat, oat), legumes (e.g., hairy vetch, faba bean, pea, clovers), crucifers (e.g., rapeseed, fodder radish; white mustard) or mixtures of these types (Thorup-Kristensen et al., 2012; Benincasa et al., 2017).

Various reviews and meta-analyses conducted from an international perspective (e.g., Valkama et al., 2015; Norris and Congreves, 2018) concluded that cover crops provide a multitude of ecosystems services (e.g. N supply, N_2O emission reduction, NO_3^- retention, soil carbon storage, runoff and erosion control, increase of microbial biomass, suppression of weeds and pests, beneficial insect conservation, increase of insect biodiversity). In organic vegetable production this input is crucial as availability of animal manure is often limited, and the use of legumes enables self-sufficiency in nitrogen (Thorup-Kristensen et al., 1999; Farneselli et al., 2018; Tosti et al., 2019). In general, legumes are less efficient than non-legumes in preventing N leaching and are more cold-sensitive. Conversely, they pose less risk of pre-emptive competition (for both water and nutrients) to the subsequent cash crop compared to e.g. grasses and cereals (Thorup-Kristensen, 1993). Grass and cereal catch crops are highly efficient in scavenging nitrate in soil, but care must be taken at termination to avoid pre-emptive competition with the subsequent crop, when the catch crop retains N that would otherwise have been available for the cash crop (Hefner et al., 2020). Grass catch crops usually show an easy establishment, high cold tolerance and continuous growth in winter (Thorup-Kristensen, 2001).

Crucifers are both frost-sensitive and winter-hardy catch crops, and rapidly develop deep root systems (Kristensen and Thorup-Kristensen, 2004a). They have a relatively fast N release after incorporation into the soil according to their low C:N ratio (Ramirez-Garcia et al., 2015). The targeted mixing of legume and non-legume cover crops allows to manage the amount and rate of N that will be released for the succeeding crops (Tosti et al., 2014, 2019; Farneselli et al., 2018; Kramberger et al., 2013; Hefner et al., 2020).

The management of cover crops (e.g. sowing date and density, termination date and method) may greatly affect the cover crop effect on the N dynamics and ecosystem services (Murrell et al., 2017; Benincasa et al., 2017). Sowing date and density depend very much on pedo-climatic conditions. In general, an earlier termination date limits the biomass N accumulation and the effect on nitrate leaching, but allows a longer time for seed-bed preparation for the succeeding cash crop (Thorup-Kristensen et al., 2003; Vogeler et al., 2019). To terminate the cover crop, ploughing or disk incorporation is increasingly being replaced by shallow incorporation or mulching. Cover crop biomass can be mowed or roller-crimped (Hefner et al., 2020) and left on the soil surface as organic dead mulches (Campiglia et al., 2010, 2014), following the principles of conservation agriculture (i.e. farming systems that promote minimum soil disturbance, maintenance of a permanent soil cover, and diversification of plant species; FAO, 2020). The effect of this change on nitrogen availability for crop growth and nitrogen loss is depending on the cover crop type (legume or non-legume) and following crop (Hefner et al., 2010; Campiglia et al., 2014).

Fertigation may be used to mitigate the effects of the temporal or spatial mismatch between nutrient release from incorporated cover crop biomass or the nutrient demand of the wide spaced vegetables (Farneselli et al., 2013, 2018).

The effectiveness of cover crops to reduce N losses to water bodies has been clearly demonstrated (Sanchez et al., 2004; Scholberg et al., 2010): according to a meta-analysis by Tonitto et al. (2006) the reduction of N leaching was 70 % under non-legume cover crops compared to keeping the soil bare and 40 % with legume cover crops, in both cases thanks to fall and winter N uptake by the cover crop.

3.2.3. Intercropping

Intercropping refers to two or more crop species, or genotypes, that grow together or coexist for some time in the same field. The main benefit of a well-designed intercropping is a more efficient resource use such as solar radiation, water, soil, nutrients (niche complementarity), beneficial neighbor interactions (facilitation) and resource sharing through common mycorrhizal fungal networks or recycling of nutrients through leaf senescence and root turnover (Brooker et al., 2015). These benefits may lead to enhanced resource-use efficiencies - including N use efficiency - pest, disease and weed control, and higher crop productivity than corresponding monocultures; and delivery of various ecosystem services (Martin-Guay et al., 2018). The constraints are mainly related to difficulties in mechanization, conflicts in management timing, increased labor requirements and use of agro-chemicals, but also competition resulting in yield imbalance, which limit a wide adoption in intensive farming systems as vegetable production systems.

There is a need to develop knowledge for management tools for improved competition control (e.g. system design, species combination, root pruning, displacement of sowing time) (Xie et al., 2017). Therefore, intercropping potentially plays an important role in organic agriculture, but is not implemented much in conventional large-scale production. However, intercropping is seen with increasing interest as an alternative practice for a sustainable agriculture in conservation farming systems (Lithourgidis et al., 2011).

Intercropping cauliflower with overwintering grass-clover and moderately reduced N fertilization was feasible in organic cauliflower production, with regard to maintaining marketable yield and reducing the risk of nitrate leaching in the agroecosystem (Xie and Kristensen, 2016). The intercropping of a shallow-rooted leek crop and a deep-rooted catch crop (*Isatis tinctoria* L., dyer's wood, crucifer) resulted in highly complementary root systems, increasing the rooted zone from 0.5 m in monocropped leek to more than 2 m depth in the intercropped system. Intercropping reduced late autumn soil nitrate by more than 50 kg N ha^{-1} under leek known for high leaching losses (Xie and Kristensen, 2017). Across similar trials of vegetable and catch crop intercropping in Italy, Slovenia, Germany and Denmark reductions of $17-52$ kg N ha^{-1} of the risk of nitrate leaching were obtained at best (Xie et al., 2017). In several cases, legumes (white clover, burr medic) sown at the time of cauliflower or leek transplanting had limited effects on reducing soil nitrate and negative effects on cash crop N uptake (Tempesta et al., 2019).

3.2.4. Plant breeding

Breeding of N-efficient *genotypes* characterized by a low susceptibility to yield depression at reduced N fertilization levels is another approach to improve the sustainability of N management. In fact, both species and cultivars show differences in nitrogen use efficiency (NUE). Plant morphological and physiological traits that contribute to N efficient crops and cultivars are numerous and interacting at different plant organizational levels, from root characteristics to differences at the cell level with the involvement of biochemical and molecular traits (Ferrante et al., 2017; Lammerts van Bueren and Struik, 2017).

Spinach has a low N uptake efficiency due to the shallow rooting depth and a low N utilization efficiency (optimum N shoot concentration 50 mg N g^{-1} DM) while carrot have a high N uptake efficiency thanks to a deep and expanded root system and low optimum N shoot concentration (30 mg N g^{-1} DM) (Schenk, 2006). Most brassica crops have a low N harvest index resulting in high amounts of N in crop residues. Schulte auf'm Erley et al. (2010) found that white cabbage genotypes differed both in N efficiency (head fresh weight at low N supply) and in yield at high N supply and that these differences were not related to N uptake but to harvest index. For earlier maturing cultivars a slower leaf emergence was responsible for the low harvest index, which was mainly dependent on temperature. This suggests that breeding of cultivars with generally low-temperature tolerance could contribute to enhancing N utilization. For late cultivars, a high N retranslocation from leaves to the heads was related to yield both at low and high N supply. Similar results have been reported for cauliflower (Rather et al., 1999).

This review by Lammerts van Bueren and Struik (2017) described that head-forming crops, as cabbage (Schulte auf'm Erley et al., 2010) and lettuce (Kerbiriou et al., 2014), depend on the prolonged photosynthesis of outer leaves to provide the carbon sources for continued N supply and growth of the photosynthetically less active, younger inner leaves. In spinach, studies conducted by Chan-Navarrete et al. (2014) on several cultivars under both low and high N availability in controlled conditions, showed that NUE was highly correlated with shoot fresh weight, shoot dry weight, leaf area, and root dry weight while there was a moderate negative correlation with specific leaf area and root/shoot ratio. Chlorophyll content showed significant correlation with NUE only under high N availability. In potato the main factor explaining NUE was maturity: the late varieties show higher yield and higher NUE correlated to a longer growing period and an extended period of maximum leaf canopy and photosynthesis activity (Ospina et al., 2014). In general root performance is relevant for all crops but especially for short-cycle vegetable crops that benefit from early below-ground growth (Lammerts van Bueren and Struik, 2017).

All the studies suggest that breeding of N-efficient cultivars is not only a potential tool to reduce N release to the environment by reducing the necessary N input and reducing the N content remaining in the crop residues, but also a strategy to allow crop productivity in farming systems where access to fertilizers is limited. Ferrante et al. (2017)

commented that "*to this aim, several strategies should be adopted, involving crop management in the short period, and genetic improvement in the long one. Hence, breeding should be oriented to increase traits that improve NUE under different growing conditions. The increasing knowledge about the molecular and physiological bases of a complex trait as NUE and the development of innovative emerging molecular technologies for the study of the genome and transcriptome will provide useful tools for supporting the modern breeding programmes*".

