Chapter 6
Decreasing Nitrate Leaching in Vegetable Crops with Better N Management

F. Agostini, F. Tei, M. Silgram, M. Farneselli, P. Benincasa, and M.F. Aller

Abstract The relatively low cost of fertiliser and the increasing demand and competition for cheap food have encouraged the over-fertilisation of field vegetables over the past few decades. However, more recent scientific and public concern over eutrophication of water and the accumulation of nitrates in vegetables for human consumption requires a more effective use of nitrogen fertilisers in a more sustainable manner, which minimises the potential risk of negative effects on the environment and human health. In this review, we present the current state of the art in knowledge of N dynamic in vegetable crops and the latest advances in nutrient management, which could be used to mitigate nitrate losses from vegetables fields to the wider environment. Findings are based on published data and personal communications with researchers and consultants across Europe. Areas of research where further work is required are identified and described. A conclusive chapter reports on the economic and environmental impact of technology transfer of improved nitrogen management in three south European states and in the Netherlands.

Keywords Vegetable crops • nitrate leaching • nutrient management • soil and water pollution • Decision Support System • Integrated Crop Management • soil N • chlorophyll meter • fertigation • slow release fertiliser • nitrification inhibitor • intercropping • mulch • cover crop

---

F. Agostini (✉)
Department of Energy and Technology, SLU, Uppsala Ulls Väg 30A 756 51, Sweden
e-mail: Francesco.agostini@et.slu.se

F. Tei, M. Farneselli, and P. Benincasa
Department of Agricultural and Environmental Sciences, University of Perugia, Borgo XX giugno 74, 06121 Perugia, Italy

M. Silgram and M.F. Aller
ADAS UK Ltd., Wergs Road Wolverhampton, WV6 8TQ, UK

E. Lichtfouse (ed.), *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming,* Sustainable Agriculture Reviews 4,
DOI 10.1007/978-90-481-8741-6_6,

6.1 Introduction

Nitrogen fertilisation is a conventional practice in the management of field vegetables to ensure a good yield and quality of the marketable product (Bianco 1990). However, the amount of nitrogen fertiliser applied may often exceed the actual crop demand, taking account of other sources of plant-available nitrogen such as the soil, decomposing residues, and applied manures and slurries. This occurs because fertiliser costs are relatively modest compared to the price of the crop product, and the negative environmental effects of supra-optimal application rates of nitrogen fertiliser are often not immediately obvious. In recent years, there has been scientific and public concern about the relationship between land management practices and the enrichment of freshwaters and groundwater (Greenwood 1990; Meinardi et al. 1995; European Commission 1998, 1999; Neeteson and Carton 2001; Tilman et al. 2001; Ramos et al. 2002) and nitrate accumulation in edible portions of vegetables (Maynard et al. 1976).

In order to protect the environment and human health (Cantor 1997; Barret et al. 1998), several organisations have set NO_3–N concentration limits for drinkable water: the World Health Organization and the European Union impose limits of 11.3 mg NO_3–N L^{-1}, which is equivalent to 50 mg NO_3 L^{-1} (European Commission 1998), while the US Environmental Protection Agency (1989) and Health Canada (Health Canada 1996) set the limit at 10 mg NO_3–N L^{-1} (equivalent to 43 mg NO_3 L^{-1}). Moreover, the European Commission has promulgated several directives (CEC 1991; European Commission 1998, 1999) concerning the protection of waters against pollution caused by nitrates from agricultural sources, in order to respect the above-mentioned limits and minimise the risk of excess nutrient loss to rivers promoting eutrophic status in freshwater and coastal environments. As an overall consequence, ecologically sound fertilisation strategies for field vegetable production (Greenwood 1990; Greenwood and Neeteson 1992; Hochmuth 1992; Neeteson 1995; Rahn 2002; Hartz 2003; Remie et al. 2003; Bertschinger 2004) can allow a significant reduction in both environmental and health risks associated with vegetable production.

The nitrogen (N) fertiliser consumption in the world in 2005–2006 was estimated about 98 Mt, of which 15% was used to support the growing of fruit and vegetables (Heffer 2008). In the EU-15 states, N fertiliser consumption in fruit and vegetables was about 720,000 t (Heffer 2008), and in field vegetables, it was only nearly 0.3 million tonnes (FAO 2000). Typically, the potential nitrate-leaching losses from land growing vegetable crops exceed that from arable cropped soils (Goulding 2000), as a result of the combination of the short crop growth cycle, relatively high N fertiliser requirements, the high water requirements by vegetable crops, which are often partly provided via irrigation (Greenwood et al. 1989), and the nitrogenous nature of vegetable crop residues (e.g. peas), which can mineralise rapidly and lead to increased nitrate leaching in the months following harvest (e.g. Silgram 2005). In addition, lighter sandy textured soils, which are more prone to leaching losses, represent often some of the main production areas of vegetable crops in several European countries.

Land management practices can affect the N fate and the availability of potentially leachable NO_3–N (Li et al. 2007), since there is a direct relationship between large NO_3–N losses and inefficient fertilisation and irrigation management. The nitrate not captured by plant roots can move in drainage waters promoted by rainfall and/or irrigation because nitrate has a weak negative charge and is not strongly adsorbed to soil particles. The downward movement of NO_3 through the soil profile occurs when significant irrigation water is applied, or under European conditions primarily in autumn and spring when precipitation exceeds evapotranspiration and the soil is at field capacity (Belanger et al. 2003; Kraft and Stites 2003).

In most agricultural areas, drainage represents the main cause of off-site transport of NO_3–N (Randall and Goss 2001). In some regions, irrigation or intense precipitation events on sloping landscapes can represent the main mechanism of NO_3–N loss in surface run-off to water bodies, especially for soils with low permeability (Bjorneberg et al. 2002). In particular, in Mediterranean countries, the relatively dry growing season during spring and summer creates a relatively low risk of drainage (and hence nitrate leaching) from vegetables. However, the relatively high amount of mineral nitrogen left in soil and/or residues after the harvest of some crops, such as sweet peppers, tomatoes and lettuce, coupled with intense rainfall in the autumn–winter period, which can far exceed the soil infiltration rate, can present a high risk of nitrate losses to groundwaters (Tei et al. 1999).

Moreover, with excessive or poorly timed irrigation, readily available N sources such as ammonium nitrate will be readily leached and present a potential hazard for the environment as the ammonium is rapidly nitrified, and the drainage and/or run-off caused by the intense irrigation application will promote NO_3–N loss. Some ammonium and organic-N compounds do also leach from agricultural soils, but in intensively managed systems, their contribution to total loss is typically relatively small (except where livestock manures or slurries have been applied).

Leaching losses can be extremely variable depending on the intensity and distribution of rainfall, on the amount and location of soil and fertiliser N in the profile, on soil physical properties that influence the efficiency with which N is displaced in the percolating water and on plant root distribution. In general, there is a positive relationship between fertiliser N applied and nitrate-leaching losses, given sufficient drainage volume (Fig. 6.1). There is also strong evidence that encouraging farmers to reduce fertiliser N inputs can reduce losses of nitrate, leaving the soil root zone – although due to the transit time of percolating water, it can take many years before this impact may be detected in reduced nitrate concentrations in groundwaters (e.g. Silgram et al. 2004).

At the same time, the irrigation management also influences the amount of nitrate leached and taken up by the crops (Karaman et al. 2005) because of the effects on the width and depth of root distribution in soils. Indeed, leaching of nitrate–N from the root zone depends on the drainage of water out of this zone (Knox and Moody 1991, Zhang et al. 2005; Li et al. 2007) and water-use efficiency (Shaffer and Delgado 2002; Delgado et al. 2006).

Not only do nitrogen losses from agriculture relate to nitrate leaching but they also include gaseous losses as nitrous oxide and ammonia, which are both pollutants

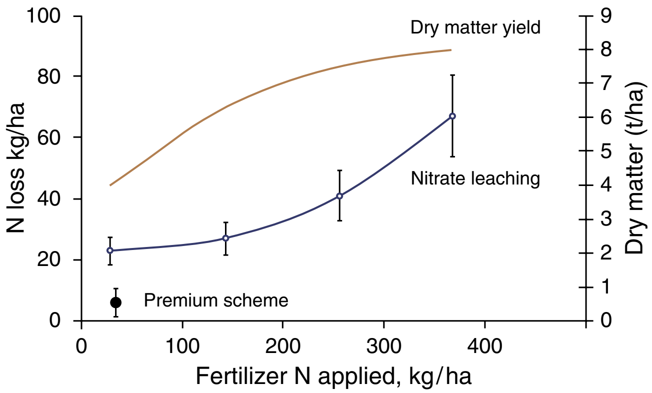

Fig. 6.1 Example of N losses by leaching and yield as dry matter versus amount of applied N fertilised to grass (Modified from Lord et al. 1999)

linked to climate change and acidification (Neeteson and Carton 2001). Therefore, a holistic approach that broadens concerns over nitrate leaching to include the management of nitrogen in the soil–plant system (accounting for N in crop residues and biomass) must also take into consideration the extent of the impact of gaseous losses related to agricultural practices. If practices lead to increased gaseous N emissions by buffering against nitrate losses from fields to water bodies, the environmental pollution risk has only been shifted from one point of impact or 'receptor' (water) to another (air). Recent studies on fertiliser management have highlighted the danger of this so-called pollution-swapping between nitrate leaching and ammonia loss in fruit production as a function of the type of nitrogen fertilisers and the application schedule (Cantarella et al. 2003, Stevens and Quinton 2009).

So in order to achieve more sustainable nitrogen management, the research activity should be focused on determining the most effective N-fertilisation systems by investigating the whole dynamic of N in the soil, plant, water and atmosphere.

The aim of this review is to present some of the current advances in nutrient management applied to vegetable production, to highlight the effective application of such methods within the EU as tools to reduce nitrate leaching and to identify areas of research and technology transfer where further work is required.

6.2 Fertiliser Management in Vegetable Crops

Efficient fertiliser management requires adequate tools such as an integrated approach to plant nutrition, while further work is needed to optimise the use of high-tech irrigation–fertilization systems (Battilani et al. 2003). The main consideration, which must be kept in mind in planning measures to limit nitrate leaching, is that only a small proportion of the nitrogen applied to land is actually utilised by plants, in the cases about 40–45% and an even smaller proportion is contained in the commercially harvested material (Davies 2000). Sound N-fertiliser management, which is necessary to avoid excessive nitrate concentrations both in vegetables and in drainage (and hence drinking) water, requires the farmer to judge the balance between processes that contribute nitrogen to the soil for crop uptake and growth (inputs) and processes that remove mineral nitrogen from the plant root zone (outputs). Since nitrogen in the soil is in a continuous state of flux between organic and mineral pools, these pools, fluxes and losses need to be considered across the whole crop-management cycle. Once all the elements in the N balance have been assessed, the optimum N rate can be evaluated as a result of the difference between inputs and outputs that occur for a specific crop, location, soil and climate situation. Proper N management also requires careful management of other technical aspects, such as the timing and method of application and the choice of the fertiliser to apply (slow or fast release).

However, studies carried out on the impact of good practices in the USA suggest that only a minority of growers may follow fertiliser-management programmes, and empirical criteria are still often preferred by farmers over objective-monitoring methods (Hartz 2003). It is well known that the 'general' assessment of nitrogen in the soil–water–plant–air system is not an issue, but the extreme variability due to local conditions makes its practical management a demanding challenge in agriculture (Owen et al. 2003). Some countries, i.e. UK farming press and magazines (http://www.fwi.co.uk; http://www.farmersguardian.com) produced recommendations to the industry adjusted every spring based on that specific winter's data on soil mineral nitrogen (SMN) levels and over-winter drainage volumes.

6.2.1 N Balance

Burns (2006) defined that the amount of N taken up by a crop (U_N) is equal to the sum of that recovered from the fertiliser (U_F) and from the soil (U_S) as in the following equation:

$$U_N = U_F + U_S + f_F \bullet N_F + f_S \bullet N_S \tag{6.1}$$

where N_F and N_S are the amounts of N available to the crop from fertiliser and soil, respectively and f_F and f_S are the corresponding average recovery factors for the two types of N supply. Since the amount of N from natural source is not often sufficient to meet crops needs, the remainder must be applied as fertiliser. Burns (2006) also defined the optimum rate of N fertiliser as the minimum amount needed to achieve the required response. At the plant's optimum N-fertiliser rate (N_{Fopt}), U_N becomes equivalent to the total N demand of the crop (T_N), so

$$T_N = f_F \cdot N_{Fopt} + f_S \cdot N_S \tag{6.2}$$

where N_{Fopt} is also referred to as the N-fertiliser requirement of the crop.

A detailed N balance should take into account many inputs (mineral soil N available at planting, N from the mineralisation of crop residues and indigenous soil organic matter, irrigation and precipitation, and fertilisation) and outputs (N plant uptake, N immobilisation, denitrification, volatilisation and leaching). Since N is vulnerable to a complex variety of processes brought about by the mediating effects of weather on soil microbes, changing physical and chemical soil properties, cultural practices and the effect of preceding crops, the optimum N-fertiliser rate often varies quite considerably from site to site and from year to year (Goodlass et al. 1997). As a consequence, the reliability of N-fertiliser recommendations depends on the accuracy in the estimation of the inputs and outputs of the N balance. In some situations, this has been assisted by sampling soil cores to 90 cm depth and analysing for soil mineral nitrogen levels within the soil in autumn or spring to guide cost-effective fertiliser recommendation strategies (Burns 2006).

However, the evaluation of the optimal N rate is peculiar in vegetables because not only the yield but also other aspects such as fruit size and quality must be considered in the crop nutrient requirement concept (Olson and Simonne 2006). In fact, the concept of economic optimum yields is particularly important for vegetables because a certain amount of nutrients might produce a moderate amount of biomass, but produce negligible marketable product because of small fruit size. Farmers really need to consider the economic optimum fertiliser rate, which will be lower than the plants' optimum rate and depends on the relationship between fertiliser prices and yield price. Burns (2006) pointed out that the commonest methods to measure N requirements are based on maximising marketable or economic yields, but the former has the advantage to be independent of the price of the produce, which can vary. Furthermore, as the value of most vegetable crops far outweighs the cost of fertiliser, there is usually little difference between the two optima.

For all these reasons, in order to improve N management in a sustainable agricultural scenario, an accurate analysis of all the parameters of N balance must be done.

6.2.1.1 Total Crop N Demand

Total N demand is defined as the minimum amount of N a crop must accumulate in its tissues for optimum growth. Total crop N demand depends mainly on its total biomass since the relationship between the critical N concentration, i.e. the minimum N concentration required for maximum plant growth, %Nc (as defined by Greenwood et al. 1990) and the above-ground plant dry weight (DW, t ha^{-1}) is similar within C3 species[1] (Greenwood et al. 1990; Lemaire and Gastal 1997). Nevertheless, every species has its own N-dilution curve according to its own histological, morphological and ecophysiological characteristics, so species-specific critical N-dilution curves have been determined, for example, for potato (Greenwood et al. 1990), cabbage (Riley and Guttormsen 1999), processing tomato (Tei et al. 2002) and lettuce

[1](%Nc = 4.8 $DW^{-0.34}$ as an average relationship for C3 species) and C4 (%Nc = 3.6 $DW^{-0.34}$)

(Tei et al. 2003). Information on total crop N demand are often summarised and generalised in look-up tables based on past reliable agronomic experiments, for practical use of the farmers and technicians (see e.g. MAFF 2000). Models are also used in some cases, and European Union (EU) research efforts have included attempts to develop and test predictive models of fertiliser N requirements in European vegetable systems (Battilani et al. 2003; Karaman et al. 2005).

6.2.1.2 N Supply from Soil

The N supply from soil is the net result of inputs such as mineral soil N available at planting N_{min}; N mineralized from soil organic matter N_m; N released from residues of previous crop N_R, and outputs, such as mineral N losses due to immobilisation N_I; denitrification N_D; volatilisation N_V; and leaching N_L.

Mineral soil N available at planting depends mainly on the previous crop and its management, cultural practices such as applied N-fertiliser rate and irrigation, prevailing weather conditions (rainfall, temperature) and can be easily measured by laboratory analysis or quick field tests by using ion-specific electrodes (Sibley 2008). For example, in field research carried out in Central Italy (Tei et al. 1999) at optimum fertiliser rates, the mineral N remaining in the soil after harvest of lettuce, processing tomato and sweet pepper was 90–101, 73–89 and 223 kg/ha, respectively.