3.3. Choice and application of mineral and organic fertilizers

Much attention is currently going towards improving the sustainable use of mineral fertilizers through the 4R Nutrient Stewardship (Reetz et al., 2015; Bruulsema, 2018) that provides a framework for using the right nutrient source, applied at the right rate, at the right time, in the right place.

The right rate and right time are based on the determination and application of an adequate amount of all limiting nutrients (nitrogen in our case) to meet plant requirements in relation to yield and quality goals, and considering the interactions of crop uptake, soil supply, environmental risks, and field operation logistics, as extensively explained in other section of this review.

3.3.1. Right source

The right source of N fertilizers refers to choosing plant-available nutrient forms that provide a balanced supply of all essential nutrients, that are released in a way that best matches crop demand. *Enhanced-Efficiency N Fertilizers (EEFs)* (Chien et al., 2009; Snyder, 2017) are an example of this approach. This term encompasses slow- and controlled-release N fertilizers, nitrification inhibitor-treated N fertilizers, urease inhibitor-treated N fertilizers or products treated with both nitrification and urease inhibitors.

Slow-release fertilizers (*SRFs)* are materials that are slow to enter in solution because of their low solubility and that are converted to plant-available N through microbial decomposition and hydrolysis (Guertal, 2009; Morgan et al., 2009). Examples of SRFs include urea-formaldehyde (UF) and isobutylenediurea (IBDU). The primary mechanism of N release in UF is microbial decomposition of the polymer, but environmental factors such as soil temperature, soil moisture, pH and oxygen content all interact with microbial activity. The N release from IBDU on the contrary does not depend on microbial activity, but the N is made available through hydrolysis at low temperatures. Given that the N release is accelerated by high soil temperatures (and low pH) this fertilizer is preferred for cool-season application (Morgan et al., 2009).

Controlled-release fertilizers (*CRFs)* have a release mechanism governed by a water-insoluble coating (i.e. sulfur, polymer or both sulfur and polymer coatings) that limits or controls the rate of water penetration and N release in function of soil temperature and moisture affecting micropore coating (Simonne and Hutchinson, 2005; Morgan et al., 2009; Van Eerd et al., 2018).

Both SRFs and CRFs proved to be effective in reducing N leaching in vegetable production systems, particularly on sandy soils (Simonne and Hutchinson, 2005; Hartz and Smith, 2009). However, their use is limited as synchronization of the N-release from the fertilizer with varying N-demand of the crop is difficult, especially in crops with a short growth cycle and a high N-demand, and as they are more expensive than conventional mineral N fertilizers per unit of N (Thompson et al., 2017).

Nitrification inhibitors (*NIs*) are chemical compounds that slow down the conversion of ammonium to nitrate, thereby reducing leaching risks of nitrate. Temperature is a key factor influencing NIs efficacy. Several publications demonstrated that the use of NIs improved N fertilizer use efficiency, reduced nitrate leaching and decreased N_2O emissions (Ruser and Schulz, 2015). A meta-analysis carried out on 62 peer-reviewed publication (1984–2013) with 859 datasets across the globe (Qiao et al., 2015) found that NIs application reduced dissolved inorganic N leaching by 48 % (confidence interval 56 – 38%). Moreover, the use of NIs allows for a reduction of the number of N fertilizer applications (Pasda et al., 2001) and of nitrate concentration in leafy vegetables (Irigoyen et al., 2006). The most commonly used chemical nitrification inhibitors are 3,4-dimethylpyrazole phosphate (DMPP) and dicyandiamide (DCD) (Pasda et al., 2001; Gilsanz et al., 2016). The nitrification inhibition efficacy of DMPP is more dependent on soil type than that of DCD, although the efficacy of both inhibitors was lower in more alkaline, low-organic matter soil (Guardia et al., 2018). In incubation experiments, DCD inhibited nitrification from cauliflower residues for 50 days and DMPP for at least 95 days (Chaves et al., 2006); hence, especially DMPP shows a potential to reduce nitrate leaching after incorporation of crop residues.

Urease inhibitors (*UIs*) are chemicals that block the activity of the ubiquitous enzyme urease that catalyzes the hydrolysis of urea into ammonium. In soils with high pH or soils that are poorly buffered against pH changes, the rapid hydrolysis of urea can result in an accumulation of ammonia rather than ammonium: by keeping urea from hydrolyzing, urease inhibitors protect against ammonia volatilization. So also UIs, together with NIs, proved to be effective in increasing yields and NUE (see meta-analysis by Abalos et al., 2014). Typically, UIs can protect against ammonia loss from surface applied fertilizers for a couple of weeks, depending on temperature and moisture conditions. The main UIs are N-(n-butyl) thiophosphoric triamide (NBPT) and N-(n-propyl) thiophosphoric triamide (NPPT). Chemical compounds containing urease inhibitor plus nitrification inhibitor are also available (Snyder, 2017).

The use of NIs and UIs may not translate into yield or environmental benefits if weather and soil conditions are not conducive to N loss, or when N rates are excessive. Moreover, Thompson et al. (2017) observed that given the concern of consumers and retailers regarding healthy food, attention will need to be paid to ensure that there are no or minimal residues of NIs and their degradation products in edible vegetable products.

The overall effect of EEFs is questionable. De Ruijter et al. (2010b) examined different types of EEFs in various vegetable crops. Results for EEFs were comparable to the use of CAN (Calcium Ammonium Nitrate) when applied according to good agricultural practice (with use of e.g. split and banded applications). Snyder (2017) suggested that "*the purchase and use of EEFs may depend to a great extent on: (1) the farmer's cropping system management abilities; (2) the agronomic and environmental knowledge of the agricultural retailer and professional crop adviser; (3) regional crop and fertilizer economics; (4) the soil and water conservation practices also implemented by the farmer on each field; (5) the availability and costs of nutrient management technology; (6) risks and magnitudes of the dominant environmental N losses; and (7) any governmental support or regulatory policies that may affect crop or cropping system choices and/or record-keeping (i.e. tracking) of nutrient performance over time*".

3.3.2. Right place

The right placement of nutrients refers to placing the fertilizer close to the growing roots (by banding or fertigation) in order to maximize absorption and to minimize nutrient losses.

Banding of fertilizers refers to concentrating the fertilizers under or along the plant row of vegetables with usually a wide planting distance. The fertilizer may be placed with the seed at planting as a "pop-up" fertilizer or placed under the seed or the transplant as "starter" fertilizer. Both pop-up and starter fertilizer, that are generally low in N and relatively high in P, increased early crop growth (both root and shoot), yield and N use efficiency in carrot, cabbage, onion, lettuce and green bean (Costigan, 1988; Stone, 1998; Burns et al., 2010). Side-dress fertilization on the soil surface, in e.g. cauliflower, onion, lettuce, potato, reduced N rates and increased apparent N recovery in comparison with broadcast application (Burns et al., 2010). Recently, Kristensen and Stavridou (2017) found that small N fertilizer applications in rocket improved NUE through the stimulation of N uptake by deeper roots, thus allowing to reduce the amount of fertilizer given in frequent applications or reducing applications given in the late growth phase.

Fertigation, i.e. the agronomic practice in which fertilizers are dissolved in the irrigation water and as such delivered to the root zone (usually micro-irrigation system), is the most effective technique to synchronize N uptake with N availability, increase NUE and reduce N leaching (Benincasa et al., 2011; Farneselli et al., 2018). The main advantages of fertigation are the flexibility to split the fertilizer application according to the crop N demand during the entire crop growth cycle, localizing N close to the root zone and maintaining relatively low and constant N availability in the soil solution (i.e. all the 4R principles are implemented). Exhaustive reviews on fertigation management in irrigated vegetable cropping have been published by Simonne et al. (2017) and Incrocci et al. (2017).

3.3.3. Organic fertilizers

Organic fertilizers are an important source of nitrogen both in conventional and organic vegetable cropping systems and contribute to maintain soil organic matter. A recent review by Möller (2018) provides detailed information on the effect of organic management on soil fertility and on the composition of several organic amendments currently available to organic farmers. Organic fertilizers can be either bulky organic materials (e.g. solid animal manures, slurries, composts, digestates based on anaerobic digestion of vegetative biomass or household wastes) with a relatively low nutrient concentration commonly used as base dressing, or more concentrated commercial organic fertilizers (e.g. feather meal, hoof and horn meal, meat and bone meal, fertilizers derived from plants and plant products processing) used to finetune the nutrient supply to the crop requirements. Solid animal manures and composts are characterized by a relatively high C:N ratio (20–30) and therefore a limited N release in the year of application, while keratins (20–30) or liquids like vinasse (2–3) or digestates (2–7) showed much higher and fast N availability (IFOAM, 2013, cited by Möller, 2018). In the Mediterranean area, compost, anaerobic digestate, and municipal solid waste gave good yield results in tomato, zucchini and lettuce (e.g., Montemurro et al., 2010; Alburquerque et al., 2012). Some liquid organic fertilizers can also be used for fertigation: for example, Farneselli et al. (2018) found that broadcast applications of poultry manure (N_{org} = 4%; C:N = 10) and by-product from a leather factory (N_{org} = 5%, C:N = 5) at a low N rate of 100 kg ha^{-1} were inadequate to meet the N-requirements of processing tomato in Central Italy while the by-product from a leather factory, added as a liquid fertilizer (N_{org} = 8%; C:N = 3) to the irrigation water at a similar rate showed the same efficacy of the mineral fertigation, with higher environmental sustainability.