Soil organic matter mineralisation is a microbially mediated process and in most cultivated soils ranges from around 0.6 to 0.9 kg N ha^{-1} day^{-1} during the growing season. The amount of N from mineralisation process is usually estimated by look-up tables (CRPV-RER 2007) or empirical function (Rühlmann 1999), both based on soil organic matter content and soil physical characteristics (i.e. soil texture). Effects such as cultivation method and timing can have a mediating effect on the mineralisation process as microbes are brought into contact with fresh, previously unavailable substrate (Silgram and Shepherd 1999).

Crop residues and green manures represent the highest potential source of N for vegetable cropping system with the exception of chemical fertilizer (Rahn et al. 1992, 1993; Müller and Thorup-Kristensen 2001; Thorup-Kristensen 1994; Thorup-Kristensen and Nielsen 1998, 2003). For instance, brassica residues can contain up to 250 kg N ha^{-1}, which is more than equivalent to the total N demand of many vegetable crops (Burns et al. 1997), sweet pepper up to 130 kg ha^{-1} and processing tomato about 100 kg ha^{-1} (Tei et al. 1999, 2002). Guerette et al. (2000) reported that vegetables crops leave behind more mineral nitrogen for the next crop than cereal crops. A wide range of residues quality factors have been found to be correlated with N release (Harrison and Silgram 1998); these include the C/N ratio (Giller and Cadisch 1997; Bending et al. 1998; Bending and Turner 1999), N content (Janzen and Kucey 1988; Vigil and Kissel 1991), lignin content (Frankenberger and Abdelmagid 1985; De Neve et al. 1994; Giller and Cadisch 1997) and lignin-to-N ratio (Vigil and Kissel 1991). The C/N ratio is easy to calculate and is a highly reliable indicator of the nitrogen mineralization from organic compounds. Tremblay et al. (2003) summarised mean values of potential N released as affected by the residues from the previous crop in order to develop a more practical approach for N-fertiliser management in vegetable systems. However, although the mineralisation of organic nitrogen into mineral N forms available to plants or for leaching has been widely studied, it is a complicated process and results are difficult to predict with confidence.

Recent land use, *cultivations and fertilisation history* should be taken into account when evaluating the risks of nitrate leaching through their effect on mineralisation, nitrification and hence on the magnitude of the pool of N available for plant uptake or leaching (Neeteson and Carton 2001). For example, long-term monitoring of a field receiving pig slurry applications indicated an enhanced nitrate leaching over 10 years after the applications had ceased (Mantovani et al. 2005). This is an indication that a large, highly labile pool of organic and mineral N had been established over many years and this should be taken into account by reducing future fertiliser N recommendations. In a similar manner, the ploughing up of rotational or long-term grass for vegetable production can release large quantities of mineral N as soil micro-organisms are brought into contact with fresh, previously unavailable substrate (Silgram and Shepherd 1999), and this effect can last for several years after the original cultivation event took place (Silgram 2005). Despite attempts to adjust fertiliser applications to match crop requirements, some rotation systems are at inherently greater risk of nitrate leaching than others due to the release of nitrate from the mineralisation of crop residues which can be difficult to predict and may not be synchronised with the N demands of the subsequent crop. For example, late-harvested crops such as sugar beet leaf tops may mineralise rapidly and may either leach nitrate that same winter when the land is bare, or alternatively may contribute to leaching risk the following winter (termed a 'grandfather effect', Lord and Mitchell 1998). Neeteson and Carton (2001) reported that residual soil nitrogen after the application of the recommended amount of nitrogen is relatively low in Brussels sprouts, white cabbage and onions (20–75 kg N ha^{-1}), but for spinach, leeks and cauliflower the residual (i.e. post-harvest) soil nitrogen can reach values as high as 200 kg N ha^{-1}. In contrast, the incorporation of carbon-rich residues (e.g. wheat straw) has well-known abatement effects against nitrate leaching by temporarily stimulating net N immobilisation (N_I). However these effects are transient, can be subtle (Silgram and Chambers 2002; Agostini and Scholefield 2005) and may be antagonistic (Garnier et al. 2003). A practical application of the effect has been tested in field vegetables (*Brassica napus*) to control nitrate leaching from plant residues: several biodegradable materials rich in carbon including straw and paper mill by-products were added to the soil or composted with the crop residues before application, and both treatments induced a decrease in nitrogen lost as leached and as nitrous oxide (Rahn et al. 2003).

Denitrification losses (N_D) in arable soils are important only when heavy rainfall occurs after a recent N-fertiliser application, but in that case no more than 15–20 kg N ha^{-1} are denitrified per major rainfall event. In practice, both denitrification and volatilisation losses are usually deemed negligible in an N balance for a vegetable crop and so they can be omitted as occurs in calculations carried out by the Organisation for Economic Co-operation and Development or OECD.

Leaching can occur at any time during the growing season in relation to the pattern and intensity of rainfall and the frequency, intensity and method of irrigation applications, the amount and distribution of N within the soil profile, the biochemical and physical soil properties, and the depth and the architecture of roots, i.e. all factors that influence the soil solution movement below the root zone. For example, the amount and chemical characteristics of the clay-sized fraction in the soil will influence the adsorption of ammonium and consequently nitrate availability, creating a potential retardation mechanism for mineral N leaching; however this delay can only be effectively exploited if deep-rooted plants can subsequently recover the N (Suprayago et al. 2002). In general, most of the N leached during the growing season originates from N_S rather than from N_F, because the former tends to be more uniformly distributed to depth, and is more readily displaced from the lower parts of the rooting zone (Burns 1976). While the dynamics of soil N transformation and movement have been comprehensively studied, predicting the net effect of the interplay of immobilization, denitrification, N cycling and leaching processes on the soil–plant system is complex and still deemed problematic (Hartz 2003), especially in a predictive context.

6.2.1.3 N Supply from Irrigation and Rainfall

Nitrogen concentrations in irrigation water can be significant, depending on its source, and particularly in areas with high livestock density. Land also receives wet and dry atmospheric N deposition derived from nitrogen oxides generated by the use of fossil fuels from individual or industrial users (Scudlark et al. 1998; Cape et al. 2004), although the relative importance of industrial inputs varies greatly on a regional and national basis.

6.2.1.4 N Recovery

Greenwood et al. (1989) defined the apparent recovery (REC) of fertilizer N by the crop as

$$\mathrm{REC} = (U_F - U_0)\,/\,N_F \tag{6.3}$$

where N_F = fertiliser-N rate; U_F = N uptake when N_F is applied; U_0 = N uptake when no fertiliser is applied. *REC* corresponds to f_F in equations (6.1) and (6.2).

The same authors showed that in vegetables the relationship between N-fertiliser rates and N uptake decreased linearly according to the following general equation:

$$\mathrm{REC} = \mathrm{REC}_0 - bN_F \tag{6.4}$$

where REC_0 = the fitted value of *REC* with an infinitely small amount of fertiliser N; $(-b)$ = the gradient of *REC* against N_F.

Table 6.1 Typical apparent recoveries from yield expressed as Dry Matter (DM) at optimum N-fertiliser rates for a range of field vegetable crops (D.J. Greenwood, personal communication in Burns 2006)

Crop	Yield (t/ha DM)	Uptake (kg/ha)	Percent of Recovery	Response value
Carrots	10.7	193	49	19
Leeks	13.7	268	35	108
Lettuce	2.0	53	7	68
Onion (bulb)	5.1	120	28	214
Radish	1.0	35	14	13
Red beet	11.3	298	34	162
Spinach	1.7	87	11	190
Summer cabbage	7.0	211	85	210
Swede	8.8	356	39	28
Turnip	7.7	309	54	24

The relationship (6.4) is species-specific (Greenwood et al. 1989; Jones and Schwab 1993; Karitonas 2003; Tei et al. 1999, 2000, 2002, Burns 2006) because it depends on the efficiency with which plants extract N from the soil due to differences in root functioning and architecture (Thorup-Kristensen and Sørensen 1999; Thorup-Kristensen and Van der Boogard 1999), but it is also affected by soil conditions, weather conditions, agronomic practices and fertiliser application methods. Although it was a rough estimation of the N-recovery efficiency of a crop, the knowledge of REC value for a species (Table 6.1) is useful for the determination of the optimum N-fertiliser requirements and gives clear information on the proportion of N fertiliser not taken up by the crop and so at risk of leaching (Burns 2006).

The recovery factor for soil N (f_S in equations 6.1 and 6.2) is usually estimated from the uptake of N when no fertiliser is applied (U_0 in equation 6.3), although it is a rough estimation because there is an interaction between N-fertiliser rate, available N from soil and recovery factor for soil N (i.e. in general all crops are more efficient at recovering N when the N-fertiliser rate is relatively small) (Burns 2006).

Instead of the apparent recovery, some authors introduce the concept of a ‘safety margin’ (Tremblay et al. 2003) that is an amount of additional nitrogen to be present in the soil to safeguard the crop from nitrogen shortages that could occur if only the amount of nitrogen required for uptake were present in the soil. In fact below a critical concentration of soil nitrogen, represented by the safety margin (Table 6.2), a plant’s efficiency at extracting soil nitrogen is diminished and so the safety margin allows the plant to extract its full quotient of nitrogen from the soil. Crops that have small, shallow roots with few root hairs (leeks and onions) are inefficient at extracting nitrogen, so the safety margin provided must be relatively large. Conversely, plants with long, deep, extensive root systems are more likely to extract soil nitrogen in its different form, so a smaller safety margin can be assumed.

Table 6.2 Mineral nitrogen safety margin required up until harvest (Tremblay et al. 2003)

Mineral nitrogen safety margin required up until harvest (kg/ha)		
<30	30–60	60–90
Carrots (planted late)	Broccoli (harvested in fall)	Cauliflower
Brussels sprouts	Beans	Broccoli (harvested in summer)
Cabbage (planted late)	Chinese cabbage	Leeks
	Iceberg lettuce	Spinach
	Endive	
	Curly kale	
	Kohlrabi	
	Cabbage (planted early)	
	Garden lettuce	
	Carrots (planted early)	
	Radicchio	
	Radishes	
	Beets	
	Celery	

6.2.1.5 Perspectives

Nutrient budgets are being used increasingly by farmers and policy makers at farm and country scales either to increase the understanding of nutrient cycling, as performance indicators and awareness raisers for improved nutrient management and environmental policy, or as regulating policy instruments to enforce a certain nutrient management policy in practice (De Walle and Sevenster 1998).

However, some uncertainties are associated with the budgeting approach due to wrong combination of N type, N source and N-application frequency, which should be taken into consideration for proper uses of the N balance (Oenema et al. 2003). Tests on irrigated crops in high-intensity agricultural regions between the French Alps and the Rhone valley were carried out for 3 years and showed how more than 30% of the applied nitrogen was lost due to irrational timing and unnecessarily high dosages (Normand et al. 1997). Further work is needed to educate farm managers to better exploit the pool of mineralised nitrogen already present in the soil, and consider nitrate leaching losses as ‘lost fertiliser’ (= money) in the context of farm profitability.

Given the limited efficiency of fertiliser use by crops, and the associated residual N available for leaching after harvest, a further consideration is that some authors of N cycle studies comment that they cannot realistically envisage annual reductions of more than 20 kg N ha^{-1} in open field farming. This implies that regions with low drainage will risk breaking the Nitrates Directive limit on nitrate concentration in surface and groundwaters (e.g. Silgram et al. 2003), and in some areas the only practical solution may be the change from intensively managed and fertilised horticultural systems to a lower input and more extensive land used based on pasture land (Goulding 2000).

So several methods for estimating the different components of the N balance and for relating them to the N requirements have been developed by researchers and used by technicians and farmers although they differ in terms of feasibility, reliability and accuracy.

6.3 Methodologies and Strategies for Improved N Fertilisation

Several methods are available to estimate the N-fertiliser requirements of vegetable crops. The most simple and practical methods, spread among farmers but entirely empirical, are based on *experience and observations*. The *experience method* considers the average N rate applied in the past, which was associated with good yields for a specific local condition, then reduces or increases fertiliser N rates in light of empirical observations such as a large quantity of crop residues, a dry or wet previous winter, later planting, and yields below average, applying traditional 'rules of thumb'. The *observation method* judges the nitrogen requirement of a crop by the use of diverse 'diagnostic tools' (Tremblay et al. 2003) such as plant colour, non-fertilised window (an adjustment of the N fertilisation by comparison of unfertilised plot within the crop used as a soil N availability indicator) or indicator plants (fast-growing plants that have a deep rooting system and a strong ability to extract nutrients from the soil, for example radishes, grown on a small non-fertilised section of the field).

Look-up tables are widely used throughout the world and their complexity varies in relation to the required information, such as previous crop, crop residues, soil texture and depth, average rainfall, to be used for estimating soil N availability at planting and during the crop growth (see e.g. MAFF 2000). Burns (2006) pointed out that 'the advantage of this method is that it is relatively simple and makes use of accumulated wisdom built up from response data for a wide range of crops grown on different soils over many years, but recent evidence suggests that this approach may not be as reliable as others where N_{min} is measured directly (Goodlass et al. 1997)'.

The possibility to keep monitoring measurements of soil and plant N ongoing during the period of crop growth is pivotal to the sustainable management of vegetable crop production, where large spatial variability in soil and plant nutrient status is a well-known issue that tends to lead to over-irrigation and over-fertilisation as farmers 'play safe' (De Tourdonnet et al. 2001), due to the variability in N supply and because economics dictate extra 'contingency' fertiliser is less costly than the (potential risk of) lost yield. However, the recent sharp increase in fertiliser prices could help to limit the risk of supra-optimal fertiliser applications.

6.3.1 Methods Based on Soil Mineral N Content

Soil analyses aim to characterise the soil nitrogen status or to predict its availability during the crop growth phase (Dachler 2001). Several tests are available to determine

Table 6.3 Rooting depth of some vegetable crops (Scharpf 1991a)

0–30 cm	30–60 cm	60–90 cm
Kohlrabi	Beans	Asparagus
Lettuce, leaf	Broccoli	Brussels sprouts
Lettuce, iceberg	Cabbage, early	Cabbage, late
Peas	Cauliflower	Cereals
Radish	Celery	Corn
Spinach	Endive	Rape
	Leek	
	Potato	

N requirements and their reliability depends on many variables. *Nmin* and *KNS* (*Kulturebegleitende Nmin Sollwerte*) are two methods for developing fertilizer recommendations based on measurements of soil mineral nitrogen.

In the *Nmin method* (Wehrmann and Scharpf 1986), the N-fertiliser requirement of the crop (N_{rate}) is estimated as $N_{rate} = N_{target} - N_{min}$. N_{target} is a specific target level of nitrogen that must be available for maximum growth and yield to occur (Feller and Fink 2002); the target value is determined experimentally and takes into account both nitrogen already in the soil and nitrogen supplied by the application of fertilisers. N_{min} is determined from soil samples collected early in the field season, just before seeding or transplanting, taken to a depth of 0.3, 0.6 or 0.9 m depending on the root depth of the crop (Table 6.3). The method makes no adjustment for N mineralised during growth.

The *KNS* (*Kulturebegleitende Nmin Sollwerte*) *method*, instead of just one target value, uses target values that differ throughout the season (Lorenz et al. 1989), so the KNS method recommends nitrogen to apply at planting and as top-dress or side-dress applications during the growing season.

Goodlass et al. (1997) found that the recommendations from an N_{min} method were marginally closer to experimental estimates of the N-fertiliser requirement of the crop based on maximum yields than most other methods tested. However, some other researchers have found the N_{min} method less robust (e.g. Neeteson 1989).

The soil tests can be done at the laboratory or by a quick test using several tools (e.g. Nitracheck 404, Mercoquant, Cardy meter), but their reliability is limited by the representativeness of the field sampling procedure, since the spatial distribution of nitrate in soils is not homogeneous. Moreover, the samples must be chilled quickly to prevent any changes in nitrate content while awaiting analysis, as poor protocols for sample storage and transit can lead to large additional releases of mineral N which can render results meaningless.

However, the measurement of the magnitude of the soil mineral nitrogen (SMN) pool accessible to plant roots is not very reliable when there are periods with high rainfall during the growing season, or under high temperatures, or in soils with high organic matter contents (Wehrmann and Scharpf 1986). Stoniness is also a factor, as laboratory results in milligrams per kilogram need to be converted to kilograms per hectare to a given sample depth using an assumed bulk density for the soil. Bulk density values vary with soil texture and organic matter content, and stone content will reduce this soil bulk density. Application or incorporation of high amounts of slurry or green manure and crop residues can also produce misleadingly high values (Dachler 2001). The accuracy of soil N content and load indicators should also be verified (Makowsky et al. 2005). An attempt to improve the use of SMN data is the creation of spatial statistic maps as has been tested within the Nitrogen Sustainable Management Programme in Agriculture (PGDA) implemented in Wallonia, Belgium (Curtois et al. 2005). A nitrogen balance based even on single local determination (i.e. before the growing season) can differ by 10–20 kg ha^{-1} or more from a balance calculated from empirical tables. However, direct analysis of soil sampled at farm level presents the problem of correct sampling methodology and appropriate storage. It is easy to understand how the required facilities and technical skills to correctly sample, handle, store and analyse soil samples are seldom available to vegetable producers. Therefore, direct determination in the field of soil and plant nitrogen through sensors can be a more practical and cost-effective methodology (Dachler 2001).

The different methods to predict nitrogen availability and their modifications look not only to the current state of mineral N in the soil but also to the soil mineralisable N pools, which are more stable than mineral nitrogen. Several soil analytical techniques have been developed and modified (Table 6.4) for this purpose, and the joint use of this methodology with the measuring of mineral nitrogen could provide a better evaluation of the soil nitrogen supply to the crop (Dachler 2001). However, in soils with high organic matter content or treated with organic matter and crop residues, the estimation of N_{min} is a problematic task. The nitrogen released from humus during the vegetable growing period is affected by environmental events, soil characteristics and cropping practices, and therefore the N_{min} target values can vary spatially and must be measured at a local level (Tremblay et al. 2003). However, even with soil analysis results, farmers do not always translate knowledge of adequate nutrient supply in the soil into a lower input of fertilisers as suggested by findings in Finnish vegetable production (Salo et al. 2001).

An alternative method to complement conventional soil analysis, where several determinations are required over a long period, is the use of electrical conductivity (EC) measurements carried out on the soil solution by probes based on Time Domain Reflectometry (TDR) (De Neve et al. 1999) or Frequency Domain Reflectometry

Table 6.4 Determination method for available nitrogen (Adapted from Dachler 2001)

Method for determination of available soil N	Year of development
Hot-water-soluble N	1976
Organic soil substances	1978
Electro-ultrafiltration extractable N	1979
Free organic N	1982
Soluble organic N	1987
Water-soluble organic substances	1988
Anaerobic incubation, organic N	1988
N-rich non-humic substances	1990
Potential mineralisable nitrogen	1993

(ThetaProbe). The use of TDR probes allows the estimation of available soil nitrogen and immobilised N in non-saline soils (De Neve and Hofmann 2001), and further calibration and development of specific TDR instruments could extend the use of this method, which has so far been limited to experimental work on study farms. The time and the frequency of a reflected TDR wave in the soil depends on its water content and on the quality and quantities of the ions in it, while mathematical models can be built to use the quality of the reflected wave to calculate the concentration of such ions (Krishnapillai and Sri Ranjan 2009, Souza et al. 2006). However, an extended comparison between chemical and EC based N measurements has proved how only the first one can give a constant reliable assessment of N soil (Baumgarten 2006), and factors such as soil texture, organic matter and stone content can influence the accuracy of results.

6.3.2 Methods Based on Evaluation of the Crop Nutritional Status

Various measurements can be made to determine nitrogen-fertiliser requirements based on plant tissue nitrogen content. The use of these methods in vegetable production systems is deemed particular relevant in the 'dynamic optimisation of N supply', i.e. a method of N management based on periodic monitoring of nitrogen content in vegetables during their growth.

As with soil sampling, plant analysis must be conducted carefully, because also the nitrate concentration in plants is heterogeneous (Mills and Jones 1996; Lorenz and Tyler 2007). Standard laboratory analysis involves analysing the most recently matured leaf of the plant for an array of nutrients based on dried plant parts. The resulting analyses can be compared against published ranges for the specific crop (Mills and Jones 1996; Lemaire and Gastal 1997; Gastal and Lemaire 2002; Tei et al. 2002, 2003) to determine if the crop is at sub-optimal, optimal or at 'luxury' (i.e. supra-optimal) levels of uptake. Standard laboratory analysis can result in very accurate measurements (Mills and Jones 1996), and therefore it can represent one of the most accurate methods of estimating plant N status. However, this procedure is time consuming for most diagnostic situations in the field (Lemaire 2008); especially if a rapid crop N status evaluation is required to adjust the N recommendation rate in a dynamic N-management system. Thus, quick tests like *sap test* or *chlorophyll readings* have been developed and are increasingly used operationally (Matthaus and Gysi 2001, Simonne and Hochmuth 2006; Farneselli et al. 2007a, b).

The '*sap test*' measures the NO_3–N present in xylem and phloem sap plus the apoplastic, citosolic and vacuolar water on the leaves; thus, it results a direct measure of current N supply. Once absorbed by roots, nitrogen is transported to the leaves where it is transformed and incorporated into living material. Thus, nitrate concentrations in the aerial part of the plant provide a good indication of the adequacy of N applied to the crop. In particular, nitrate in the leaf petioles seems to give the best indication of crop nutritional status because it is more sensitive to fluctuations in N availability than the sap extracted by leaf blades. Nitrate content in sap can be measured by different tools which, in general, are highly correlated with results from conventional laboratory analysis (Errebhi et al. 1998; Coulombe et al. 1999; Hartz et al. 2000). The most common are: Merkoquant test strips, which react to the NO_3–N content by producing a colour, the intensity of which varies directly with the concentration; an ion-specific electrode, as Horiba-Cardy Meter, which reads directly the NO_3–N concentration in the sap. Several plant sap quick test kits have been calibrated for N in many crops including vegetables (Coltman 1987; Vitosh and Silvia 1994; Delgado and Follet 1998; Errebhi et al. 1998; Coulombe et al. 1999; Taber 2001; Jimenez et al. 2006; Farneselli et al. 2006a; Erdal et al. 2007). Even if the sap test procedure is markedly affected by many factors (Paschold and Scheunemann 1989; Vitosh and Silvia 1996; Farneselli et al. 2006a), when carefully undertaken it can be a reliable tool for monitoring the crop nutritional status of many vegetable crops (such as processing tomato) and with results consistent with the critical N-curve method (Tei et al. 2002) for the most important time period in fertiliser management (Farneselli et al. 2007a).

The *chlorophyll meter readings*, such as SPAD-502 meter by Minolta, is another common quick test (Hoel 2003; Swiader and Moore 2002; Sexton and Carroll 2002; Arregui et al. 2006). It detects differences in leaf nitrate content by measuring the light transmittance through leaves. The device is simple to use and, since it estimates the nitrate content in the tissue of intact and growing leaves, it is not destructive and does not require the preparation of any chemical samples for analysis. SPAD readings are an accurate method to evaluate the crop nutritional status because the chlorophyll content is usually highly correlated with the nitrogen level and yield, but, at the same time, it is affected by several factors such as cultivar, environmental conditions, plant growth stage, pests and diseases (Piekielek and Fox 1992; Gianquinto et al. 2006). The SPAD meter is therefore best used together with other crop and meteorological monitoring tools. The reliability of the SPAD method has been tested with good results on several crops including corn (Piekielek and Fox 1992), cereals (Arregui et al. 2006), potato (Gianquinto et al. 2003; Olivier et al. 2006), tomato (Gianquinto et al. 2006, Farneselli et al. 2007a), pumpkins (Swiader and Moore 2002) and beets (Sexton and Carroll 2002).

These approaches helped to implement good practices in vegetable N management in several Canadian states (Westerveld et al. 2003). Tremblay et al. (2003), in their guide to vegetable nitrogen fertilisation, give a very good judgement on the use of these field devices, but consider them as a complement to more conventional soil analysis. Others (Neurkirchen and Lammel 2002; Schroder et al. 2000) judged such methods – if calibrated according to different varieties and environments – to be so precise as to be able to provide all the necessary laboratory determinations for plants and soils. However, most crop indicators seem to be more effective at diagnosing N deficiencies rather than N excesses, with the exception of the sap test (Radersma and van Evert 2005). The main benefit of the new methods tested is mostly as a ‘field troubleshooter’ for identifying low nitrogen status situations – in contrast, their use for reducing over-fertilisation could be more problematic. Indeed, a review of the available quick test tools including test strips and SPAD meters, Hartz (2003) highlighted this method’s limitations due to the high equipment cost and demanding calibration process, and the sometimes weak relationship between apparent plant N status and the real plant N demand.

Nevertheless, if the scope of the recommendation is limited to fertiliser top-dressings of nitrogen during vegetable growth, then sap nitrogen content has proved to be cheap, more accurate in characterising spatial variability (i.e. in broccoli CV = 9% against CV = 29% where CV is coefficient of variability), faster, and less weather-dependent compared to conventional N_{min} determination (Matthaus and Gysi 2001). An improvement on the crop indicators approach can be achieved using 'crop windows', which are field plots where the crop is kept at maximal N status, if the difference between the crop indicator index between the window crop and the field crop is large, an additional application amount can be calculated for the field crop (Radersma and van Evert. 2005, Wiesler et al. 2002). Such reference plots should also set accordingly the growth stage when each diagnostic system is planned to be used (Tremblay and Belec 2005).

Another contemporary approach, which is currently being studied in France and in Italy for tomatoes, melon, aubergine and other uncovered field vegetables, is the "Index of Nitrogen Nutrition" (INN), which is the ratio of the percentage N content in the plant to the critical percentage N content at which the plant stops growing. Its development implies the identification of a part of the plant in which the N content is representative of the whole plant N status, and the development of a specific function linking N dose applied and plant growth. This methodology is applicable only if a diagnostic instrument is developed and calibrated for plant N testing in the field (Le Bot et al 2001; Dumoulin et al. 2002a, b).

The choice of the best method of assessing N requirement using soil or plant analyses depends on the crop and soil type. While researchers agree that adjusting fertiliser recommendations according to soil mineral nitrogen test is a good practice especially in high N situations (Goodlass et al. 1997; Hartz 2003; Burns 2006), there is no consensus on the best method for monitoring dynamic crop nutritional status during the growing season. For evaluating crop nutrient status, results from different studies have lead to different conclusions: certain crops appear to be assessed accurately using the sap test, while others do not show as strong a correlation between sap nitrate content and crop nitrogen supply and are therefore better managed using soil nitrate testing. Research carried out in lettuce and broccoli concluded that there was a higher accuracy associated with soil testing compared to sap testing (Coulombe et al. 1999; Hartz et al. 2000); while in potato, fertiliser cost and leaching losses were reduced based on the sap test. However, other researchers have found that the status of many others vegetables crops such as potato, cabbage, carrots, onion and tomato was accurately assessed using the sap test (University of Minnesota 1996; Westerveld et al. 2003; Farneselli et al. 2007a).

6.4 Nutrient Modelling and System Analysis

Concerns in recent decades over the loss of nutrients from agriculture to water bodies have had to balance the commercial pressure for yield maximisation against environmental policy agendas including water quality legislation, climate change targets and environmental sustainability. The resulting investigations have led to a ‘holistic’ new approach to nitrogen fertilisation in vegetable production at farm and regional scale (Huffman et al. 2001). Although some general recommendations can be derived from experimental results for specific case study scenarios, the variability in soils, climate, hydrology and management means that it is not possible to provide a fully exhaustive range of fertiliser parameters for all the species of vegetable produced in the EU on all the different soils (Goulding 2000).

Mechanistic simulation models have been developed representing system processes at different levels of detail in order to simulate, test and explore the interactions in soil–plant systems for crop growth and nutrient uptake (Le Bot et al. 1998; Marcelis et al. 1998). In general, simulation models are intended for researchers in order to study the nitrogen interaction in the plant–soil system, by supplying data sets collected from experiment with data on local meteorological conditions. With the application of those models, researchers are able to evaluate which parameters are important in the nitrogen balance and may be modified to determine which factors are critical in the nitrogen balance. Since simulation models usually need accurate information on several eco-physiological parameters they are generally unsuitable for providing practical advice to farmers and technical advisory services (Grignani and Zavattaro 2000) unless they are embedded in user-friendly computer-based Decision Support Systems (DSS) for use in commercial practice (Battilani and Fereres 1999).

Exploring system dynamics and responses using simulation models is clearly less labour-intensive and more flexible than field-based experimental work (Whitmore 1996) but very few N models are based specifically on vegetable studies. One widely used software packages is WELL_N (Greenwood et al. 1987; Rahn et al. 1996) that since its release has been used widely by large sectors of the UK field vegetable industry (Burns 2006). It was developed by Greenwood et al. (1987) to present the response of winter wheat to N fertilizer and was later extended to include the simulation of growth of 25 vegetables and major arable crops and the release of N from crop residues. The DSS WELL-N uses an embedded simulation model of crop N response (N_ABLE) simulation model (Greenwood et al. 1996), which includes a complete crop rotation, and is able to evaluate the effects of different soil management strategies on nitrate leaching from intensive vegetables rotations. Other examples of DSS are N-Expert (Fink and Scharpf 1992; Stenger et al. 1999), Irriguide (Bailey and Spackman 1996; Silgram et al. 2007), Conseil-Champs (http://www.agrigestion.ca) and Agri-Champs (htpp://www.lavoieagricole.ca). Battilani et al. (2003) also developed a simple tool-model (FERTIRRIGERE) for managing water and nutrient supply in drip-irrigated processing tomatoes.

Catchment-scale assessments based on models using spatial data on soil, weather and crops are needed for planning the reorganisation of (and scenarios for) changes in agricultural activity in a more sustainable way. Such methods can estimate the potential for nitrate leaching over a large area from different production and nitrogen-management systems by linking simulation models, soil and climate data and geographical information systems (Hoffmann and Johnsson 1999; Lilburn and Web 2002). The end results are tools that allow judgments of the potential impacts of 'good practice' (Huffman et al. 2001; Haberlandt et al. 2002), and help identify 'hot spots' at high risk of nutrient pollution due to a combination of land use, soils, climate and hydrological conditions. Areas posing a high risk of diffuse pollution from agriculture (due to the combination of land use, soil, management, climate, slope, location, etc.) can then be targeted in a focused, spatially defined manner either within the EC Nitrates Directive (within Nitrate Vulnerable Zones (NVZs)) or the EC Water Framework Directive (within River Basin Management Plans). Member States are already developing such approaches, at national or regional level, for some or all crop types (e.g. Italy - project for Soil Quality for Sustainable Agriculture and Forestry, M. Pagliai, personal communication; UK – 'MAGPIE', Lord and Anthony 2000, in UK same approach is followed for P management also, PSYCHIC, Davison et al. 2008; Collins et al. 2007). Ideally, the models should provide also a 'cost curve' analysis of the required costs and benefits associated with different mitigation measures in a range of farm systems involved (Anthony et al. 2005).

However, the use of mechanistic models at field/farm level is often hampered by the lack of localised data or the required level of competence (Grignani and Zavattaro 2000). With limited relevant calibration datasets, it is not surprising that in many cases, Decision Support Systems (DSS) at farm level related to vegetable production tend to underestimate nitrate leaching (Uhte 1995). However, this does not imply that the systems approach is not highly valuable in terms of its potential for improving the sustainability of horticulture (Rabbinge and Rossing 2000; Visser de et al. 2005). At regional scale, advanced statistical methods (such as fuzzy statistics: Bardossy et al. 2003) and research techniques (e.g. linear programming, neural networking or genetic algorithms: Gary 2003) can provide the required data and expert knowledge to fully exploit the potential associated with different modelling approaches. For simulation exercises at this scale, a smaller (e.g. 2 × 2 km) grid and the use of more detailed datasets are always advisable (Borgensen et al. 2005).

Similar exercises have been carried out also at smaller scales (100–200 km^2) on vegetable production in the Valencia region in Spain (De Paz and Ramos 2002). Their results, supported by the application of spatial and multivariate analyses, helped to define critical patterns in soils and climate, which were then used to limit N fertilisation according to crop demand to minimise the risk of leaching associated with periods of greatest drainage. From the farmers' point of view, nitrate leached out of the soil root zone represents money wasted on 'lost' fertiliser.

These kinds of projects can also generate information for developing farm-level databases to identify agro-ecological indicators, which can evaluate the sustainability of different elements in vegetable production systems (Mempel and Meyer 2002). For instance, the 'Indigo method', developed in France to analyse vineyards and fruit production (Gary 2003), allows the linking and ranking of each factor in the cropping system in relation to a set of environmental parameters. Each user can then select a minimal number of variables to monitor in a specific strategy such as nitrate-leaching reduction, pesticide limitation etc.