The main constraints to the use of organic fertilizers both in conventional and organic vegetable production systems (De Neve et al., 2004; De Neve, 2017; Sambo and Nicoletto, 2017; Möller, 2018) can be summarized as follows: i) the lack of uniformity, the bulkiness and instability; ii) the difficulties in synchronizing N mineralization with crop N demand; iii) the risk of N losses by volatilization; iv) the higher cost per unit of nutrients in comparison to mineral fertilizers (except for regions with a large manure surplus); v) national or international legislation prohibiting or limiting their use. For example, in the EU, large manure applications are not allowed due to the limit of 170 kg N ha^{-1} in Nitrate Vulnerable Zones and the application periods are limited according to each country's action program. In some EU countries the use of slurries is forbidden in vegetables. The value of organic fertilizers is more than the value of the nutrients in the fertilizer. de Haan and Van Geel (2018) give indicative values for the value of the organic matter in slurries of 37 €/ton cattle slurry and 12 €/ton pig slurry.

The use of legume-based fertilizers of fresh or silage material may achieve a better synchronization with plant N demand (Möller, 2018). Such plant-based (cut-and-carry) fertilizers were found useful to replace conventional animal-based fertilizers (Sørensen and Grevsen, 2015). Perennial legumes of alfalfa, white clover, red clover and a grass-clover mixture produced 400 – 500 kg N ha^{-1} year^{-1} by two to four harvests per year. Annual legumes of broad bean, lupin and pea produced around 200 kg N ha^{-1} year^{-1}, and the harvest of seeds resulted in similar amounts. A strategy with frequent cuts resulted in cut-and-carry fertilizers with low C:N ratios suitable for precise fast-release organic fertilization for vegetable production.

Split-dose fertilization of leek was studied by step-wise incorporation of white clover after intercropping during the early growth phase of the leek (Xie et al., 2018). Leek growth was maintained or increased despite interspecific competition for N between leek and clover. The N input from N_2 fixation was increased to better match leek N demands, and the N retention was improved in the plant-soil system compared to full incorporation before leek planting.

3.4. Other agronomic options in N management

3.4.1. Tillage systems

Soil tillage operations can influence nitrogen cycling in various ways. We focus in this review on the effects of Controlled Traffic Farming and Reduced and No-tillage on crop yield and N dynamics.

Controlled Traffic Farming (CTF) where all machinery traffic is restricted to long-term permanent lanes, as opposed to Random Traffic Farming (RTF), is a potential management tool to alleviate the problems associated with soil compaction (Johansen et al., 2015). CTF adoption increases soil porosity and water infiltration but did not increase nitrate leaching in vegetables (Vermeulen and Mosquera, 2009). Conversion to CTF showed positive effects after 2–3 years on vegetable yields, root growth and nitrogen availability (Hefner et al., 2019). White cabbage, potato, beetroot and winter squash yields increased by 27–70 % on sandy loam, they grew 1.3–25 times more roots under CTF than RTF on sandy loam and coarse sandy soil. Soil mineral N and potential net N mineralization were equal or higher in CTF, while N leaching did not increase. The cropping system resilience, defined as a similar production level over a couple of years, increased for CTF (Hefner et al., 2019).

Reduced tillage (RT) and no-tillage (NT) cropping systems have been tested in vegetables with varying results but little is known about the implications for N management. From arable farming it is known that reducing tillage intensity changes both crop N demand due to change in yield potential and the supply of N due to changes in net N mineralization and N losses (Malhi et al., 2001). Vegetable yields were very much reduced under NT combined with roller-crimping of cover crops for weed suppression when compared to bare soil in the USA (Leavitt et al., 2011). In Europe, the system showed promising results in a Mediterranean climate (Canali et al., 2013), but diverse results on yields, depending on cover crop species and sufficient N fertilization in Denmark. The risk of nitrate leaching was suggested to be decreased by NT combined with roller-crimping (Hefner et al., 2020). Knowledge of RT and NT effects on N dynamics and the applicability in vegetable production in other climates is scarce.

3.4.2. Organic and conventional farming systems

In general, conservation and organic farming systems tend to pay more attention to the crop rotation than conventional farming systems, where short-term economic aspects often prevail over agronomic and environmental considerations, unless imposed by regulation. This leads to short crop rotations and open nutrient cycles, mainly in large-scale specialized vegetable farms (Möller, 2018).

The differences in N use efficiency and N losses (mainly nitrate leaching) between organic and conventional agriculture, including horticultural crops, is still a matter of debate. Comparisons of nitrate leaching between the systems often come to contradictory conclusions, which is not surprising given the enormous diversity in both organic and conventional farming management. A main difficulty is the inherent differences in the farming systems, which make direct comparison difficult, such as management practices affecting e.g. size of seedlings, sowing/planting and harvest time, use of cover crops, fertilizers and amendments and harvest quality criteria, which interact with the N management practices. Another difficulty is the interpretation of results (e.g. nitrate leaching per kg applied N, per ha of land or per kg of marketable yield).

One good example of the limited number of studies of nitrate losses scaled per yield shows lower nitrate leaching losses in organic as compared to conventional arable fields (0.2 ± 0.1 kg N kg^{-1} N $year^{-1}$ versus 0.3 ± 0.1 kg N kg^{-1} N $year^{-1}$) when calculated across 37 fields in 8 crop rotations (Benoit et al., 2014). A meta-analysis (Seufert et al., 2012) showed greater yield reduction for vegetable crops than for cereals and oilseed crops in organic compared to conventional management.

However, the organic systems better maintained or improved soil health indices such as soil fertility and organic matter content (Scialabba and Müller-Lindenlauf, 2010). Thorup-Kristensen et al. (2012) showed that plant nutrition and N use efficiency could be optimized in a vegetable crop rotation by replacing N fertilization by the use of non-legume and legume cover crops combined with a design of the crop rotation based on rooting depth and N demand (Thorup-Kristensen, 2006). The change of fertilizer input, plant cover and rotation design turned out to be more important to secure high yields and low nitrate leaching than if the farming practice was conventional or organic. The yield across all crops in rotation was reduced to 82 % in organic compared to conventional systems calculated per hectare of cropped land, while mineral N contents in 1–2 m soil depth were 74 and 61 kg N ha^{-1} in the conventional and organic systems, respectively, *without* cover crops; and 22 kg N ha^{-1} in the organic systems *with* cover crops.

3.4.3. Biostimulants

Plant biostimulants have been included among the tools that may have potential in sustainable N fertilization management (De Pascale et al., 2017, 2018). There is absence of a biostimulant definition universally accepted by the regulatory bodies (Colla and Rouphael, 2015). In a recent review the following definition was proposed "*A plant biostimulant is any substance or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrients content. By extension, plant biostimulants also designate commercial products containing mixtures of such substances and/or microorganisms*" (du Jardin, 2015). The following main categories of plant biostimulants were suggested: i) humic and fulvic acids; ii) protein hydrolysates and other N-containing compounds; iii) seaweed extracts and botanicals; iv) chitosan and other biopolymers; v) inorganic compounds; vi) beneficial fungi; vii) beneficial bacteria.

Different researches demonstrated a significant effect on plant nitrogen uptake in general (Calvo et al., 2014; Bulgari et al., 2015). Protein hydrolysates increased N use efficiency in greenhouse spinach (Carillo et al., 2019) and rocket (Di Mola et al., 2019) while humic acids improved yield in field grown onion (Kandil et al., 2013).

However, more research is needed to deepen knowledge of the mode of action of biostimulants to improve nutrient availability and uptake (De Pascale et al., 2017) and very importantly to quantify the actual potential to contribute to a sustainable N management of cropping systems.