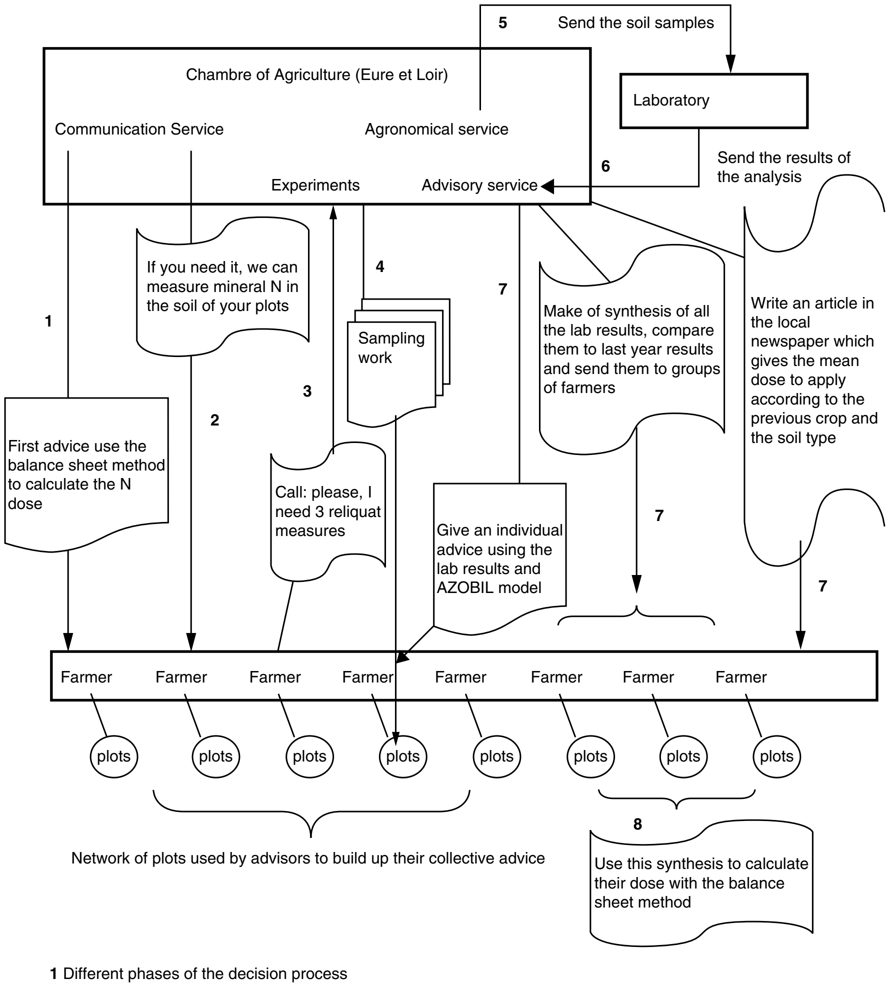

Fig. 6.2 Interaction between technical consultants and vegetable farmers using a Decision Support System (Meynard et al. 2002)

However, the implementation of DSSs over large areas cannot be effective without a well-connected network including farmers, technical advisory services, and local authorities. Meynard et al. (2002) described this interaction between farmers and advisory services using a DSS to generate guidelines in crop management (Fig. 6.2). However, care is required to prevent the quality of the information supplied losing detail and integrity during the communication process from farmer or farm adviser to modeller, which could result in misleading recommendations being produced. The use of such DSS tools is necessarily limited to the range of typical situations (crop, soil, climate, hydrology) for which they were originally developed. Realisation of the potential advantages of using DSSs to guide more sustainable vegetable management and production systems is dependent on (i) appropriate tools to allow upscaling from field to regional level, (ii) appropriate parameters at different spatial scales and (iii) specific procedures to promote dialogue and help disseminate the resulting information and advice back to farmers.

At a farm level, a careful monitoring of nitrogen status in soils and crops at a local level coupled with simulation models of water and N cycling in the plant–soil system can be translated into targeted crop management based on the spatial variability of agronomic characteristics using geographic positioning system (GPS) instruments linked to geographic information system (GIS) references. This methodology of 'precision farming' is becoming more widely used in open field vegetables and fruit orchards (Van Alphen and Stoorvogel 2000, Smit et al. 2000). For example, in Sweden, this precision farming technique is being used to characterise within-field variability in fertiliser N requirements, water status, or pest/disease risk in vegetable systems, where it has proved to be cost-effective (H. Sandin, August 2006). Although such methods can prove cost-effective, such approaches require high technological input in terms of equipment and training of the operator, which means that this is not a practical option in some situations. Some researchers have suggested coupling biophysical simulations with economic modelling at the planning stage to identify the most profitable management of N inputs (Smit et al. 2000). Carrying out such an economic optimisation, Smit et al. (2000) found the use of precision agricultural systems was highly cost-effective for N input management in ware potato in the Netherlands, and concluded that in precision farming the best economic return was reached when applying good agricultural practices.

6.5 Agronomic Options in N-Fertilizer Management

There is a broad recognition of the need to improve the adoption of best management irrigation and fertiliser management practices in vegetable growing. Since NO_3–N is mobile and relatively unreactive (Rajput and Patel 2006) and, therefore, susceptible to movement through diffusion and mass transport in the soil water, water management is inevitably linked to N management. Careful timely applications of N fertiliser and irrigation water can limit the amount of nitrate leaching below the root zone (Drost and Koeing 2001), such as occurs with well-managed fertigation techniques. Once the optimum N rate is applied, a suitable evaluation of plant nutritional status during the growing season is necessary to make adjustments accounting for N availability (Coltman 1987; Smith and Loneragan 1997; Simonne and Hochmuth 2006). Other key aspects of N fertilization and irrigation management which must be correctly evaluated to improve N management include rate, application timing and method and type of fertiliser (Neeraja et al. 1999). For example, field experiments carried out for 3 years on irrigated crops in high intensity agricultural regions between the French Alps and the Rhone valley showed that more than 30% of the applied nitrogen was lost due to inappropriate timings, which were not synchronised with crop N demand and comprised unnecessarily high dosages (Normand et al. 1997).

Since the relationship between N applied and nitrate leaching is non-linear, with nitrate leaching increasing sharply once optimal N application rates are approached, nitrate leaching could be disproportionately reduced for a relatively modest reduction in N application rates. If farmers were somehow compensated for the resulting lower yield, a possibility could be modifying the Common Agricultural Policy to include a grant-type payment for lower impact agriculture, then this approach could be the solution for high-risk land uses such as vegetable production systems (Tremblay et al. 2003). However, this is unlikely to be compatible with the 'polluter pays principle' underpinning EC environmental legislation.

Compared to other agricultural land uses, the growing of vegetable crops are associated with amongst the highest soil mineral nitrogen values in the spring (e.g. Silgram 2005). The mineralisation of N from these residues can proceed rapidly (especially under warm Mediterranean conditions in the spring) thereby making it difficult to capture this N using cover crops except if rainfall is limited during the growing season (Kraft and Stites 2003). Possible solutions include considering low or zero fertiliser input systems (i.e. organic land management), soil-less systems (hydroponics), or reversion to low impact vegetable crops to compensate for the decreased yield due to low fertiliser inputs (Kraft and Stites 2003). There is also the relatively new idea of accepting a limited reduction of yield through a sub-optimal fertiliser regime, with the reduction varying as a function of crop type. Such sub-optimal applications may also promote a higher concentration of sugar and vitamin C in the harvested material, which may have implications for market prices with traders (such as supermarkets and food manufacturers).

Where the nitrate leaching risk is high post-harvest, then the irrigation and fertilisation management have limited potential as control tools (by improving fertiliser use efficiency through placement, timing, rooting, or variety), with alternative solutions involving modifications to the crop rotation and/or *inter-cropping with deep rooted crops providing a potential solution to reduce the N available for leaching (Sidat et al. 2000).

6.5.1 Localised Fertilisation

Placement of N fertilisers close to the plant can play an important role to help prevent or minimise the risk of nitrate leaching, especially in vegetable crops which are usually grown in rows, by increasing N fertiliser recovery. This localised placement of N is particularly efficient in reducing leaching risks at the beginning of the growing season (i.e. starter fertiliser technique) as when plants are small, roots exploit a very limited soil volume and the N uptake is slow. The use of starter fertiliser, in comparison with conventional N application timings, promotes both faster and higher root and top growth, increasing yield and reducing N losses (Costigan 1988; Ma and Kalb 2006; Osborne 2006). This placement of soluble nutrients close to the seed is especially important in cold, wet soil in which nutrient availability and root growth are generally reduced. Localised fertiliser placement can also be performed by banding fertiliser on the crop rows. I.G. Burns (personal communication) suggested to restrict first applications to a narrow band and to apply a second application as top dressing at the normal rate. For example, in cauliflower, roots expanded laterally to exploit about half the row width within 4–8 weeks of planting and crops planted with the optimum rate of base dressing recovered most of the applied N within 8 weeks. Such banded fertiliser approaches can be effectively used for cauliflower, onion, lettuce and potato. However, the most effective technique to synchronize as much as possible N uptake with N availability is fertigation.

6.5.2 Fertigation Techniques

Fertigation methods tend to increase the nitrogen use efficiency (NUE) while N losses to the environment are minimised, maintaining a balance between food production and environmental quality (Farneselli 2008). Since micro-irrigation has emerged as an appropriate water-saving technique especially for row crops, and applying fertiliser in the water via drip irrigation can be a more efficient fertiliser management practice, the fertigation technique is becoming very common on vegetable crop systems. The advantages of the fertigation over broadcast method of fertilizer applications are emphasized by several researchers (Phene 1999; Singandhupe et al. 2003; Mohammad 2004).

The high water- and N-use efficiency of fertigation (which represent the major benefits of this technique) are due to rate splitting according to the crop requirement at any growth phase and due to the localised placement of fertiliser close to the roots. As a consequence, fertigation can reduce the risks of nitrate leaching, surface evaporation and deep percolation without any decrease of yield and quality in produce (Battilani 2001, 2006; Singandhupe et al. 2003; Hebbar et al. 2004; Janat 2004; Battilani and Solimando 2006). Several studies conducted on different crops (Li et al. 2004) showed an increase in yield of crops grown with fertigation techniques compared to conventional ones: Singandhupe et al. (2003) recorded a 3.7–12.5% increase in yield and 31–37% decrease in water consumption for tomato grown with drip irrigation compared to furrow irrigation systems; while Hebbar et al. (2004) recorded a tomato fruit yield 19% higher in drip irrigation compared to furrow irrigation. Nevertheless, fertigation is often managed empirically, both for irrigation and mineral nutrition aspects, so that its advantages are not fully exploited, and mismanagement of fertigation can lead to nitrate contamination of surface waters, groundwaters and soils (Battilani 2001).

Achieving maximum fertigation efficiency requires knowledge of crop-specific water and nutrient requirements at any site throughout the growth cycle (Tei et al. 2002) and attention to the timing of water and N delivery to meet (but not overwhelm) crop needs. At a given water and nutrient supply, fertigation frequency affects water volume and N rate per application, and thus soil moisture and nutrient concentration in the rhizosphere between irrigations, with consequent changes in crop growth, N uptake and yield (Cook and Sanders 1991; Locascio and Smajstrla 1995; Silber et al. 2003). As a consequence, the careful management of irrigation and/or fertigation frequency is one of the major management variables affecting fertigation efficiency. High fertigation frequency is often advocated in the technical literature (Bar-Yosef and Sagiv 1982) because it keeps soil moisture and nutrient concentration constant near the root zone, so that nutrient diffusion in the soil is easy (Silber et al. 2003). At the same time, water movement is mainly controlled by capillary forces instead of gravitational ones (Phene 1999) with consequent leaching reduction. Moreover, high fertigation frequency makes it possible to more precisely modulate the concentration of the nutrient solution in the irrigated root zone according to crop needs at any growth stage (Bravdo 2003).

Some authors (Cook and Sanders 1991; Locascio and Smajstrla 1995; Silber et al. 2003) have found that for processing tomato, a daily or weekly fertigation significantly increased yield compared to less frequent fertigation; although differences between daily and weekly intervals were not significant even on a sandy soil. The authors hypothesised that yield limitation at low fertigation frequency is mainly the result of nutrient deficiency rather than water deficiency. However, crops are able to counteract small, short-lived nutrient concentration variations, and therefore plants do not necessarily show nutrient stress. Moreover, some studies have demonstrated that if a little stress is given, root penetration increases and the yield may increase with reduction in the cost of irrigation (Dalvi et al. 1999).

There is a need to evaluate lower-fertigation frequency in greater detail, because there is limited evidence of the benefit of higher-frequency fertigation. This is because frequent fertigation regimes are not easy to manage and increase water waste due to both evaporation from the constantly wet soil surface and the large portion of the irrigation cycle used for system charge and flush (Simonne et al. 2005). Previous research conducted by Li et al. (2003, 2004) observed that the water distribution pattern is affected by several variables with consequences on the root growth and N leaching. The emitter discharge rate and the application rates of water and nitrogen affect the wetting pattern and solute movement; in particular an increase in the water application rate allows greater water distribution in a vertical direction for a given volume applied (Farneselli et al. 2008). The fertigation–irrigation frequency may also affect biomass accumulation and partitioning because a different water and nutrient availability in the root zone can affect plant water and nutritional status with possible consequences on root growth and shoot/root ratio, leaf assimilation and transpiration, canopy architecture, light absorption and distribution inside the canopy (Hebbar et al. 2004). Results from experiments carried out in Central Italy in processing tomato have suggested that high fertigation–irrigation frequencies increased the above-ground crop dry matter (DM) accumulation and N uptake only when N supply was very high and exceeded crop critical requirements (i.e. for luxury N consumption) while for optimal and sub-optimal crop N status it had no effect (Farneselli et al. 2007b). In contrast to patterns of biomass and N accumulation, the size ratio between the different parts of the plant did not change with the fertigation frequency. Moreover fertigation frequency can affect the timing of ripening and/or fruit quality (breaks, rottenness, size and size uniformity, nutritional parameters) (Hebbar et al. 2004; Colla et al. 2001; Erdal et al. 2007). However, the strategy of controlling nitrate leaching based on split fertiliser applications and careful irrigation management may only have a low impact on nitrate-demanding crops with shallow-rooting systems (i.e. potato, faba bean) especially under heavy unpredictable rainfall (Andrasky and Bundy 1999). In the slightly more strict regime applied in the USA, where the nitrate (NO_3–N) limit in agricultural groundwater is 43 mg L^{-1} against the 50 mg L^{-1} applied in the EU, the control of nitrate leaching through the management of irrigation and fertilisers has proved a complete failure (Kraft and Stites 2003).

6.5.3 Slow-Release Fertilisers

The use of slow-release fertilisers serves the same purpose as split applications, providing nitrogen more slowly as the plant requires it (Li 2003; Khah 2003). This kind of fertiliser has the benefit of saving time, since all fertiliser can be applied in a single dressing at the beginning of the season, although it also has some notable disadvantages such as the need for special application equipment and the more expensive product compared to conventional fertilisers (Jin 1996; Schaller 2000; Khah 2003; Prasad et al. 2004) with N release not always coinciding with crop N requirements (Peltonen 1994). Moreover, the use of organic fertiliser (Heeb 2005; Herencia 2007; Pavlou 2007) or fertiliser with the appropriate nitrate–N/ammonium–N ratio or nitrification inhibitors could also be a valuable strategy for improving N-fertiliser management (Narayan 2002).

6.5.4 Nitrification Inhibitors

The use of new nitrification inhibitors 3.4 Dimethylpirazole phosphate (DMPP) has also been considered in addition to urea (Pasda et al. 2001). Linaje et al. (2005) in central Spain measured a reduction of 50% of N leaching with the application of DMPP to broccoli. Mantovani et al. (2005) obtained similar results by adding DMPP to pig slurry. This approach could be considered as an alternative to calendar-linked applications of manure (e.g. in the context of restrictions on the timing of manure applications imposed by the EC Nitrates Directive), thus avoiding the costly need for storage facilities.

6.5.5 Intercropping

The aim of an intercropping system is to increase the crop root density, and this approach is most successful when implemented using 'compatible' species, which have different peak times of N uptake and different rooting depths (Baumann et al. 2003). When implemented in this manner there need not be significant effects on overall yields.

One species may exploit available nitrogen, which is not accessible or required by the other crop. For example, testing different intercropping systems with faba bean undersown with brassicas such as oil radish (*Raphanus sativus* var. *oleiformis*) or white mustard (*Sinapis alba*) proved more efficient than ryegrass and cereal which reduced the faba grain yield (Justus and Kopke 1995). The depth of the rooting zone will give an indication of potentially viable intercrop combinations in vegetable systems (see Table 6.3). Paschold et al. (2003) carried out research in intensive vegetable production systems in Germany which provided evidence of the potential for intercropping in vegetable production in Europe to serve as an effective tool for controlling nitrate leaching. These authors reported that the growth of oil radish (*Raphanus sativus* var. *oleiformis*) between asparagus ridges was a useful technique for reducing nitrate leaching after the growing season of asparagus had ended (rather than leaving the soil bare over winter). The N_{min} residual in the soil (0–90 cm depth) decrease in average from 250 kg ha^{-1} to 150 kg ha^{-1}, with an average increase in asparagus yield of 1.2 t ha^{-1}. A further element of a mixed-intercropping system is the creation of a green cover, which covers the soil surface otherwise unoccupied by growing plants and thereby achieves the same effect as mulching. This is an established feature of the management of some vegetable fields and fruit orchards, which is carried out using inert materials such as polyethylene.