3.4.4. Grafting

Grafting is a cultural technique that consists in the union by different methods (i.e. cleft, tongue approach grafting, hole insertion, tube or pine grafting) of a rootstock and a scion of two different species or of two different cultivars of the same species. In vegetable crops grafting is practiced worldwide from decades mainly in *Cucurbitaceae* (melon, watermelon and cucumber) and *Solanaceae* (tomato, eggplant, pepper) species to provide tolerance to biotic stress (e.g. soil borne fungi, virus, bacterial diseases) and abiotic stresses (e.g. cold, salinity, drought, heavy metal toxicity), to increase plant vigor, to influence sex expression, to improve quality traits and, overall considered, to increase yield in greenhouse or open field crops (Kiriacou et al., 2017; Rouphael et al., 2018). Several studies showing enhanced N use efficiency of grafted plants e.g. in melon (Colla et al., 2010), tomato (Djidonou et al., 2013) and pepper (Ropokis et al., 2019), which indicates that grafting can contribute to the sustainable N management in vegetable production systems (Simonne et al., 2017; De Pascale et al., 2018). All researchers pointed out that the impact of grafting depended not merely on the rootstock genotype but on the rootstock-scion combination.

4. Final considerations

Vegetable production systems are typically intensive cropping systems with high N input and high risk of N leaching. Specific problems of N management in vegetables include the often large N mineralization potential of soils and the high N release of incorporated vegetable crop residues, which complicates the synchronization between N supply and crop N demand.

The most crucial factor is the correct quantification of the different N balance components in the soil-crop-atmosphere continuum by using established estimation methods for these components, and possibly monitoring tools of the crop N status throughout the growing season. In addition, the correct choice of N fertilizer type, timing and application method can further increase N use efficiency and reduce N losses, notably by using fertigation techniques.

However, further improvements in N use efficiency should not only be limited to the further refinement of N fertilizer advices and more precise fertilization techniques, but also include in a wider systems' approach. This would mean that more attention should go to the overall design of the crop rotation, e.g. a judicious choice of crops in the rotation that are complementary with respect to N demand and N uptake efficiency, also including non-vegetables. Also the use of less common techniques (intercropping, reduced tillage, controlled traffic farming) should further be explored for the potential to increase N use efficiency. However, this will need to be reconciled with a number of economic constraints. Finally, the success of all these tools will crucially depend on the adoption rate by farmers. There is therefore also a need to include all these aspects in user friendly Decision Support Systems that can be directly implemented in farmers' practice.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abalos, D., Jeffery, S., Sanz-Cobena, A., Guardia, G., Vallejo, A., 2014. Meta- analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. Agr. Ecosyst. Environ. 189, 136–144. https://doi.org/10.1016/j.agee.2014.03.036.

Agneessens, L., De Waele, J., De Neve, S., 2014. Review of alternative management options of vegetable crop residues to reduce nitrate leaching in intensive vegetable rotations. Agronomy 4, 529–555. https://doi.org/10.3390/agronomy4040529.

Agostini, F., Tei, F., Silgram, M., Farneselli, M., Benincasa, P., Aller, M.F., 2010. Decreasing N leaching in vegetable crops with better N management. In: In: Lichtfouse, E. (Ed.), Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming. Sustainable Agriculture Reviews, vol. 4. Springer, Dordrecht, The Netherlands, pp. 147–200. https://doi.org/10.1007/978-90-481-8741-6_6.

AHDB, 2020. Nutrient Management Guide (RB209). Section 6 Vegetables and Bulbs.

(accessed 27 May 2020). https://ahdb.org.uk/knowledge-library/rb209-section-6-vegetables-and-bulbs.

Albornoz, F., 2016. Crop responses to nitrogen overfertilization: a review. Sci. Hortic. 205, 79–83. https://doi.org/10.1016/j.scienta.2016.04.026.

Alburquerque, J.A., de la Fuente, C., Campoy, M., Carrasco, L., Nájera, I., Baixauli, C., Caravaca, F., Roldán, A., Cegarra, J., Bernal, M.P., 2012. Agricultural use of digestate for horticultural crop production and improvement of soil properties. Eur. J. Agron. 43, 119–128. https://doi.org/10.1016/j.eja.2012.06.001.

Benincasa, P., Guiducci, M., Tei, F., 2011. The nitrogen use efficiency: meaning and sources of variation – case studies on three vegetable crops in Central Italy. HortTechnology 21 (3), 266–273. https://doi.org/10.21273/HORTTECH.21.3.266.

Benincasa, P., Tosti, G., Farneselli, M., Guiducci, M., Tei, F., 2017. Crop rotation as a system approach for soil fertility management in vegetables. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer International Publishing AG, Cham, Switzerland, pp. 115–147. https://doi.org/10.1007/978-3-319-53626-2_5.

Benoit, M., Garnier, J., Anglade, J., Billen, G., 2014. Nitrate leaching from organic and conventional arable crop farms in the seine Basin (France). Nutr. Cycl. Agroecosys. 100, 285–299. https://doi.org/10.1007/s10705-014-9650-9.

Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., et al., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol. 206, 107–117. https://doi.org/10.1111/nph.13132.

Bruulsema, T., 2018. Managing nutrients to mitigate soil pollution. Environ. Pollut. 243, 1602–1605. https://doi.org/10.1016/j.envpol.2018.09.132.

Bulgari, R., Cocetta, G., Trivellini, A., Vernieri, P., Ferrante, A., 2015. Biostimulants and crop responses: a review. Biol. Agric. Hortic. 31 (1), 1–17. https://doi.org/10.1080/01448765.2014.964649.

Burns, I.G., 2006. Assessing N fertiliser requirements and the reliability of different recommendation systems. Acta Hortic. 700, 35–48. https://doi.org/10.17660/ActaHortic.2006.700.2.

Burns, I.G., Hammond, J.P., White, P.J., 2010. Precision placement of fertiliser for optimising the early nutrition of vegetable crops: a review of the implications for the yield and quality of crops, and their nutrient use efficiency. Acta Hortic. 852, 177–187. https://doi.org/10.17660/ActaHortic.2010.852.21.

Calvo, P., Nelson, L., Kloepper, J.W., 2014. Agricultural uses of plant biostimulants. Plant Soil 383, 3–41. https://doi.org/10.1007/s11104-014-2131-8.

Cameira, M.R., Mota, M., 2017. Nitrogen related diffuse pollution from horticulture production - mitigation practices and assessment strategies. Horticulturae 3 (1), 25. https://doi.org/10.3390/horticulturae3010025.

Campiglia, E., Mancinelli, R., Radicetti, E., Caporali, F., 2010. Effect of cover crops and mulches on weed control and nitrogen fertilization in tomato (*lycopersicon esculentum* Mill.). Crop Prot. 29, 354–363. https://doi.org/10.1016/j.cropro.2009.12.001.

Campiglia, E., Mancinelli, R., Di Felice, V., Radicetti, E., 2014. Long-term residual effects of the management of cover crop biomass on soil nitrogen and yield of endive (*Cichorium endivia* L.) and savoy cabbage (*Brassica oleracea* var. *sabauda*). Soil Till. Res. 139, 1–7. https://doi.org/10.1016/j.still.2014.01.003.

Canali, S., Campanelli, G., Ciaccia, C., Leteo, F., Testani, E., Montemurro, F., 2013. Conservation tillage strategy based on the roller crimper technology for weed control in Mediterranean vegetable organic cropping systems. Eur. J. Agron. 50, 11–18. https://doi.org/10.1016/j.eja.2013.05.001.

Carillo, P., Colla, G., Fusco, G.M., Dell'Aversana, E., et al., 2019. Morphological and physiological responses induced by protein hydrolysate-based biostimulant and nitrogen rates in greenhouse spinach. Agronomy 9 (450), 22 pp. https://doi.org/10.3390/agronomy9080450.

Chan-Navarrete, R., Kawai, A., Dolstra, O., Lammerts van Bueren, E.T., Van der Linden, C.G., 2014. Genetic diversity of nitrogen use efficiency in spinach (*Spinacia oleracea* L.) cultivars using the Ingestad model on hydroponics. Euphytica 199 (1–2), 155–166. https://doi.org/10.1007/s10681-014-1186-1.

Chaves, B., Opoku, A., De Neve, S., Boeckx, P., Can Cleemput, O., Hofman, G., 2006. Influence of DCD and DMPP on soil N dynamics after incorporation of vegetable crop residues. Biol. Fertil. Soils 43, 62–68. https://doi.org/10.1007/s00374-005-0061-6.

Chaves, B., De Neve, S., Boeckx, P., Van Cleemput, O., Hofman, G., 2007. Manipulating nitrogen release from nitrogen-rich crop residues using organic wastes under field conditions. Soil Sci. Soc. Am. J. 71, 1240–1250. https://doi.org/10.2136/sssaj2005.0379.

Chien, S.H., Prochnow, L.I., Cantarella, H., 2009. Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. Adv. Agron. 102, 267–322. https://doi.org/10.1016/S0065-2113(09)01008-6.

Christiansen, J.S., Thorup-Kristensen, K., Kristensen, H.L., 2006. Root development of beetroot, sweet corn and celeriac, and soil N content after incorporation of green manure. J. Hortic. Sci. Biotech. 81, 831–838. https://doi.org/10.1080/14620316.2006.11512146.

Colla, G., Rouphael, Y., 2015. Biostimulants in horticulture. Sci. Hortic. 196, 1–2. https://doi.org/10.1016/j.scienta.2015.10.044.