6.5.6 Mulching

Sweeney et al. (1987) worked in an open field growing tomato with overhead irrigation and mulching with polyethylene. This system reduced water drained from the soil and enabled nitrogen uptake to reach 53% of the applied amount, with 42% of N applied remaining in the soil and 5% lost as leached nitrate. Similar results have been reported for the growth of pepper (Romic et al. 2003).

6.5.7 Cover Crops

Many researchers have pointed out the feasibility of using autumn crop covers to manage the nitrogen husbandry for the succeeding cash crop, prevent the nitrogen leaching and improve the soil characteristics especially by increasing the soil organic matter (Harrison and Silgram 1998; Thorup-Kristensen et al. 2003; Macdonald et al. 2005). As broadly accepted, the phrase ‘catch crop’ is used when dealing with cover crops that are grown to catch available nitrogen in the soil and thereby minimising nitrate-leaching losses, while the term ‘green manure’ is used when dealing with cover crops that are grown mainly to improve the nutrition of the subsequent crops (Tosti 2008). A good catch crop (e.g. cereals and crucifers) should have an early sowing date (Thorup-Kristensen and Pedersen 2006), a prompt germination and fast growth rate at both above and below-ground levels (Thorup-Kristensen 2001), and a deep root apparatus (Kristensen and Thorup-Kristensen 2004). Green manures for supplying N are usually leguminous species able to accumulate considerable amount of nitrogen: in a Mediterranean environment like central Italy, values ranging from 150 to 250 kg ha^{-1} for annual clover (Campiglia et al. 2005) with maximum values of more than 300 kg ha^{-1} (Benincasa et al. 2004) for faba bean and hairy vetch green manures. In southern Italy nitrogen supply of 45 and 165 kg ha^{-1} are reported for vetch and cow pea respectively, while faba bean supply was between 72 and 193 kg N ha^{-1} (Fagnano et al. 2005; De Luca et al. 2006; Sulas et al. 2007). The net contribution in terms of nitrogen input to the system (i.e. the nitrogen derived from atmosphere) was estimated 70–80% of the total nitrogen supplied by legumes (Seddaiu et al. 2007; Sulas et al. 2007).

Recent research found that it is possible to modulate N supply and release from green manures to a subsequent crop by mixing grass and legumes (Boldrini et al. 2006; Tosti et al. 2008) and that the unit cost of nitrogen from green manures is much lower if compared to nitrogen from organic fertilisers (Chaves et al. 2006; Guiducci et al. 2004). However, because the N release will depend on the C/N ratio in residuals and the mineralisation rate, experimental results can be contradictory (Harrison and Silgram 1998). The use of mixtures of hairy vetch (*Vicia villosa* Roth.) and barley (*Hordeum vulgare* L.) with high proportion of vetch (>50%), for example, allowed an optimal N nutritional status of processing tomato without promoting luxury N consumption (Tosti et al. 2008).

The use of cover crops or catch crops is limited by farmers' reluctance to adopt voluntarily a practice which demands extra time associated with establishment and destruction, possible extra seed costs, and the risk of encouraging the persistence of weeds, pests, or diseases which may interfere with the growth and yield of the next main crop (Tremblay et al. 2003). Only some form of incentive scheme or their compulsory use as a requirement under Code of Good Agriculture Practice would assure their more widespread adoption by farmers (Vos and Putten 2004; Vos et al. 2005).

6.5.8 Cultivar Nitrogen Efficiency

For nitrogen, it has been noted that differences in nitrogen efficiency occur at the crop level and also in some cases at the cultivar level. N-efficient crops and cultivars are characterised by deep rooting depths (with enhance N uptake efficiency) and high utilisation efficiency. Schenk (2006) stated that 'nutrient use efficiency is a potential tool for sustainable vegetable production in the field. Some breeders are going down this avenue and are selecting cultivars under nutrient limiting conditions. The development of nutrient efficient cultivars is a challenge for horticultural science not only with a view to reducing the flow of nutrients into natural compartments of the environment but also taking into consideration production conditions in countries where access to fertilisers is limited'.

6.6 N-Leaching Assessment

The quantification of nitrate leaching from soils to water has specific difficulties (Kucke and Kleeberg 1997). A rapid and reliable estimation of NO_3–N moving below the root zone is crucial to reducing the risk of nitrate leaching (Aveline and Guichard 2005; Makowsky et al. 2005). Since water movement in the soil and NO_3–N concentrations in the soil solution are strictly linked, both these phenomena have to be investigated. Several different approaches could be adopted to assess N leaching. Load may be determined directly by soil sample analysis or by collecting leachate from drainage lysimeters. Mathematical simulation models have become also useful tools in assessing and understanding the movement of fertilisers through soil into groundwater (Shaffer et al. 1991; Jabro et al. 1994; Bailey and Spackman 1996; Karaman et al. 2005; Silgram et al. 2007).

Monitoring the NO_3–N concentrations in the soil solution by suction cup lysimeters placed at different depths, is also another method to assess nitrate leaching below the root zone. This method seems to be particularly useful when the measurements of nitrate–N concentration are used to calculate the N leached by integrating them with estimates of drainage volume between successive samplings, or by changes in soil moisture readings taken simultaneously using soil moisture probes (Moreno et al. 1996; Vazquez et al. 2005, 2006; Farneselli et al. 2007b). The accuracy of the resulting load assessment greatly depends on the hydraulic conductivity of the soil and the evapo-transpiration of the crop. The nitrate concentration component is affected mainly by the accuracy in sampling the soil solution, which is affected by the resident soil nitrogen pools and applied fertilisers or manures. The different sampling methods of the soil solution may sample the nitrate from the two sources in different proportions, and may sample different pore sizes of soil water, and therefore results are most reliable when incorporated into long-term monitoring programmes with replication (Kerft and Zuber 1978; Lord et al. 2007). However, due to difficulties in maintaining good hydraulic contact between the soil and the ceramic (or similar) material, suction cups often do not operate well in chalk soils where water is held very tightly in the smallest pores. Another method of nitrate-leaching assessment could be to calculate the load by multiplying the NO_3–N concentration in soil samples by the wetted soil volume (Farneselli et al. 2006b, 2007b). Results produced using this method can be useful in drip irrigation systems, where knowledge of the wetted zone volume can be gained by visualising soil water movement using soluble blue dye (German-Heins and Flury 2000; Simonne et al. 2003, 2005, 2006; Farneselli et al. 2006b, 2007b).

6.7 Research and Technology Transfer in European Union: Case Studies

EU States have applied the Nitrates Directive by developing research frameworks, funding specific research projects, and developing consulting committees, which have produced documents to help advising farmers on agriculture practices with more sustainable environmental impacts. Some specific documents have been designed to address nitrogen and phosphorus management issues, whereas in others instances, case studies and initiatives have been more holistic and have focused on the management of a given crop or crop group. Several examples are given below, focusing on Mediterranean countries with specific case studies.

6.7.1 Italy

In Italy field vegetables in 2005 were grown in about 470,000 ha with a total production of about 13 million tonnes. Organic vegetable production was about 12,000 ha (i.e. about 1% of total land in organic cultivation) (Pimpini et al. 2005). Greenhouse production was about 34,000 ha with a total production of 1.5 million tonnes (mainly *Solanaceae*, *Cucurbitaceae*, lettuce and strawberry). Total value of vegetable production was about €6.6 billion. Fresh markets represent the main destination of vegetables, but minimally processed vegetables show the highest rate of increase (about +17% year^{-1}). Vegetable production is widespread in all the regions even if production from the south are mainly destined for the fresh market while those from the north mostly go to processing (except Puglia region in the south that is the lead area for processing tomato with about 30% of national production).

Peculiar characteristics of vegetable production in Italy are the small farm size (c. 1.7 ha) with two to three crops per year in a wide range of crop combinations (e.g. pepper–fennel–spinach; early potato–tomato–fennel; tomato–French bean–cauliflower; peas–beans–spinach; carrots/peas–chicory; tomato/zucchini–fennel/salads; potato–eggplant) and products destined for the fresh market. Large farms are not frequent, with cropping systems usually simpler and oriented around the food industry (e.g. processing tomato; spinach or peas for frozen food), well-mechanised and with use of external manpower.

Due to the Mediterranean climate, spring–summer vegetables are always irrigated, often using saline or partially saline waters. This has pushed towards the more widespread use of low-pressure irrigation systems, which also produce little or no risk of leaching.

According to a study from the Istituto Sperimentale per l’Orticoltura (Research Institute for Horticulture), published as an integration of the PANDA framework, Italian vegetable production is a strange dichotomy: horticulture is the most highly productive agricultural sector (on a gross income basis) after beef, but it is also associated with the smallest average farm investment in terms of land use.

A large framework project (Produzione Agricola Nella Difesa dell’Ambiente, PANDA) has been carried out since 1996 in Italy to develop environmentally sustainable agricultural technologies. The whole framework deals with soil resilience, pollution from agriculture, and pollution from non-agricultural sources. The PANDA project comprised three elements (Environmental vulnerability, Field trials, Analytical systems), which did not explicitly cover vegetable production, but which included related technical management practices. Great importance was paid to soil protection, which was judged as the most critical environmental factor in the Mediterranean area. Among the aims of PANDA was an inventory of areas vulnerable to inputs of nitrogen and other nutrients from agriculture as well the design of a Code of Good Agriculture Practice ('Codice di buona pratica agricola') for Italy according to the framework given in the Nitrates Directive. Research projects were undertaken on irrigation and fertiliser management with special attention to nitrogen and phosphorus inputs from organic sources including biomass and livestock effluents (Mastrorilli 1999). The field experiments were focused mainly on cereals, or mixed cereal and dairy/beef systems, and in smaller scale on peach and citrus fruit systems. Considerable emphasis was given to modelling studies for several different example crops (Francavigli and Benedetti 1995) and at a larger scale for regional assessment of pollution from agriculture (Coccato and Di Luzio 1996; Boatto et al. 1996). The Good Agricultural Practices designed within the PANDA framework was adopted by the Italian government (DM 19/04/99) as a general framework for the rules designed at regional level for each crop. In Italy, each regional government is responsible for the application of environmental and agricultural EU Directives. Concerning the inputs of nitrogen, the code gave very general background information and proposed accounting for the nitrogen already present in the soil or returned in crop residues when calculating the N requirement for the next crop. The code does not detail sampling methodologies or specific analyses, or the use of DSS at farm level. For some open field vegetable crops, the suggested amounts of nitrogen input (kilograms per hectare) for standard expected yields (tonne per hectare) are provided in Table 6.5.

A national advisory system on vegetable fertilisation does not exist, but instead there is an advisory service at a local level through farmer associations and local governments. The local network provides the farmers with recommended amounts of nutrient inputs for each growth stage using results from monitoring trials. The codes for Integrated Production applied by each Regional Government often include Nutrient Balance Systems (NBS) for calculation of the fertiliser crop

Table 6.5 Suggested N inputs based on standard yields for different vegetable crops in Italy (http://www.politicheagricole.it/norme/mezzitec/19990419__DM.htm)

Species	N-fertiliser requirement	Target yield	Species	N-fertiliser requirement	Target yield
	kg N ha^{-1}	t ha^{-1}		kg N ha^{-1}	t ha^{-1}
Garlic	120	12	Asparagus	180	5
Carrots	150	40	Artichokes	200	15
Onions	120	30	Cabbage	200	30
Rape	120	25	Broccoli	150	15
Cucumber	150	60	Melon	120	35
Watermelon	100	50	Sweet pepper	180	50
Strawberry	150	20	Tomatoes	160	60
Aubergine	200	40	Courgette	200	30

requirements. However, several researchers consider that a more 'scientific' approach is needed with a monitoring network for soil mineral nitrogen (N_{min}) and the use of DSS within the local advisory services due to the high variability of Italian soils and climates.

Extensive programmes of research and monitoring on nitrogen management in vegetable crops, mainly in open fields, have been undertaken since 1990 by several universities in Italy via EU (e.g. LIFE) and national (e.g. COFIN, PRIN, FISR) framework projects. These research programmes have studied the effect of N-fertiliser rate, fertilisation methods and N-fertiliser source (i.e. mineral, organic and green manures) on growth and N uptake of the most important vegetables (i.e. processing tomato, lettuce, sweet pepper, aubergine, potato) to provide parameters needed to model growth and N uptake in vegetables, and indices to evaluate the nutritional condition of the crop, and the environmental risks associated with different cropping systems. Within this context, in June 2004, an ISHS international meeting 'Towards ecologically sound fertilisation strategies for field vegetable production' was organised by the Department of Agricultural and Environmental Sciences, University of Perugia (proceedings published in Acta Horticulturae 700, 2006) with about 100 participants from 26 countries throughout the world and 50 scientific contributions. In the conclusion of this symposium, it was noted that the development of sound fertilisation strategies has to take into account the needs and suggestions of, researchers, policy makers, farmers and consumers who have to interact with each other.

In Italy, fertigation is becoming the standard method of nutrient applications to vegetables in order to increase fertiliser-use efficiency and limit the risk of diffuse pollution via run-off and leaching. This technique is applied on about 70% of the open field production area. However, if the high nitrate content in irrigation water is not adequately taken into account in the calculation of N-fertiliser crop requirements, then this can lead to an over-fertilisation of vegetable crops. For example, in the South Lazio region, nitrate levels in water tables at 10 m depth can easily fluctuate between 50 and 300 mg L^{-1} (V. Magnifico, personal communication).

6.7.2 Spain

The highly differentiated climate present within Spain, coupled with large differences in soil types, results in high spatial variability in nitrogen-fertiliser requirements and use. Considering scientific literature and statistical data, in Spain only around 35% of the total N applied is effectively used by crops, which is much less than the global average efficiency of around 50% (Soler-Rovira et al. 2005).

The Autonomous Communities (Spanish local governments) are the main authorities responsible for implementing the Nitrates Directive (91/676/EEC) including the associated codes of Good Agricultural Practices relevant for their areas. However, the responsibility to carry out and implement agricultural and environmental research is shared between the Spanish government, Autonomous Communities and universities, sometimes with the collaboration of private companies.

In order to group all researchers and projects about nitrogen in agriculture and to properly disseminate their results, in 2002 the Spanish government, many Spanish universities, and Autonomous Communities Research Centre created the Network of Efficient Use of Nitrogen in Agriculture (RUENA), (Red del Uso Eficiente del Nitrogeno en la Agricultura). The aims of the network are (i) to provide a forum for all people investigating the efficient use of nitrogen fertilizer in agricultural systems and (ii) to create a 'round table' to support the development of consensus and consistent recommendations concerning the management of nitrogen fertilizer applied to crops. The RUENA network is involved in the development of all relevant European, National and Regional legislations on nitrogen in agriculture, including those concerning fruit and vegetable crops, and includes researchers and institutions specifically involved in such area of study. A specific website (http://www.ruena.csic.es) provides information on the current and past projects, publications, and contact details for the thematic area of nitrogen use in agriculture.

Before RUENA, Spain had developed some national research projects on the correct use of nitrogen in agriculture such as the 'Dynamic of nutrients and improvement of fertilisation techniques in citrus trees' (1993–1996); the 'Monitoring of nitrate contamination in aquifers in Jarama river basin' (1992–1995); 'The efficient use of water and nitrogen in horticultural crops in the open air by application of plastic padding and fertigation' (1998–2001) and 'The application of pig slurry to olive crops' (1998–2000). Under the RUENA umbrella, there are currently several framework research programmes relevant to the use and misuse of nutrients in agriculture, including some dealing with the environmental impact of vegetables and fruit crops.

Within the RUENA framework projects, investigations identify optimum nitrogen-fertiliser rates and timings to obtain optimal yields and harvest quality, and to limit potential risks of nitrate leaching to water bodies. The main aspects include studies on the spatial and temporal distribution of nitrogen fertilisers applied to crops, the methods of quantifying nitrogen demand, the role of crop rotations in N requirements and the use of models to predict fertiliser nitrogen requirements. However, current activities are focused on maize crops, which have the highest rate of nitrate leaching due to the common practices of applying nitrogen at a rate 2 or 2.5 higher than the recommended amount. In this same framework, the Agricultural Research Technologic Institute of Calaluña (IRTA) jointly with Fundació Mas Badia (Estació Experimental Agrícola) and regional governments have developed the 'Programme to improve nitrogen fertiliser use in agriculture in Baix Emporda (Cataluña)' (Plan Pilot per la Millora de la Fertilització Nitrogenada a L'agricultura del Baix Empordà). The research objective is the identification of optimal nitrogen rates, maintaining high crop yield and quality, but minimising the negative effect to the environment (F.D. Olivé, personal communication). Recently, this programme has been extended to cover horticultural crops and fruit trees.