Colla, G., Suãrez, C.M.C., Cardarelli, M., Rouphael, Y., 2010. Improving nitrogen use efficiency in melon by grafting. HortScience 49, 559–565. https://doi.org/10.21273/HORTSCI.45.4.559.

Colla, G., Kim, H., Kyriacou, M.C., Rouphael, Y., 2018. Nitrate in fruits and vegetables. Sci. Hortic. 237, 221–238. https://doi.org/10.1016/j.scienta.2018.04.016.

Congreves, K.A., Van Eerd, L.L., 2015. Nitrogen cycling and management in intensive horticultural systems. Nutr. Cycl. Agroecosyst. 102, 299–318. https://doi.org/10.1007/s10705-015-9704-7.

Conversa, G., Elia, A., 2019. Growth, critical N concentration and crop N demand in butterhead and crisphead lettuce grown under Mediterranean conditions. Agronomy 9, 681. https://doi.org/10.3390/agronomy9110681.

Conversa, G., Lazzizera, C., Bonasia, A., Elia, A., 2019. Growth, N uptake and N critical dilution curve in broccoli cultivars grown under Mediterranean conditions. Sci. Hortic. 244, 109–121. https://doi.org/10.1016/j.scienta.2018.09.034.

Costigan, P.A., 1988. The placement of starter fertilizers to improve the early growth of drilled and transplanted vegetables. Proceedings of the Fertiliser Society 274, 1–24.

Council of the European Communities, 1991. Council directive of 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Off. J. Eur. Communities L135, 1–8.

Danish Ministry of Environment and Food, 2020. The Agricultural Agency. Guidelines for Fertilization and Equivalence Regulation. Management Period of 1. August 2019 to 31. July 2020. In Danish: Vejledning om gødsknings- og harmoniregler. Planperioden 1. august 2019 til 31. juli 2020. pp. 199 p.

de Haan, J.J., Garcia Diaz, A., 2002. Integrated and Ecological Nutrient Management. (VEGINECO Project Report; No. 3). Wageningen: Appl. Plant Res. . https://edepot.wur.nl/11787.

de Haan, J., van Geel, W., 2018. Animal manure use in vegetable production in the Netherlands. Acta Hortic. 1192, 73–80. https://doi.org/10.17660/ActaHortic.2018.1192.8.

de Haan, J.J., Wesselink, M., Verstegen, H.A.G., 2019. Leek production in conventional and organic arable-vegetable rotations in the Netherlands. Acta Hortic. 1253, 351–358. https://doi.org/10.17660/ActaHortic.2019.1253.46.

De Neve, S., 2017. Organic matter mineralization as a source of nitrogen. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer International Publishing AG, Cham, Switzerland, pp. 65–83. https://doi.org/10.1007/978-3-319-53626-2_3.

De Neve, S., Gaon Saez, S., Chaves Daguilar, B., Sleutel, S., Hofman, G., 2004. Manipulating N mineralization from high N crop residues using on- and off-farm organic materials. Soil Biol. Bioch. 36, 127–134. https://doi.org/10.1016/j.soilbio.2003.08.023.

De Neve, S., Hofman, G., 1996. Modelling N mineralization of vegetable crop residues during laboratory incubations. Soil Biol. Bioch . 28, 1451–1457. https://doi.org/10.1016/S0038-0717(96)00154-X.

De Pascale, S., Rouphael, Y., Colla, G., 2017. Plant biostimulants: innovative tool for enhancing plant nutrition in organic farming. Eur. J. Hortic. Sci. 82 (6), 277–285. https://doi.org/10.17660/eJHS.2017/82.6.2.

De Pascale, S., Rouphael, Y., Gallardo, M., Thompson, R.B., 2018. Water and fertilization management of vegetable: state of art and future challanges. Eur. J. Hortic. Sci. 83 (5), 306–318. https://doi.org/10.17660/eJHS.2018/83.5.4.

de Ruijter, F.J., Huijsmans, J.F.M., Rutgers, B., 2010a. Ammonia volatilization from crop residues and frozen green manure crops. Atmos. Environ. 44, 3362–3368. https://doi.org/10.1016/j.atmosenv.2010.06.019.

de Ruijter, F.J., ten Berge, H.F.M., Smit, A.L., 2010b. Strategies to increase nitrogen use efficiency and reduce nitrate leaching in vegetable production in the Netherlands. Acta Hortic. 852, 107–114. https://doi.org/10.17660/ActaHortic.2010.852.11.

Delphin, J.E., 2000. Estimation of nitrogen mineralization in the field from an incubation test and from soil analysis. Agronomie 20, 349–361. https://doi.org/10.1051/agro:2000132.

Di Gioia, F., Gonnella, M., Buono, V., Ayala, O., Santamaria, P., 2017. Agronomic, physiological and quality response of romaine and red oak-leaf lettuce to nitrogen input. Ital. J. Agron. 12 (806), 47–58. https://doi.org/10.4081/ija.2017.806.

Di Mola, I., Ottaiano, L., Cozzolino, E., Senatore, M., et al., 2019. Plant-based biostimulants influence the agronomical, physiological, and qualitative responses of baby rocket leaves under diverse nitrogen conditions. Plants 8 (522), 15 pp. https://doi.org/10.3390/plants8110522.

Djidonou, D., Zhao, X., Simonne, E.H., Koch, K., 2013. Yield, water-, and nitrogen-use efficiency in field-grown, grafted tomatoes. HortScience 48 (4), 485–492. https://doi.org/10.21273/HORTSCI.48.4.485.

du Jardin, P., 2015. Plant biostimulants: definition, concept, main categories and regulation. Sci. Hortic. 196, 3–14. https://doi.org/10.1016/j.scienta.2015.09.021.

Ekbladh, G., Witter, E., 2010. Determination of the critical nitrogen concentration of white cabbage. Eur. J. Agron. 33, 276–284. https://doi.org/10.1016/j.eja.2010.08.001.

Engel, R., Jones, C., Wallander, R., 2011. Ammonia volatilization from urea and mitigation by NBPT following surface application to cold soils. Soil Sci. Soc. Am. J. 75, 2348–2357. https://doi.org/10.2136/sssaj2011.0229.

European Commission, 2000. Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy. Offic. J. Eur. Commun. L 327, 1–73.

EUROSTAT, 2019. Available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=The_fruit_and_vegetable_sector_in_the_EU_-_a_statistical_overview (accessed 5 November 2019).

FAO, 2020. Conservation Agriculture. (accessed 28 May 2020). http://www.fao.org/conservation-agriculture/overview/what-is-conservation-agriculture/en/.

Farneselli, M., Tosti, G., Benincasa, P., Guiducci, M., Tei, F., 2013. Fertigation and winter cover crops as complementary tools for the N nutrition of processing tomato. In: Proc. of Congress on Nutrient Management, Innovative Techniques and Nutrient Legislation in Intensive Horticulture for an Improved Water Quality (NutriHort). Ghent, Belgium. 16-18 September 2013, pp. 302-306. ISBN 9789040303463.

Farneselli, M., Tosti, G., Onofri, A., Benincasa, P., Guiducci, M., Pannacci, E., Tei, F., 2018. Effects of N sources and management strategies on crop growth, yield and potential N leaching in processing tomato. Eur. J. Agron. 98, 46–54. https://doi.org/10.1016/j.eja.2018.04.006.

Feller, C., Fink, M., 2002. Nmin target values for field vegetables. Acta Hortic. 571, 195–201. https://doi.org/10.17660/ActaHortic.2002.571.23.

Ferrante, A., Nocito, F.F., Morgutti, S., Sacchi, G.A., 2017. Plant breeding for improving nutrient uptake and utilization efficiency. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer

International Publishing AG, Cham, Switzerland, pp. 221–246. https://doi.org/10.1007/978-3-319-53626-2_8.

Gabriel, J.L., Munoz-Carpena, R., Quemada, M., 2012. The role of cover crops in irrigated systems: Water balance, nitrate leaching and soil mineral nitrogen accumulation. Agr. Ecosyst. Environ. 155, 50–61. https://doi.org/10.1016/j.agee.2012.03.021.

Gallardo, M., Elia, A., Thompson, R.B., 2020. Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. Agr. Water Manage In this issue.

Gilsanz, C., Báez, D., Misselbrook, T.H., Dhanoa, M.S., Cárdena, L.M., 2016. Development of emission factors and efficiency of two nitrification inhibitors, DCD and DMPP. Agr. Ecosyst. Environ. 216, 1–8. https://doi.org/10.1016/j.agee.2015.09.030.

Greenwood, D.J., Kubo, K., Burn, s I.G., Draycott, A., 1989. Apparent recovery of fertilizer N by vegetable crops. Soil Sci. Plant Nutr. 35, 367–381. https://doi.org/10.1080/00380768.1989.10434770.

Greenwood, D.J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., Neeteson, J.J., 1990. Decline in percentage N of C3 and C4 crops with increasing plant mass. Ann. Bot. 66, 425–436. https://doi.org/10.1093/oxfordjournals.aob.a088044.

Greenwood, D.J., Rahn, C., Draycott, A., Vaidyanatha, L.V., Paterson, C., 1996. Modelling and measurement of the effects of fertilizer-N and crop residue incorporation on N-dynamics in vegetable cropping. Soil Use Manage. 12, 13–24. https://doi.org/10.1111/j.1475-2743.1996.tb00525.x.

Guardia, G., Marsden, K., Vallejo, A., Jones, D.L., Chadwick, D.R., 2018. Determining the influence of environmental and edaphic factors on the fate of the nitrification inhibitors DCD and DMPP in soil. Sci. Total Environ. 624, 1202–1212. https://doi.org/10.1016/j.scitotenv.2017.12.250.

Guertal, E.A., 2009. Slow-release nitrogen fertilizers in vegetable production: a review. HortTechnology 19 (1), 16–19. https://doi.org/10.21273/HORTSCI.19.1.16.

Hartz, T.K., Smith, R.F., 2009. Controlled-release fertilizer for vegetable production: the California experience. HortTechnology 19 (1), 20–22. https://doi.org/10.21273/HORTSCI.19.1.20.

Heffer, P., Gruére, A., Roberts, P., 2017. Assessment of Fertilizer Use by Crop at the Global Level - 2014-2014/15. International Fertilizer Industry Association (IFA) and International Plant Nutrition Institute (IPNI), Paris, France, pp. 20.

Hefner, M., Labouriau, R., Nørremark, M., Kristensen, H.L., 2019. Controlled traffic farming increased crop yield, root growth, and nitrogen supply at two organic vegetable farms. Soil Till. Res. 191, 117–130. https://doi.org/10.1016/j.still.2019.03.011.

Hefner, M., Gebremikael, M.T., Canali, S., Sans Serra, F.X., Petersen, K.K., Sorensen, J.N., De Neve, S., Labouriau, R., Kristensen, H.L., 2020. Cover crop composition mediates the constraints and benefits of roller-crimping and incorporation in organic white cabbage production. Agr. Ecosyst. Environ. 296 (106908), 1–11. https://doi.org/10.1016/j.agee.2020.106908. 1 July 2020.

IFOAM, 2013. Position Paper on Organic Greenhouse Production. (accessed 25 Novembre 2019). http://www.ifoam-eu.org/sites/default/files/page/files/ifoameu_reg_greenhouse_production_position_201302.pdf.

Incrocci, L., Massa, D., Pardossi, A., 2017. New trends in the fertigation management of irrigated vegetable crops. Horticulturae 3. https://doi.org/10.3390/horticulturae3020037.

Irigoyen, I., Lamsfus, C., Aparicio-Tejo, P., Muro, J., 2006. The influence of 3, 4-dimethylpyrazole phosphate and dicyandiamide on reducing nitrate accumulation in spinach under Mediterranean conditions. J. Ag. Sci. 144 (6), 555–562. https://doi.org/10.1017/S0021859606006472.

Johansen, T.J., Thomsen, M.G., Loes, A.-K., Riley, H., 2015. Root development in potato and carrot crops - influences of soil compaction. Acta Agr. Scand. 65, 182–192. https://doi.org/10.1080/09064710.2014.977942.

Kandil, A.A., Sharief, A.E., Fathalla, F.H., 2013. Onion yield as affected by foliar application with amino and humic acids under nitrogen fertilizer levels. eSci J. Crop Prod. 2, 62–72.

Kerbiriou, P.J., Stomph, T.J., Lammerts van Bueren, E.T., Struik, P.C., 2014. Modelling concept of lettuce breeding for nutrient efficiency. Euphytica 199 (1–2), 167–181. https://doi.org/10.1007/s10681-014-1198-x.

Kiriacou, M.C., Rouphael, Y., Colla, G., Zrenner, R., Schwarz, D., 2017. Vegetable grafting: the implications of a growing agronomic imperative for vegetable fruit quality and nutritive value. Front. Plant Sci. 8, 741. https://doi.org/10.3389/fpls.2017.00741.

Kramberger, B., Gselman, A., Podvrsnik, M., Kristl, J., Lesnik, M., 2013. Environmental advantages of binary mixtures of *Trifolium incarnatum* and *Lolium multiflorum* over individual pure stands. Plant Soil Environ. 59, 22–28. https://doi.org/10.17221/223/2012-PSE.

Kristensen, H.L., Stavridou, E., 2017. Deep root growth and nitrogen uptake by rocket (*Diplotaxis tenuifolia* L.) as affected by nitrogen fertilizer, plant density and leaf harvesting on a coarse sandy soil. Soil Use Manage. 33, 62–71. https://doi.org/10.1111/sum.12334.

Kristensen, H.L., Thorup-Kristensen, K., 2004a. Root growth and nitrate uptake of Three different catch crops in deep soil layers. Soil Sci. Soc. Am. J. 68, 529–537. https://doi.org/10.2136/sssaj2004.5290.

Kristensen, H.L., Thorup-Kristensen, K., 2004b. Uptake of ^{15}N labeled nitrate by root systems of sweet corn, carrot and white cabbage from 0.2–2.5 meters depth. Plant Soil 265, 93–100. https://doi.org/10.1007/s11104-005-0696-y.

Kristensen, H.L., Thorup-Kristensen, K., 2007. Effects of vertical distribution of soil inorganic nitrogen on root growth and subsequent nitrogen uptake by field vegetable crops. Soil Use Manage. 23, 338–347. https://doi.org/10.1111/j.1473-2743.2007.00105.x.

Lammerts van Bueren, E.T., Struik, P.C., 2017. Diverse concept of breeding for nitrogen use efficiency. A review. Agron. Sustain. Dev. 37 (50), 24 pp. https://doi.org/10.1007/s13593-017-0457-3.

Leavitt, M.J., Sheaffer, C.C., Wyse, D.L., Allan, D.L., 2011. Rolled winter rye and hairy vetch cover crops lower weed density but reduce vegetable yields in No-tillage organic production. HortScience 46, 387–395. https://doi.org/10.21273/HORTSCI.46.3.387.

Lemaire, G., Gastal, F., 1997. N Uptake and Distribution in Plant Canopies. In: Lemaire, G. (Ed.), Diagnosis of nitrogen status in crops. Springer, Berlin, Heidelberg, pp. 3–43. https://doi.org/10.1007/978-3-642-60684-7_1.

Lemaire, G., Jeuffroy, M.H., Gastal, F., 2008. Diagnosis tool for plant and crop N status in vegetative stage. Theory and practices for crop N management. Eur. J. Agron. 28 (4), 614–624. https://doi.org/10.1016/j.eja.2008.01.005.

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A., Vlachostergios, D.N., 2011. Annual intercrops: an alternative pathway for sustainable agriculture. Aust. J. Crop Sci. 5, 396–410. Available at. https://www.cropj.com/anastasios_5_4_2011_396_410.pdf.

Lorenz, H.P., Schlaghecken, J., Engel, G., Maync, A., Ziegler, J., Strohmeyer, K., 1989. Ordnungsgemaesse Stickstoff-Versorgung Im Freiland-Gemuesebau Nach Dem, Kulturbegleitenden-Nmin-Sollwerte-(KNS)-System. Ministerium fuer Landwirtschaft, Weinbau und Forsten Rheinland-Pfalz, Mainz, pp. 85 pp (in German).

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. https://doi.org/10.1016/S0167-1987(01)00176-3.

Martin-Guay, M.O., Paquette, A., Dupras, J., Rivest, D., 2018. The new Green revolution: sustainable intensification of agriculture by intercropping. Sci. Total Environ. 615, 767–772. https://doi.org/10.1016/j.scitotenv.2017.10.024.

Möller, K., 2018. Soil fertility status and nutrient input–output flows of specialised organic cropping systems: a review. Nutr. Cycl. Agroecosyst. 112, 147–164. https://doi.org/10.1007/s10705-018-9946-2.

Montemurro, F., Ferri, D., Tittarelli, F., Canali, S., Vitti, C., 2010. Anaerobic digestate and on-farm compost application: effects on lettuce (*Lactuca sativa* L.) crop production and soil properties. Compost Sci. Util. 18, 184–193. https://doi.org/10.1080/1065657X.2010.10736954.

Morgan, K.T., Cushman, K.E., Sato, S., 2009. Release mechanisms for slow- and controlled-release fertilizers and strategies for their use in vegetable production. HortTechnology 19 (1), 10–12. https://doi.org/10.21273/HORTSCI.19.1.10.

Murrell, E.G., Schipanski, M.E., Finney, D.M., Hunter, M.C., Burgess, M., LaChance, J.C., Baraibar, B., White, C.M., Mortensen, D.A., Kaye, J.P., 2017. Achieving diverse cover crop mixtures: effects of planting date and seeding rate. Agron. J. 109, 259–271. https://doi.org/10.2134/agronj2016.03.0174.