Several investigations were carried out on plant demand for nitrogen, optimal timing for nitrogen-fertiliser applications, the most efficient use of irrigation systems in nitrogen application to crops and nitrogen supply in the soil. The design and development of a software family to manage sustainable irrigation systems (or ADOR: 'una familia de programas de ordenador para la gestión y la planificación del uso del agua de riego y sus implicaciones medioambientales'; http://web.eead.csic.es/oficinaregante/ador) have been carried out within this framework since 2001 by researchers from Estación Experimental de Aula Dei (CSIC), technical personnel from Aragon Regional Government, and Aragon farmers, funded by the Spanish Government. The ADOR software helps farmers to manage irrigation systems by planning the irrigation season, and supporting cost analysis evaluating the opportunities to modernise irrigation facilities. A large database was implemented to support the software, which can be used with any irrigation system (surface, drip, sprinkling) and in any water distribution net (canal or piping). No information is available on the dissemination of the software and its use by farmers and its impact on the current practices. However, comments collected by researchers in the field suggest that even when farmers were involved, they did not adopt new practices until there was an economic incentive to do so.

In the main vegetable production areas of Spain (i.e. Aragon, Valencia, Murcia, Extremadura, Andalucia, Aragon, Rioja, Cataluña, Navarra), prior to the introduction of the Nitrates Directive legislation there was a general lack of consideration by farmers about the environmental problems associated with nutrient leaching caused by irrigation and fertilisation. This led to a high level of mineral nitrogen (from 173 to 232 kg ha^{-1}) in the soil profile (0–90 cm depth) and to the subsequent high risk of groundwater contamination by nitrate leaching (Gimenez et al. 2001). The unwillingness of the farmers to comply with this Directive suggests that the situation even after its implementation remains unchanged; however, no monitoring studied has been so far carried out to effectively quantify the real impact of the Nitrates Directive.

More recently, however, several monitoring studies have been implemented to assess the potential and actual contamination caused by nitrogen applications to agricultural soils. The results of those activities have highlighted problems in several horticultural and fruit regions. In the AC of Valencia, Ramos et al. (2002) has shown that around 8% of the Valencia Community population have water supplies with nitrate concentrations above 50 mg L^{-1}. This is confirmed by the studies of the Instituto Valenciano de Investigaciones Agraria (IVIA), which demonstrated that agricultural nitrogen inputs were much higher than the values recommended by research, and that nitrate leaching values were in most cases within the range of 150–300 kg N ha^{-1}. In the Valencia region, GIS/modelling studies (De Paz and Ramos 2001) on a typical 2-year crop rotation (potato-lettuce-onion-cauliflower) showed that the whole open field vegetables area of about 230 km^2 in the North of Valencia is at high risk of nitrate leaching due to the lack of awareness of farmers on the risks posed by excessive fertiliser N applications. As shown in Table 6.6, the N-fertiliser rates applied to vegetable crops in Valencia are higher than actual N crop requirements. Artichoke, early potato and onion were the three crops with higher leaching rates than other crops. From these crops, nitrate leaching typically varied between 240 and 340 kg N ha^{-1} depending on the nitrogen-fertiliser treatment,

Table 6.6 Crops and N fertilizer applied and N uptake by crops (kg ha^{-1}) in AC of Valencia (Ramos et al. 2002)

Crop	N fertilizer applied kg N ha^{-1}	N crop uptake kg N ha^{-1}
Artichoke	470 ± 260	130–210
Onion	500 ± 280	110–210
Lettuce	460 ± 210	45–54
Potato	700 ± 450	180–270
Pepper	1030 ± 630	180–270
Tomato	940 ± 245	225–365
Cauliflower	220	40–310

Table 6.7 Maximum values of nitrogen applied in vegetable crops in Andalucia, Spain

Crops	N rates kg N t^{-1} of yield
Artichoke	11.5
Asparagus	5.0
Aubergine	11.5
Broad Bean	11.5
Cabbage	11.5
Carrot	5.0
Cauliflower	5.0
Courgette	11.5
Cucumber	2.6
Garlic	6.8
Green beans	11.5
Lettuce	5.0
Melon	3.5
Onion	3.5
Peas	11.5
Pepper	5.0
Potatoes	4.2
Tomato	3.5
Watermelon	3.5

representing about 66–70% of total N input in the onion crop and 38–65% of total N input in the potato crop (Ramos et al. 2002).

Also in Andalucia (Table 6.7) and Navarra (Table 6.8) N crop requirements recommended by the codes for Good Agricultural Practice are by default increased by the farmers who wish to apply additional fertiliser as a safety margin to guarantee high yields.

In Almeria province (Andalucia region), there are approximately 25,000 ha of plastic greenhouses used for intensive vegetable production and which represent a significant potential source of nitrate leaching. Studies carried out on nitrate leaching from greenhouse pepper (Gallardo et al. 2006) showed that fertigation with a reduced

Table 6.8 Optimal N-fertiliser rates recommended for vegetable crops in Navarra, Spain

		Fertilisation (kg N ha^{-1})			
Crop	Cultural practices	Total rate	Before crop	During crop cycle	No. applications during crop cycle
Artichoke	First year with manure	160	0	160	2–3
	First year without manure	220	60	160	2–3
	Second year	80	0	80	1–2
	Sprinkling irrigation	180–200	60	120–140	3
Garlic		140	40	100	2
Aubergine	With manure	120–180	0	120–180	2–3
Courgette		145	45	100	2–3
Onion		160	60	100	2–3
Cauliflower		175–200	50	125–150	2–3
Brussels sprouts		180–200	50	130–150	2–3
Asparagus	Without irrigation	100	0	100	1
	With irrigations	180–200	0	180–200	2–3
Spinach	Sprinkling irrigation	140	40	100	3–4
Green pea		30	30	0	0
Melon		160	50	110	2–3
Potato		110	40	70	2
Pepper		100–130	0–30	100	2–3
Leek		150	50	100	2–3
Processing tomato	Mechanical harvest	90–110	40–50	50–60	2
	Manual harvest	190–200	70–80	120	2–3

concentration of N (i.e. 7–9 mmol N L^{-1} = 168 kg N ha^{-1}) compared to the standard (i.e. 10–12 mmol N L^{-1} = 194 kg N ha^{-1}) reduced nitrate leaching by 7%. Thompson et al. (2002, 2005) confirmed that in Almeria region the contribution to nitrate leaching to surface water was much higher, in terms of surface area, from open hydroponic systems than from conventional vegetable production in clay soils.

6.7.3 France

The former Agriculture and Environment Ministry of France, now Ministry of Ecology and Sustainable Development, has organised a consulting committee for dealing with pollution from agriculture (CORPEN) since 1984. This committee has been in charge of the Code of Good Practice since 2001, with special attention to N and P losses. CORPEN produces several documents and studies, some of which are focused on vegetable crops.

The French legislation applying the Nitrates Directive demands generally that the fertilisation must be done according to a nitrogen balance which accounts for irrigation water and soil mineral nitrogen (SMN). SMN is calculated differently according to the environmental conditions and crop type. Specifically for vegetable crops, it details different timings and amounts for the application of N fertilisers taking into account the soil organic matter contents, climatic regime and soil characteristics in different regions. CORPEN produced edited tables for the most common vegetables (beans, tomatoes, lettuce, etc.) where the N balance was described for the more common crop rotations used in France.

In some leguminous vegetables (e.g. peas), N fertilisation is largely avoided because the symbiotic N fixation is assumed to supply 75% of the vegetable crops' N requirements in French soils. Also, early sowing to increase the root depth and the use of catch crops has been suggested for vegetables with high N contents in their residues. The implementation of the Nitrates Directive in France is undertaken at Regional and Departmental (county) level after 'contracting' with the professional association of producers and advisers. Results have an extremely variable impact in relation to crops and regions with a little evidence of coordination and consistency at a broader national level. CORPEN has so far limited itself to scientific advice and providing communication between the different stakeholders.

Vegetable crops of primary interest for controlling nitrate leaching are tomatoes, lettuce, strawberry and melon in the South East; cauliflowers in Brittany, carrot in Normandy, Brittany and the southern part of Bordeaux (where sandy soils once used for intensive corn crops have been converted to high-quality carrot production). Soil-less and soil-based systems in glasshouses are widespread in the South West in the Pyrenees region.

In contrast to Italy, France has a strong national network of support and technical advice to the producers based on professional associations and local authorities. This allows an easier transfer of knowledge from main research institutions

(Universities and INRA) to farmers (mainly the units based at Rennes, Avignon and Montpellier). For fruit and vegetables this role is played by the CTIFL (http://www.ctifl.fr) jointly with regional research station and local agriculture associations (Chambres d'agriculture). This organisation offers support in designing sustainable fertilisation and rotation plans, and publishes fertilisation tables for the main vegetable and fruit production systems. However the efficacy of this knowledge transfer depends mainly on the dialogue between advisory services and producers' associations and this is extremely variable between different regions and departments.

In France, help to the horticultural sector is equivalent to only 5% of farm income compared to 50% of farm income for a farmer involved in grain production. This difference makes the regional associations more sensitive to the requirements of the Nitrates Directive. Many producers are too preoccupied with the introduction of a pest management initiative required under other EC Directives to have the time and will to tackle fertilisation issues. For example, in the processing tomato production area around Avignon, most farmers still apply 300 kg N ha^{-1} when uptake is only 120–150 kg N ha^{-1}, largely because they perceive it as too complicated and potentially risky to switch to new, reduced N-input management. (P. Robin, personal communication). However, an alternative example is the intensive production of cauliflower in Brittany, which is traditionally based on widespread use of pig slurry. After long-standing pressure from the authorities and with the support of INRA in Rennes, producer associations suspended N applications for 5 years and are now slowly introducing a more rational approach to fertilisation based on N balance.

In the South West, only the more 'enlightened' producers in open field vegetables tend to use N-balance systems and some simple Decision Support System tools. In the 'Midi', the main area for melon, lettuce and chicory production, 80% of farmers use a sap test and 20% use an N-balance system for determining N-fertiliser crop requirements.

At national level, the original methodology promoted by CORPEN (before the Nitrates Directive) included a programme to monitor and advise farmers on their fertiliser management ('Fertimiuex'), which was on a voluntary basis and mainly tackled grain production. In the south-west of Normandy region in 2000, partially in response to the Nitrates Directive, an integrated management programme (i.e. 30% reduction of fertiliser rates, crop rotations with less vegetables and at least 30% of cereals, establishment of hedgerows) was introduced to reduce eutrophication of the coastal area: results showed a decrease of about 30% in nitrate concentrations in groundwaters (P. Robin, personal communication). Many technical advisers and researchers consider this scheme a good demonstration of a practical approach for the effective implementation of the Nitrates Directive. CTIFL and INRA are continuing similar trials on fertilisation management for the main vegetable crops, mainly tomatoes, cauliflowers and melon, in the Midi region and in Brittany.

The design of a sustainable N management for melon production has been the aim of joint research between INRA in Avignon and CTIFL-Balandran: a diagnostic method (PILazo-melon) for N requirements based on petiole sap test has been successfully tested across a wide range of soil and climate in France on different varieties of melon (Le Bot, personal communication; Dumoulin et al. 2002a, b).

6.7.4 The Netherlands

In most parts of North and Central Europe, national advisory systems are all based on N_{min} target values (Scharpf 1991b; Rahn et al. 2001). This, however, does not avoid the risk that amounts of nitrogen applied may exceed requirements, because of either the limitations of the method or the unwillingness of farmers to strictly adhere to the advice provided. The determination of soil mineral nitrogen often takes place in the autumn; although the long time lag between this sampling and the period of highest N demand can generate errors in estimating fertiliser requirements (Paschold et al. 2001) it can also provide a useful measure of the N potentially available for leaching following harvest of the previous crop. Improved systems (e.g. KNS, Nitrogen Balance System) which account for the N_{min} level through the growing season, still sometimes overestimates the crop demand and requires large amounts of soil analysis and careful fertiliser management, which may result in a less user-friendly solution for the farmer. However, a similar approach in the USA (pre-side dressing nitrate test [PSNT]) seems capable of equivalent or better results by only measuring soil nitrate in the top 30 cm of soil just before the application (Hartz 2003). Those methodologies could be greatly improved if coupled with models specifically developed for vegetable crops, accounting for the potential N losses during the season as a function of weather conditions (EU_Rotate_N project newsletter 2003), which is definitely the most unpredictable factor involved (Paschold et al. 2001).

A completely different approach that avoids the use of models and can be an improved 'rule of thumb' for farmers to top-dress crops is the so-called Nil-N-plot system, based on the concept of 'unfertilised windows'. A 2-year test on 12 different vegetable fields in Germany (Weier et al. 2001) showed great differences due to the use of the N_{min} system. The suggested application rates were from 20% lower to 10% higher than those calculated as a function of the amount of mineral N at the start of the season, but no yield decrease was recorded. This method may be a simpler way to take account of the effect of nitrogen released from crop residues during the growing season without the use of expensive soil analysis or complex mechanistic models, although soil mineral nitrogen testing certainly still retains value in situations where levels are expected to be high (e.g. in fields with a manure/slurry history, of fields following legumes, potatoes, etc.).

In the last 3 years, a worldwide network of researchers, mainly based in Germany and Quebec, have developed a set of recommendations to improve the N-balance approach as a main tool for controlling N leaching. The result of their efforts has been synthesised in a guide to sustainable nitrogen management in fruit and vegetable crops which is published on-line and has been designed to be updated to ensure continued relevance (Owen et al. 2003).

In the Netherlands, a group of regulations has been set up to support implementation of the Nitrates Directive and to consider the need to reduce ammonia emissions from agriculture. The main measure to reduce nitrate leaching is a ban on the spreading of animal manure, and to keep overall control of the nutrient input in agricultural systems, levies have been designed linked to annual surpluses of nitrogen and phosphorus (Neeteson et al. 2003). This system, originally known as the MINAS or MINerals Accounting System, was introduced in the 1998 with the aim to cut down in 5 years the allowable N surplus in grassland from 300 to 180 kg N ha^{-1} and in arable land from 175 to 100 kg N ha^{-1}; in case of over-surplus, a levy is required of €2.3 kg^{-1} of nitrogen and €9 kg^{-1} of phosphate.

However, the system's compatibility with the Nitrates Directive was overestimated and the system was challenged by the EC. Several technical differences in nutrient balance persisted between MINAS and the Nitrates Directive: nutrient balance in the Nitrates Directive was fixed ahead of the crop cycle, in MINAS is calculated instead immediately before the grown season with the nutrient supplies from soil, crop residues, animal manure, atmosphere and biological N_2 fixation accurately estimated; however, the nutrient from manure generated in farm was not explicitly accounted. The system has been updated several times, but eventually was found to be incompatible with the Nitrates Directive and was ultimately closed in 2005.

To test the effect of these policies, a joint project ('Telen met toekomst' or 'Farming with a future') on four experimental farms and 33 commercial ones (where land management was based on the initial results from the experimental units) was established. Two main systems were tested: one, 'economically feasible', where nitrogen was applied according to measurements carried out by the NBS Dutch scheme, and second, 'environmentally desirable', where the nitrogen application was carried out with strategy tailored to the different farms with the aim of cutting down nitrogen inputs. The project also accounts for phosphorus inputs. The main aim was to explore if it was possible for commercial farming to reduce inputs over a 5-year period without a significant decrease in farm income (Neeteson et al. 2001). The overall results reported so far vary greatly between crop types and locations. However, the nitrogen surplus was still much higher than the target of 100 kg N ha^{-1} in both systems. Even if the project continued into 2005, evidence reviewed so far suggests that decreasing nitrogen inputs in isolation is not sufficient to reduce N inputs to this target value, but this needs to be combined with site-specific management initiatives (e.g. timing, placement, variety) to help increase the nitrogen-use efficiency, even if these actions cause an increase in costs (Van Dijk and Smit 2006, Smit et al. 2005). The nitrogen inputs on the farms under the 'economically feasible' system were higher than the recommendations due to incomplete account of the nitrogen added in organic manures; the decrease in manure applications was also compensated by a slight increase in chemical N to avoid a yield penalty. However, the complete cessation of organic manure applications without replacing with fertiliser under the environmentally feasible system had no effect on yield. Under both the schemes low phosphorus inputs were applied and no yield reduction occurred.

Results from trials in leek fields (Neeteson et al. 2003) showed how operating under an ‘environmentally desirable’ management scenario induced a soil mineral nitrogen reduction of around 50% without any notable yield loss. However, the system used in this case to limit the N input was a fertigation scheme which cost about €1,000 ha^{-1} more than the classical Nutrient Balance scheme. Further investigations (Radersma et al. 2005) also found that N-crop quick tests were more effective than N-soil quick tests for managing N split application in crop and decreasing N leaching.

6.7.5 Final Considerations

The technical impact of the most recent research on N management in fruit and vegetable production systems has been reviewed in relation to the implementation of the Nitrates Directive in some EU states. The state of knowledge in management practices is generally fairly advanced and there are tested methodologies supported by published data which allow a more sustainable horticultural sector without decreases in yield or quality. However, although there is still scope to refine and improve the technologies, the major challenge is disseminating results to farmers and farm advisers and promoting changes in farm management practices that minimise the risk of diffuse pollution from vegetable production systems.

Some issues, such as nitrate concentrations in surface water systems used for irrigation, are increasingly becoming an environmental pollution risk (e.g. in Spain and Italy, Padana valley). Measures such as more widespread use of drip irrigation systems have become more widely applied at field level over the past few years through the broader adoption of advanced technologies, which are more efficient in terms of water use. Other measures have had more limited success, including the farm-scale use of software tools (Decision Support Systems, DSS), the use of regular soil nutrient analyses, and the use of nitrogen probes and sensors.

In all the countries investigated, the farmers have rarely taken into account the suggestions evolving from the latest research, and they often continue to over-fertilise at levels between 20% (Italy, France) and 200% (Spain) above recommended levels. The high irrigation input required by some crops makes this behaviour increasingly dangerous for the environment. This is the case for crop systems such as tomatoes, strawberry in protected systems; aubergine, pepper and lettuce in open fields and citrus trees in Spain where immersion irrigation is still in use. In the case of open field crops in North France and North Italy, specific tests to measure N status in certain crops and the associated crop N requirement are still missing (cauliflower, carrots, cabbage, Brussels sprouts, spinach, onion). Simpler approaches to calculating N balances and N requirements, which may include soil mineral nitrogen testing, are still not as widely used as they could be to help estimate crop N requirements more accurately in these high-residue situations. The amount of leaching from vegetables crops varies greatly across the countries reviewed. For example, glasshouse tomatoes in south France can leach up to 1,000 kg N ha^{-1} (Le Bot et al. 2001).

Although leaching is much less from similar systems in south and central Italy, it is still sufficient to contribute to nitrate levels in water tables fluctuating from 50 to 300 mg l^{-1} (V Magnifico, personal communication). The evidence reviewed suggests that open field vegetable crops in southern Europe can leach 100–300 kg N ha^{-1} $year^{-1}$ from the soil root zone towards groundwaters depending on the soil, precipitation, irrigation, and management factors.

6.8 Conclusion

This review has described advances in N management to reduce nitrate leaching applied to vegetable production and their effective application. Areas of research where further investigations are required have been recognised such as (i) relation between crop residues and following crop management, (ii) prediction of the net effect of the different components of the soil N cycle on the soil-plant system, (iii) farmers' perception of N leaching as monetary loss, (iv) creation of spatial statistical maps of soil mineral nitrogen, (v) relation between N plant status and N plant effective demand.

Current research in nitrogen management aims to design the most effective N-fertiliser management systems that are able to produce a profitable and high-quality yield together with a more sustainable environmental 'footprint'. This research combines investigations on nitrogen soil dynamic and its use by crops, focusing on understanding the merits of alternative methods, tailored to each crop, climate and soil, for assessing (i) the effective plant N requirement; (ii) the soil availability of N which the plant roots can access; (iii) the associated losses, mainly due to nitrate leaching, which can be particularly high in field vegetable crops where irrigation is required. This fundamental research is currently leading to sophisticated technical solutions such as (i) innovative measurement instrumentations and methods, (ii) computerised tools for management and simulation of 'if then' scenarios, (iii) new crop-management systems. However, these advances are not always implemented by farmers at the scale required to produce an effective and lasting impact on the environment. The proper N budget, which all these techniques allow, implies an increase of available data from local datasets, whose realisation is demanding in terms of time and finance. The empirical approaches are generally still preferred because they can be more reliable for specific local conditions when detailed data are missing. Moreover, some tools (the so-called decision support systems) are generally not sufficiently user-friendly for farmers; they have been designed for farm advisers and agronomists, who are professionally qualified to choose from the large number of available techniques and methods and interpolate their results using their own experience tailored to specific regional conditions.

Recent advances in agronomy such as improved irrigation timing schemes, localisation of fertiliser applications in time and space and the combination of these elements in fertigation schemes where a crop calibration frequency is a key point all appear effective for decreasing N leaching without yield losses. In some specific cases, the use of slow-release fertilisers or nitrification inhibitors have also yielded encouraging results, but their more widespread use is difficult to generalise. In many cases, other more classic agronomical methods such as catch crops, mulching and intercropping that are unappealing for conventional farming due to the increased input of time and resources needed can be considered when the higher value of yield can justify the increased inputs as occur sometime in organic farming.

Finally, it must be noted that there is a natural limit on our ability to minimise nitrate leaching, which is governed by plant physiology, soil characteristics and weather conditions; even with the most advanced cultural tools a sustainable but still profitable management of field vegetable is not always within reach and so the only option left can be a land use different from vegetable crop.

Acknowledgements The authors thank the following researchers for useful suggestions and valuable information on several aspects of the topic reported in this review: Professor P Sequi and Dr. A. Benedetti, CRA-Centro di Ricerca per lo Studio delle Relazioni tra Pianta e Suolo, ISNP, Roma, Italy; Dr.M. Pagliai, Centro di ricerca per l'agrobiologia e la Pedologia, ISSDS, Firenze, Italy; Dr. M. Mastrorilli, Istituto Sperimentale Agronomico, ISA, Bari; Dr. A. Rosati, CRA-Centro di ricerca per l'olivicoltura e l'industria olearia, Spoleto, Italy; Dr. V. Magnifico, CRA-Centro Ricerca per l'Orticultura, Pontecagnano, Italy; Dr. Jose Antonio Diez Lopez, Centro de Ciencias Mediambientales (CSIC) Departamento de Contaminacion ambiental. Control de la contaminacion nitrogenada, Madrid, Spain; Frances Domingo, Instituto de Investigacion y Tecnologia Agraroalimentaria (IRTA) Estacion Experimental Mas Badia, Gerona, Spain; Dr. Carlos Ramos Monpo, Instituto Valenciano de Investigaciones Agrarias (IVIA), Valencia, Spain; Dr. Rod Thompson, Depto. Producion Vegetal, Universidad de Almeria, Spain; Dr. C. Gary, CIRAD Montpellier, France; Dr. J. Le Bot and Dr. Stéphane Bellon, INRA Avignon, France; Dr. Paul Robin, INRA-ENSAM, Montpellier, France; C. Reynal, CTIFL, France.

References

AA.VV (2006) Acta Hortic 700

Agostini F, Scholefield P (2005). Simulation of carbon and nitrogen in the soil after straw incorporation. Ital J Agron (8) 2:63–71

Andrasky TW, Bundy LG (1999) Nitrogen cycling in crop residues and cover crops on an irrigated sandy soil. Agron Abstr 1999, 224

Anthony S, Chadwick D, Granger S, Haygart P, Harris D (2005) Cost-cube: a measure centric model for characterization of diffuse pollution. In: Schroder JJ, Neeteson JJ (eds) N Management in agrosystems in relation to the Water Frame Directive, Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 7–11

Arregui LM, Lasa B, Lafarga A, Iraeta I, Baroja E, Quemada M (2006) Evaluation of chlorophyll meters as tools for N fertilization in winter wheat under humid Mediterranean conditions. Eur J Agron 24:140–148

Aveline A, Guichard L (2005) Comparing indicators of nitrate leaching in various cropping systems. In: Schroder JJ, Neeteson JJ (eds) N Management in agro-systems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 64–67

Bailey RJ, Spackman E (1996) A model for estimating soil moisture changes as an aid to irrigation scheduling and crop water use studies. I. Operational details and description. Soil Use Manage 12:122–128

Bardossy A, Haberlandt U, Krysanova V (2003) Automatic fuzzy-rule assessment and its application to the modelling of nitrogen leaching for large regions. Soft Comput 6:370–385

Barret JH, Parslow RC, McKinney PA, Law GR, Forman D (1998) Nitrate in drinking water and incidence of gastric, esophageal, and brain cancer in Yorkshire, England. Cancer Cause Control 9:153–159

Bar-Yosef B, Sagiv B (1982) Response of tomatoes to N and water applied via trickle irrigation system. Nitrogen Agron J 74:633–637

Battilani A (2006) Water and nitrogen use efficiency, dry matter accumulation and nitrogen uptake in fertigated processing tomato. Acta Hortic 724:67–74

Battilani A, Solimando D (2006) Yield, quality and nitrogen use efficiency of fertigated watermelon. Acta Hortic 700:85–90

Battilani A, Bussieres P, Dumas Y (2003) FERTIRRIGERE: a simple tool-model for managing water and nutrient supply in drip-irrigated processing tomatoes. Acta Hortic 613:155–158

Battilani A (2001) Calcolare correttamente la fertirrigazione con il minimo input. Inf Agrario 57:35–42

Battilani A, Fereres E (1999) The use of decision support systems to manage fertigation and to minimize enviromental effects: a challange for the future. Acta Hortic 487:547–555

Baumann DT, Bastiaans L, Kropff MJ (2003) Analysis and design of a leek-celery intercropping system using mechanistic and descriptive models. Acta Hortic 638:59–68

Baumgarten A (2006) Evaluation of field methods for the assessment of soil Nmin–content. Acta Hortic 700:205–209

Belanger G, Ziadi N, Walsh JR, Richards JE, Milburn PH (2003) Residual soil nitrate after potato harvest. J Environ Qual 32:607–612

Bending GD, Turner MK (1999) Interaction of biochemical quality and particle size of crop residues and its effect on the microbial biomass and nitrogen dynamics following incorporation into soil. Biol Fertil Soils 29:319–327

Bending GD, Turner MK, Burns IG (1998) Fate of nitrogen from crop residues as affected by biochemical quality and the microbial biomass. Soil Biol Biochem 30:2055–2065

Benincasa P, Boldrini A, Tei F, Guiducci M (2004) N release from several green manure crops. Proceedings of the VIII ESA Congress, Copenhagen, Denmark, 11–15 July 2004, pp 971–972

Bertschinger L (2004) Making sustainability an issue in applied horticultural research. Acta Hortic 638:17–22

Bianco VV (1990) Environment, agricultural practices and quality of vegetable crops. Riv di Agron 24(2/3):81–131

Bjorneberg DL, Westermann DT, Aase JK (2002) Nutrient losses in surface irrigation runoff. J Soil Water Conserv 57:524–529

Boatto V, Pilati L, Defrancesco E, Galletto L (1996) Implicazioni economiche delle politiche di contenimento della fertilizzazione: il caso del Bacino del Meolo. Agric Ric 164:163–180

Boldrini A, Guiducci M, Benincasa P, Tosti G, Tei F (2006) Can we modulate N supply and release from green manure crops? Proceedings of the IX ESA (European Society for Agronomy) Congress, 4–7 Sept 2006, Warszawa, Poland, pp 371–372

Borgensen CD, Heidmeann T, Jorgense U (2005) Sensitivity of using different soil type representations for field and regional simulation of N leaching. In: Schroder JJ, Neeteson JJ (eds) N Management in Agrosystems in relation to the Water Frame Directive. Proceedings of 14th N Workshop, 2005, Maastricht, The Netherlands

Bravdo BA (2003) Crop improvement and production strategies in arid environments: salt, drought and heat stress. Acta Hortic 618:255–265

Burns IG (2006) Assessing N fertiliser requirements and the reliability of different recommendation systems. Acta Hortic 700:35–48

Burns IG, Rahn CR, Greenwood DJ, Draycott A, Richardson AS (1997) A user-friendly decision support system for adjusting N fertiliser requirements to local conditions. Managing soil fertility for intensive vegetable production systems in Asia. Proceedings of an international conference, AVRDC, Taiwan, 4–10 November, 1996, pp 314–324

Burns IG (1976) Equations to predict the leaching of nitrate uniformly incorporated to a known depth or uniformitly distributed throughout a soil profile. J Agric Sci (Cambridge) 86:305–313
Campiglia E, Caporali F, Paolini R, Mancinelli R (2005) Ruolo delle leguminose annuali autoriseminanti nei sistemi colturali biologici in ambiente mediterraneo. In: Cicia G et al (eds) L'agricoltura biologica fuori dalla nicchia. Edizioni Scientifiche Italiane, Napoli
Cantarella H, Mattos D, Quaggio J, Rigolin A (2003) Fruit yield of Valecnia sweet orange with different N sources and the loss of applied N. Nutr Cycl Agroecosyst 67:215–233
Cantor KP (1997) Drinking water and cancer. Cancer Cause Control 8:292–208
Cape J, Anderson M, Rowland A, Wilson D (2004) Organic nitrogen in precipitation across the United Kingdom. Water Air Soil Pollut: Focus 4:25–35
CEC (1991) Council directive of 12th December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC). Off J Eur Commun 30 Dec 1991, L135/1–8
Chaves B, Mateu PL, De Neve S, Hofman G, Van Cleemput O (2006) Conserving N from high N crop residues under field conditions by using on- and off-farm organic biological waste materials. Acta Horticul 700:255–261
Coccato M, Di Luzio M (1996) Applicazioni di un modello idrologico distribuito per il controllo dell'inquinamento agricolo di origine diffusa: il caso del Bacino del Meolo. Agricult Ric 164:181–191
Colla G, Battistelli A, Moscatello S, Proietti S, Casa R, Lo CB, Leoni C (2001) Effects of reduced irrigation and nitrogen fertigation rate on yield, carbohydrate accumulation and quality of processing tomatoes. Acta Hortic 542:187–196
Collins AL, Strőmqvist J, Davison PS, Lord EI (2007) Appraisal of phosphorus and sediment transfer in three pilot areas identified for the catchment sensitive farming initiative in England: application of the prototype PSYCHIC model. Soil Use Manage 23(Suppl 1):117–132
Coltman RR (1987) Sampling consideration for nitrate quick test of greenhouse tomatoes. J Am Soc Hortic Sci 112:922–927
Cook WP, Sanders DC (1991) Nitrogen application frequency for drip irrigated tomatoes. HortScience 26:250–252
Costigan PA (1988) The placement of starter fertilizers to improve the early growth of drilled and transplanted vegetables. Proc Fertil Soc 274:1–24
Coulombe J, Villeneuve S, Belec C, Tremblay N (1999) Evaluation of soil and petiole sap nitrate quick tests for broccoli in Quebec. Acta Hortic 506:147–152
CRPV-RER (2007) Disciplinari di Produzione Integrata 2007. (ed. Centro Ricerche Produzioni Vegetali – Regione Emilia Romagna). Bologna, Italy; http://www.crpv.it/; Access date 3/03/2007.
Curtois P, Destain P, Renardad S, Cuvelier M (2005) Field scale N-management: soil and plant diagnostic tools applied within the agricultural Surface Survey (Belgium). In: Schroder JJ, Neeteson JJ (eds) N Management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 257–261.
Dachler M (2001) Sampling and analytical methods for the determination of available soil nitrogen in Australia. Acta Hortic 506:239–245
Dalvi VB, Tiwari KN, Pawade MN, Phirke PS (1999) Response surface analysis of tomato production under microirrigation. Agric Water Manage 41:11–19
Davies DB (2000) The nitrate issue in England and Wales. Soil Use Manage 16:142–144
Davison PS, Withers PJA, Lord EI, Betson MJ, Strömqvist J (2008) PSYCHIC – A process-based model of phosphorus and sediment mobilisation and delivery within agricultural catchments. Part 1: Model description and parameterisation. J Hydrol 350 (3–4):290–302
De Luca S, Fagnano M, Quaglietta-Chiaranda F (2006) The effect of organic fertilization on yields of tomato crops in the Sele River Plain. Acta Hortic 700:103–106
De Neve S, Van Desteene J, Hartmann R, Hofmann G (1999) N mineralisation and soil solution electrical conductivity changes: on line monitoring of the mineralisation process using TDR. Proceedings of the 10th nitrogen workshop, Copenhagen, Denmark, 2, pp 122–125.
De Neve S, Hofmann G (2001) Time domain reflectometry for monitoring soil nitrogen dynamics. Acta Hortic 506:233–238