Myrold, D.D., Bottomley, P.J., 2008. Nitrogen mineralization and immobilization. In: Schepers, J.S., Raun, W. (Eds.), Nitrogen in Agricultural Systems, ASA, CSSA, SSSA Books. Wiley, pp. 157–172. https://doi.org/10.2134/agronmonogr49.c5.

Nendel, C., 2009. Evaluation of best management practices for N fertilisation in regional field vegetable production with a small scale simulation model. Eur. J. Agron. 30, 110–118. https://doi.org/10.1016/j.eja.2008.08.003.

Nendel, C., Reuter, S., Kersebaum, K.C., Kubiak, R., Nieder, R., 2005. Nitrogen mineralization from mature bio-waste compost in vineyard soils II. Test of N-mineralization parameters in a long-term *in situ* incubation experiment. J. Plant. Nutr. Soil. Sc. 168, 219–227. https://doi.org/10.1002/jpln.200420476.

Nendel, C., Melzer, D., Thorburn, P.J., 2019. The nitrogen nutrition potential of arable soils. Sci. Rep. 9, 5851. https://doi.org/10.1038/s41598-019-42274-y.

Norris, C.E., Congreves, K.A., 2018. Alternative management practices improve soil health indices in intensive vegetable cropping systems: a review. Front. Environ. Sci. https://doi.org/10.3389/fenvs.2018.00050. 12 June 2018.

Norton, J.M., Schimel, J.P., 2012. Nitrogen mineralization-immobilization turnover. In: Huang, P.M., Li, Y.C., Sumner, M.E. (Eds.), Handbook of Soil Sciences: Properties and Processes, 2nd edn. CRC Press, Boca Raton, pp. 27.8–27.18.

Ospina, C.A., Lammerts van Bueren, E.T., Allefs, J.J.H.M., Engel, B., van der Putten, P.E.L., van der Linden, C.G., Struik, P.C., 2014. Diversity of crop development traits and nitrogen use efficiency among potato cultivars grown under contrasting nitrogen regimes. Euphytica 199 (1–2), 13–29. https://doi.org/10.1007/s10681-014-1203-4.

Padilla, F.M., Gallardo, M., Peña-Fleitas, M.T., de Souza, R., Thompson, R.B., 2018. Proximal optical sensors for nitrogen management of vegetable crops: a review. Sensors 18 (2083), 23 pp. https://doi.org/10.3390/s18072083.

Padilla, F.M., Farneselli, M., Gianquinto, G., Tei, F., Thompson, R.B., 2020. Monitoring nitrogen status of vegetable crops and soils for optimal nitrogen management. Agr. Water Manage In this issue.

Pasda, G., Hähndel, R., Zerulla, W., 2001. Effect of fertilizers with the new nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) on yield and quality of agricultural and horticultural crops. Biol. Fertil. Soils 34, 85–97. https://doi.org/10.1007/s003740100381.

Peña-Fleitas, M.T., Gallardo, M., Thompson, R.B., Farneselli, M., Padilla, F.M., 2015. Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques. Ann. Appl. Biol. 167, 387–405. https://doi.org/10.1111/aab.12235.

Qiao, C., Liu, L., Hu, S., Compton, J.A., Greaver, T., Li, Q., 2015. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Global Change Biol. 21, 1249–1257. https://doi.org/10.1111/gcb.12802.

Quemada, M., Baranski, M., Nobel-de Lange, M.N.J., Vallejo, A., Cooper, J.M., 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agr. Ecosyst. Environ. 174, 1–10. https://doi.org/10.1016/j.agee.2013.04.018.

Rakotovololona, L., Beaudoin, N., Ronceaux, A., Venet, E., Mary, B., 2019. Driving factors of nitrate leaching in arable organic cropping systems in Northern France. Agr. Ecosyst. Environ. 272, 38–51. https://doi.org/10.1016/j.agee.2018.10.005.

Ramanantenasoa, M.M.J., Génermont, S., Gilliot, J.-M., Bedos, C., Makowski, D., 2019. Meta-modeling methods for estimating ammonia volatilization from nitrogen fertilizer and manure applications. J. Environ. Manage. 236, 195–205. https://doi.org/

10.1016/j.jenvman.2019.01.066.

Ramirez-Garcia, J., Carrillo, J.M., Ruiz, M., Alonso-Ayuso, M., Quemada, M., 2015. Multicriteria decision analysis applied to cover crop species and cultivars selection. Field Crop Res. 175, 106–115. https://doi.org/10.1016/j.fcr.2015.02.008.

Rather, K., Schenk, M.K., Everaarts, A.P., Vethmann, S., 1999. Response of yield and quality of cauliflower varieties (Brassica oleracea var. botrytis) to nitrogen supply. J. Hort. Sci. Biotech. 74, 658–664. https://doi.org/10.1080/14620316.1999.11511169.

Reetz Jr, H.F., Heffer, P., Bruulsema, T.W., 2015. Chapter 4: 4R nutrient stewardship: a global framework for sustainable fertilizer management. In: Drechseler, P., Heffer, P., Magen, H., Mikkelsen, R., Wichelns, D. (Eds.), Managing Water and Fertilizer for Sustainable Agricultural Intensification. International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI), Paris, France, pp. 65–86 January 2015.

Riley, H., Vågen, I.M., 2003. Critical N-concentrations in broccoli and cauliflower, evaluated in field trials with varying levels and timing of N fertilizer. Acta Hortic. 627, 241–249. https://doi.org/10.17660/ActaHortic.2003.627.31.

Ropokis, A., Ntatsi, G., Kittas, C., Katsoulas, N., Savvas, D., 2019. Effects of temperature and grafting on yield, nutrient uptake, and water use efficiency of a hydroponic sweet pepper crop. Agronomy 9, 110. https://doi.org/10.3390/agronomy9020110.

Rouphael, Y., Kyriacou, M.C., Colla, G., 2018. Vegetable grafting: a toolbox for securing yield stability under multiple stress conditions. Front. Plant Sci. 8, 2255. https://doi.org/10.3389/fpls.2017.02255.

Ruser, R., Schulz, R., 2015. The effect of nitrification inhibitors on the nitrous oxide (N_2O) release from agricultural soils—a review. J. Plant Nutr. Soil Sci. 178, 171–188. https://doi.org/10.1002/jpln.201400251.

Sambo, P., Nicoletto, C., 2017. Fertilizers: criteria of choice for vegetable crops. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer International Publishing AG, Cham, Switzerland, pp. 85–113. https://doi.org/10.1007/978-3-319-53626-2_4.

Sanchez, J.E., Harwood, R.R., Willson, T.C., Kizilkaya, K., Smeenk, J., Parker, E., Paul, E.A., Knezek, B.D., Robertson, G.P., 2004. Managing soil carbon and nitrogen for productivity and environmental quality. Agron. J. 96, 769–775. https://doi.org/10.2134/agronj2004.0769.

Schenk, M.K., 2006. Nutrient efficiency of vegetable crops. Acta Hortic. 700, 21–33. https://doi.org/10.17660/ActaHortic.2006.700.1.

Scholberg, J.M.S., Dogliotti, S., Leoni, C., Cherr, C.M., Zotarelli, L., Rossing, W.A.H., 2010. Cover crops for sustainable agrosystems in the americas. In: Lichtfouse, E. (Ed.), Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming. Springer, Dordrecht, pp. 23–58.

Schulte auf'm Erley, G., Dewi, E.R., Nikus, O., Horst, W.J., 2010. Genotypic differences in nitrogen efficiency of white cabbage (*Brassica oleracea* L.). Plant Soil 328, 313–325. https://doi.org/10.1007/s11104-009-0111-1.

Scialabba, N.E.-H., Müller-Lindenlauf, M., 2010. Organic agriculture and climate change. Renew. Agr. Food Syst. 25, 158–169. https://doi.org/10.1017/S1742170510000116.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232. https://doi.org/10.1038/nature11069.

Shlevin, E., Zilberman, A., Ben-Asher, J., 2018. Theoretical determination of a critical nitrogen dilution curve based on the carrot case study. Agr. Res. 7 (2), 239–244. https://doi.org/10.1007/s40003-018-0303-0.

Simonne, E.H., Hutchinson, C.M., 2005. Controlled-release fertilizers for vegetable production in the era of best management practices: teaching new tricks to an old dog. HortTechnology 15 (1), 36–46. https://doi.org/10.21273/HORTTECH.15.1.0036.

Simonne, E.H., Gazula, A., Ozores-Hampton, M., DeValerio, J., Hochmuth, R.C., 2017. Localized application of fertilizers in vegetable crop production. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer International Publishing AG, Cham, Switzerland, pp. 149–181. https://doi.org/10.1007/978-3-319-53626-2_6.

Snyder, C.S., 2017. Enhanced nitrogen fertiliser technologies support the '4R' concept to optimise crop production and minimise environmental losses. Soil Res. 55, 463–472. https://doi.org/10.1071/SR16335.

Snyder, C.S., Bruulsema, T.W., Jense, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agr. Ecosyst. Environ. 133, 247–266. https://doi.org/10.1016/j.agee.2009.04.021.

Sørensen, J.N., Grevsen, K., 2015. Strategies for cut-and-carry green manure production. Acta Hortic. 1137. https://doi.org/10.17660/ActaHortic.2016.1137.6.

Stefanelli, D., Goodwin, I., Jones, R., 2010. Minimal nitrogen and water use in horticulture: effects on quality and content of selected nutrients. Food Res. Int. 43, 1833–1843. https://doi.org/10.1016/j.foodres.2010.04.022.

Stone, D.A., 1998. The effect of "starter" fertilizer injection on the growth and yield of drilled vegetable crops in relation to soil nutrient status. J. Hort. Sci. Biotech. 73, 441–452. https://doi.org/10.1080/14620316.1998.11510997.

Sutton, M.A., Grinsven, H., 2011. Summary for policy makers. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge Univerity Press, Cambridge, UK, pp. 2–18.

Tei, F., Benincasa, P., Guiducci, M., 1999. Nitrogen fertilisation on lettuce, processing tomato and sweet pepper: yield, nitrogen uptake and the risk of nitrate leaching. Acta Hortic. 506, 61–67. https://doi.org/10.17660/ActaHortic.1999.506.6.

Tei, F., Benincasa, P., Guiducci, M., 2002. Critical nitrogen concentration in processing tomato. Eur. J. Agron. 18, 45–55. https://doi.org/10.1016/S1161-0301(02)00096-5.

Tei, F., Benincasa, P., Guiducci, M., 2003. Critical nitrogen concentration in lettuce. Acta Hortic. 627, 187–194. https://doi.org/10.17660/ActaHortic.2003.627.24.

Tei, F., Nicola, S., Benincasa, P., 2017. The role of research for a sustainable fertilization management in vegetables: future trends and goals. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer International Publishing AG, Cham, Switzerland, pp. 1–9. https://doi.org/10.1007/978-3-319-53626-2_1.

Tempesta, M., Gianquinto, G., Hauser, M., Tagliavini, M., 2019. Optimization of nitrogen nutrition of cauliflower intercropped with clover and in rotation with lettuce. Sci. Hortic. 246, 734–740. https://doi.org/10.1016/j.scienta.2018.11.020.

Thompson, R.B., Martínez-Gaitán, C., Giménez, C., Gallardo, M., Fernández, M.D., 2007. Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey. Agr. Water Manage. 89 (3), 261–274. https://doi.org/10.1016/j.agwat.2007.01.013.

Thompson, R.B., Tremblay, N., Fink, M., Gallardo, M., Padilla, F.M., 2017. Tools and strategies for sustainable nitrogen fertilisation of vegetable crops. In: Tei, F., Nicola, S., Benincasa, P. (Eds.), Advances in Research on Fertilization Management of Vegetable Crops. Springer International Publishing AG, Cham, Switzerland, pp. 11–63. https://doi.org/10.1007/978-3-319-53626-2_2.

Thompson, R.B., Voogt, W., Incrocci, L., Fink, M., De Neve, S., 2018. Strategies for optimal fertiliser management of vegetable crops in Europe. Acta Hortic. 1192, 129–140. https://doi.org/10.17660/ActaHortic.2018.1192.15.

Thompson, R.B., Incrocci, L., van Ruijven, J., Massa, D., 2020. Reducing contamination of water bodies from European vegetable production systems. Agr. Water Manage In this issue.

Thorup-Kristensen, K., 1993. The effect of nitrogen catch crops on the nitrogen nutrition of a succeeding crop. Effects through mineralization and pre-emptive competition. Acta Agr. Scand. 43, 74–81. https://doi.org/10.1080/09064719309411222.

Thorup-Kristensen, K., 2001. Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant Soil 230, 185–195. https://doi.org/10.1023/A:1010306425468.

Thorup-Kristensen, K., 2006. Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations. Plant Soil 288, 233–248. https://doi.org/10.1007/s11104-006-9110-7.

Thorup-Kristensen, K., Dresbøll, D.B., 2010. Incorporation time of nitrogen catch crops influences the N effect for the succeeding crop. Soil Use Manage. 26 (1), 27–35. https://doi.org/10.1111/j.1475-2743.2009.00255.x.

Thorup-Kristensen, K., 1999. An organic vegetable crop rotation aimed at self-sufficiency in nitrogen. In: Olesen, J.E., Eltun, R., Goulding, M.J., Jensen, E.S., Köpke, U. (Eds.), Designing and Testing Crop Rotations for Organic Farming. DARCOF (1), DARCOF report,1, pp. 133–140.

Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302. https://doi.org/10.1016/s0065-2113(02)79005-79006.

Thorup-Kristensen, K., Dresbøll, D.B., Kristensen, H.L., 2012. Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops. Eur. J. Agron. 37, 66–82. https://doi.org/10.1016/j.eja.2011.11.004.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agr. Ecosyst. Environ. 112 (1), 58–72. https://doi.org/10.1016/j.agee.2005.07.003.

Tosti, G., Benincasa, P., Farneselli, M., Tei, F., Guiducci, M., 2014. Barley-hairy vetch mixture as cover crop for green manuring and the mitigation of N leaching risk. Eur. J. Agron. 54, 34–39. https://doi.org/10.1016/j.eja.2013.11.012.

Tosti, G., Benincasa, P., Farneselli, M., Guiducci, M., Onofri, A., Tei, F., 2019. Processing Tomato–Durum wheat rotation under integrated, organic and mulch-based No-tillage organic systems: yield, N balance and N loss. Agronomy 9, 718. https://doi.org/10.3390/agronomy9110718.

Tremblay, N., Scharpf, H.-C., Weier, U., Laurence, H., Owen, J., 2001. Nitrogen Management in Field Vegetables: A Guide to Efficient Fertilization. Horticultural Research and Development Centre, Canada. Available at: http://publications.gc.ca/collections/Collection/A42-92-2001E.pdf (accessed 8 November 2019).

Valkama, E., Lemola, R., Känkänen, H., Turtola, E., 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agr. Ecosyst. Environ. 203, 93–101. https://doi.org/10.1016/j.agee.2015.01.023.

Van Eerd, L.L., Turnbull, J.J.D., Bakker, C.J., Vyn, R.J., McKeowan, A.W., Westerveld, S.M., 2018. Comparing soluble to controlled-release nitrogen fertilizers: storage cabbage yield, profit margins, and N use efficiency. Can. J. Plant Sci. 98, 815–829. https://doi.org/10.1007/s10705-018-9914-x.

Vermeulen, G.D., Mosquera, J., 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. Soil Till. Res. 102, 126–134. https://doi.org/10.1016/j.still.2008.08.008.

Vet, R., Artz, R.S., Carou, S., et al., 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. Atmos. Environ. 93, 3–100. https://doi.org/10.1016/j.atmosenv.2013.10.060.

Vogeler, I., Cichota, R., Thomsen, I.K., Bruun, S., Stoumann, Jensen L., Pullens, J.W.M., 2019. Estimating nitrogen release from *Brassica* catch crop residues - comparison of different approaches within the APSIM model. Soil Till. Res. 195, 104358. https://doi.org/10.1016/j.still.2019.104358.

Xie, Y., Kristensen, H.L., 2016. Overwintering grass-clover as intercrop and moderately reduced nitrogen fertilization maintain yield and reduce the risk of nitrate leaching in an organic cauliflower (*Brassica oleracea* L. var. *botrytis*) agroecosystem. Sci. Hortic. 206, 71–79. https://doi.org/10.1016/j.scienta.2016.04.034.

Xie, Y., Kristensen, H.L., 2017. Intercropping leek (*Allium porrum* L.) with dyer's woad (*Isatis tinctoria* L.) increases rooted zone and agro-ecosystem retention of nitrogen.

Eur. J. Agron. 82, 21–32. https://doi.org/10.1016/j.eja.2016.09.017.

Xie, Y., Tittarelli, F., von Fragstein, P., Bavec, M., Canali, S., Kristensen, H.L., 2017. Can living mulches in intercropping systems reduce the potential nitrate leaching? Studies of organic cauliflower (*Brassica oleracea* L. var. *botrytis*) and leek (*Allium porrum* L.) production across European conditions. Renew. Agr. Food Syst. 32, 224–239. https://doi.org/10.1017/s1742170516000211.

Xie, Y., Sorensen, J.N., Petersen, K.K., Kristensen, H.L., 2018. Stepwise incorporation of white clover (*Trifolium repens L.)* as fertiliser increases nitrogen fixation and improves nitrogen retention when intercropped with leek (*Allium porrum* L.). Plant Soil 422, 541–554. https://doi.org/10.1007/s11104-017-3471-y.