De Neve S, Pannier J, Hofmann G (1994) Fractionation of vegetable crop residues in relation to in situ N mineralization. Eur J Agron 3:267–272
De Paz JM, Ramos C (2002) Linkage of a geographical information system with the GLEAMS model to assess nitrate leaching in agricultural areas. Environ Pollut 118:249–258
De Paz JM, Ramos C (2001) The Use of a GIS_N model system to assess nitrate leaching in agricultural areas. Acta Hortic 506:225–229
De Tourdonnet S, Meynard JM, La Folie F, Roger-Estrade J, Lagier J, Sebillotte M (2001) Non-uniformity of environmental conditions in greenhouse lettuce production increases the risk of N pollution and lower product quality. Agronomie 21:297–309
De Walle FB, Sevenster J (1998) Agriculture and environment: minerals, manure and measures. Kluwer, Dordrecht, The Netherlands, 21 pp
Delgado JA, Shaffer MJ, Hu C, Lavado RS, Cueto WJ, Joose P, Li X, Rimski KH, Follet R, Colon W, Sotomayor D (2006) A decade of change in nutrient management: a new nitrogen index. J Soil Water Conserv 61:71
Delgado JA, Follet R (1998) Sap test to determine nitrate–nitrogen concentrations in aboveground biomass of winter cover crops. Commun Soil Sci Plant Anal 29:545–559
Drost D, Koeing R (2001) Improving onion productivity and N use efficiency with a polymer coated nitrogen source. Western Management Conferences, Salt Lake City, UT
Dumoulin J, Le Bot J, Mounier A, Fevre P (2002a) Azote du melon, la pratique du pilotage. Info CTIFL 185:45–48
Dumoulin J, Le Bot J, Mounier A, Fevre P (2002b) Azote du melon, de la recherche à la pratique. Info CTIFL 184:48–53
Ebrahim MKH, Aly MM (2005) Physiological Response of Wheat to Foliar Application of Zinc and Inoculation with some Bacterial Fertilizers. J Plant Nutrition 27:1859–1874. DOI: 10.1081/PLN-200026442
Erdal I, Ertek A, Senyigit U, Koyuncu MA (2007) Combined effects of irrigation and nitrogen on some quality parameters of processing tomato. World J Agric Sci 3:57–62
Errebhi M, Rosen CJ, Birong DE (1998) Calibration of a petiole sap nitrate test for irrigated "Russet Burbank" potato. Commun Soil Sci Plant Anal 29:23–35
European Commission (1999) Agriculture, environment, rural development: facts and figures – a challance for agriculture. Office for official publications of the European communities, Luxembourg
European Commission (1998) The implementation of council directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Office for official publications of the European communities, Luxembourg
FAO Land and Plant Nutrition Management Service FAO (2000) http:// www.fao.org/waicent/faoinfo/agricult/agl/agll/oldocsl.asp. Accessed 10/0972007 August 2009
Fagnano M, Merola G, De Luca S, Mori M, Zena A, Caputo R, Quaglietta Chiarandà F (2005) Ricerche Agronomiche per Sistemi Colturali Sostenibili in Italia Meridionale. In: Cicia G et al (eds) L'agricoltura biologica fuori dalla nicchia. Edizioni Scientifiche Italiane, Napoli
Farneselli M (2008) Improving fertigation management in processing tomato. Doctoral Thesis, University of Perugia, Italy, 174 pp
Farneselli M, Studstill DW, Simonne EH, Hochmuth RC, Hochmuth GJ, Tei F (2008). Depth and width of the wetted zone in a sandy soil after leaching drip-irrigation events and implications for nitrate-load calculation. Commun Soil Sci Plant Anal 39 (7&8)
Farneselli M, Benincasa P, Guiducci M, Tei F (2007a) Validazione di metodi di misura dello stato nutrizionale azotato del pomodoro da industria. Italus Hortus 14:154
Farneselli M, Benincasa P, Guiducci M, Tei F (2007b) Fertigation-irrigation frequency in processing tomato: effect on plant growth, N uptake and N leaching. Proceedings of 15th N Workshop "Towards a better efficiency in N use", Lleida, Spain, 28–30 May 2007, pp 179–184
Farneselli M, Simonne E, Studstill D, Tei F (2006a) Washing and/or cutting petioles reduces nitrate nitrogen and potassium sap concentrations in vegetables. J Plant Nutr 29:1975–1982
Farneselli M, Studstill DW, Simonne EH, Hochmuth B (2006b) Depth and width of the wetted zone after leaching irrigations on a sandy soil. HortScience 41:508

Feller C, Fink M (2002) N_{min} target values for field vegetables. Acta Hortic 571:195–201

Fink M, Scharpf HC (1992) Dünger-Dosierung im Freiland-Gemüsebau, Entscheidung sunterstützung durch; N-Expert“. Dtsch Gartenbau 46:1688–1690

Francavigli R, Benedetti A (1995) The Italian project PANDA for sustainable agriculture and protection of the environment. Hrvat Vode 3(12):289–292

Frankenberger WT Jr, Abdelmagid HM (1985) Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. Plant Soil 87:257–271

Gallardo M, Thompson RB, Lopez-Toral JR, Fernandez MD, Granados R (2006) Effect of applied N concentration in a fertigated vegetable crop on soil solution nitrate and nitrate leaching loss. Acta Hortic 700:227–230

Garnier P, Neel C, Aita C, Recous S, Lafolie F, Mary B (2003) Modelling carbon and nitrogen dynamics in a bare soil with and without straw incorporation. Eur J Soil Sci 54:555–568

Gary C (2003) Evaluation design and control of sustainable horticultural cropping systems. Acta Hortic 638:45–51

Gastal F, Lemaire G (2002) N uptake and distribution in crops: an agronomical and ecophysiological perspective. J Exp Bot 53:789–799

German-Heins J, Flury J (2000) Sorption of brilliant blue FCF in soils as affected by PH and ionic strength. Geoderma 97:87–101

Gianquinto G, Sambo P, Borsato D (2006) Determination of SPAD threshold values in order to optimise the nitrogen supply in processing tomato. Acta Hortic 700:159–166

Gianquinto G, Sambo P, Bona A (2003) The use of SPAD-502 CHLOROPHYLL METER for dynamically optimising the nitrogen supply in potato crop: a methodological approach. Acta Hortic 627:217–224

Giller KE, Cadisch G (1997) Driven by nature: a sense of arrival or departure. In: Cadisch G, Giller KE (eds) Driven by nature. Plant litter quality and decomposition. CAB International, Wallingford, UK, pp 393–399

Gimenez C, Parra M, Diaz M (2001) Characterization of current management practices with high risk of nitrate contamination in agricultural areas of Southern Spain. Acta Hortic 506:73–80

Goodlass G, Rahn CR, Shephered MA, Chalmers AG, Seeney FM (1997) The nitrogen requirement of vegetables; comparison of yield response models and recommendation systems. J Hortic Sci 72:239–254

Goulding K (2000) Nitrate leaching from arable and horticultural land. Soil Use Manage 16:145–151

Greenwood DJ, Verstraeten LMJ, Draycott A, Shutherland RA (1987) Response of winter wheat to N-fertilizer:dynamic model. Fertiliz Res 12:139–156

Greenwood DJ, Kubo K, Burns IG, Draycott A (1989) Apparent recovery of fertilizer N by vegetable crops. Soil Sci Plant Nutr 35(3):367–381

Greenwood DJ, Lemaire G, Gosse G, Cruz P, Draycott A, Neeteson JJ (1990) Decline in percentage N of C3 and C4 crops with increasing plant mass. Ann Bot 66:425–436

Greenwood DJ (1990) Production and productivity: the nitrate problem? Ann Appl Biol 117:209–231

Greenwood DJ, Neeteson JJ (1992) High yield nutrient management systems and environmental constraints: the world scene. In: Scaife A (ed) Proceedings of the 2nd European Society for Agronomy Congress, Warwick, UK, pp 386–397

Greenwood DJ, Rahn C, Draycott A, Vaidyanatha LV, 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

Grignani C, Zavattaro L (2000) A survey on actual agricultural practices and their effects on the mineral nitrogen concentration of the soil solution. Eur J Agron 12:251–268

Guerette V, Belec C, Tremblay N, Weier U, Scharpf H C (2000) N contribution from mineralization of vegetable crop residues. International society of horticultural sciences workshop “Toward an ecologically sound fertilization in field vegetable production,” 11–13 Sept 2000, Wageningen, The Netherlands

Guiducci M, Bonciarelli U, Stagnari F, Benincasa P (2004) Total N supply and profit from several green manure crops. VIII Congress of the European Society of Agronomy, 11–15 July 2004, Copenhagen, DK

Haberlandt U, Krysanova V, Bardossy A (2002) Assessment of nitrogen leaching from arable land in large river basins: Part II: Regionalisation using fuzzy rule based modelling. Ecol Model 150:277–294

Harrison R, Silgram M (1998). Final report to UK Ministry of Agriculture Fisheries and Food (MAFF) on project NT1508 (cover crops). Includes Appendix: the mineralisation of nitrogen in cover crops – a review

Hartz TK, Bendixen WE, Wierdsma L (2000) The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetables production. HortScience 35:651–656

Hartz TK (2003) The assessment of soil and crop nutrient status in the development of efficient fertilizer recommendations. Acta Hortic 627:231–240

Health Canada (1996) Guidelines for canadian drinking water quality (ed. Canadian Government Publisher). Canadian Government Publisher, Ottawa.

Hebbar SS, Ramachandrappa BK, Nanjappa HV, Prabhakar M (2004) Studies on NKP drip fertigation in field grown tomato (*Lycopersicon esculentum* Mill.). Eur J Agron 21:117–127

Heeb A (2005) Nitrogen form affects yield and taste of tomatoes. J Sci Food Agric 85:1409–1414

Heffer P (2008) Assessment of fertilizer use by crop at the global level. International Fertilizer Industry Association, Paris, France, 6 pp

Herencia JF (2007) Comparison between organic and mineral fertilization for soil fertility levels, crop macronutrient concentrations, and yield. Agron J 99:973–983

Hochmuth GJ (1992) Concepts and practices for improving nitrogen management for vegetables. HortTechnology 2:121–125

Hoel BO (2003) Chlorophyll meter readings in winter wheat: cultivar differences and prediction of grain protein content. Acta-Agric Scand Sect B, Soil Plant Sci 524:147–157

Hoffmann M, Johnsson H (1999) A method for assessing generalised nitrogen leaching estimates for agricultural land. Environ Model Assess 4:35–44

Huffman EC, Yang JY, Gameda S, de Jong R (2001) Using simulation and budget models to scale-up nitrogen leaching from field to region in Canada. Sci World 1:699–706

Jabro DJ, Jemison JM, Fox RH, Frittion DD (1994) Predicting bromide leaching under field conditions using SLIM and MACRO. Soil Sci 157:215–223

Janat M (2004) Assessment of nitrogen content, uptake, partitioning and recovery by cotton crop grown under surface irrigation and drip fertigation by using isotopic technique. Commun Soil Sci Plant Anal 35:2515–2535

Janzen HH, Kucey RMN (1988) C, N, and S mineralization of crop residues as influenced by crop species and nutrient regime. Plant Soil 106:35–41

Jimenez S, Ales JI, Lao MT, Plaza B, Perez M (2006) Evaluation of nitrate quick tests to improve fertigation management. Commun Soil Sci Plant Anal 37:2461–2469

Jin Il Cheong (1996) Effects of slow-release fertilizer application on rice grain quality at different culture methods Korean-Journal-of-Crop-Science 41(3), 286–294

Jones RD, Schwab AP (1993) Nitrate leaching and nitrite occurrence in a fine-texured soil. Soil Sci 4:272–282

Justus M, Kopke U (1995) Strategies to reduce nitrogen losses via leaching and to increase pre-crop effects when growing faba beans, nitrogen leaching in ecological agriculture. Proceedings of an international workshop, Royal Veterinary and Agricultural University, Copenhagen, Denmark, pp 145–155

Karaman MR, Saltali K, Ersahin S, Gulec H, Derici MR (2005) Modelling nitrogen uptake and potential nitrate leaching under different irrigation programs in nitrogen-fertilized tomato using the computer program NLEAP. Environ Monit Assess 101:249–259

Karitonas R (2003) Development of a nitrogen management tool for broccoli. Acta Hortic 627:125–129

Kerft A, Zuber A (1978) On the physical meaning of the dispersion equation and its solutions for different initial bounary conditions. Chem Eng Sci 33:1471–1480

Khah EM (2003) Effect of fertilizers on lettuce (*Lactuca sativa*) yield, physical and organoleptic properties. Adv Hortic Sci 17(1):47–57

Knox E, Moody DW (1991) Influence of hydrology, soil proprieties and agricultural land use on nitrogen in groundwater. Soil Sci Soc Am J 6:77

Kraft GJ, Stites W (2003) Nitrate impacts on groundwater from irrigated-vegetable systems in a humid north-central US sand plain, Agriculture. Ecosyst Environ 100:63–74

Krishnapillai M, Sri Ranjan R (2009) Non-destructive monitoring of nitrate concentration in a laboratory flow experiment using time domain reflectometry (TDR). Environ Technol 30(1):101–109

Kristensen HL, Thorup-Kristensen K (2004) Root growth and nitrate uptake of three different catch crops in deep soil layers. Soil Sci Soc Am J 68:529–537

Kucke M, Kleeberg P (1997) Nitrogen balance and soil nitrogen dynamics in two areas with different soil, climatic and cropping conditions. Eur J Agron 6:89–100

Le Bot J, Jeanniquin B, Fabre R (2001) Impacts of N-deprivation on the yield and nitrogen budget of rockwool grown tomatoes. Agronomie 21:341–350

Le Bot J, Adamowicz S, Robin P (1998) Modelling plant nutrition of horticultural crops: a review. Sci Hortic 74:47–82

Lemaire G (2008) Diagnostic tool (s) for plant and crop N status. In vegetative stage. Theory and practice for crop N management. Eur J Agron 28:614–624

Lemaire G, Gastal F (1997) N uptake and distribution in plant canopies. Diagnosis of nitrogen status in crops. In: Lemaire G (ed) Diagnosis of nitrogen status in crops. Springer, Berlin, pp 3–41

Li Z (2003) Use of surfactant-modified zeolite as fertilizer carriers to control nitrate release. Microporous and Mesoporous Material 61:181–188

Li J, Zhang J, Rao M (2004) Wetting pattern and nitrogen distributions as affected by fertigation strategies from a surface point source. Agric Water Manage 67:89–104

Li J, Hu C, Delgado JA, Zhang Y, Ouyang Z (2007) Increasing nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in North China Plain. Agric Water Manage 89:137–147

Lilburne L, Web T (2002) Effect of soil variability, within and between soil taxonomic units, on simulated nitrate leaching under arable farming. Australian Journal of Soil Research 40:1187–1199

Linaje A, Munoz-Guerra L, Carrasco I (2005) Evaluation of the use of nitrification inhibitor DMPP on the risk of nitrate leaching in different crop system in Spain. In: Schroder JJ, Neeteson JJ (eds) N Management in Agrosystems in relation to the Water Frame Directive. Proceedings of 14th N Workshop, 2005, Maastricht, The Netherlands, pp 149–152

Locascio SJL, Smajstrla AG (1995) Fertilizer timing and pan evaporation scheduling for drip irrigated tomato. In: Lamm FR (ed) Microirrigation for a changing world: conserving resources/preserving the environment 4-95. ASAE, Los Angeles, CA, pp 175–180

Lord EI, Mitchell RD (1998) Effect of nitrogen inputs to cereals on nitrate leaching from sandy soils. Effect of nitrogen inputs to cereals on nitrate leaching from sandy soils. Soil Use Manage 14(2):78–83

Lord EI, Johnson PA, Archer JR (1999) Nitrate sensitive areas: a study of large scale control of nitrate loss in England. Soil Use Manage 15:201–207

Lord EI, Anthony S (2000) MAGPIE: a modelling framework for evaluating nitrate losses at national and catchment scales. Soil Use Manage 16:167–174

Lord EI, Shepherd M, Silgram M, Goodlass G, Gooday R, Anthony A, Davison P, Hodgkinson R (2007). Investigating the effectiveness of NVZ Action Programme measures: development of a strategy for England. Final report for UK Defra project NIT18. 116pp + 11 Appendices. http://www.defra.gov.uk

Lorenz HP, Schaghecken J, Engl G, Maync A, Zegler J (1989) Ordnungsgemäβe Stikstoff-Versorgung im Freiland – Gem_sebau - KNS system. Rheinland Pfhalz: Ministerium fur Landwritschaf, Weinbau und Forsten ISSN 0931-9026 1089391-3000

Lorenz OA, Tyler KB (2007) Plant tissue analysis of vegetable crops. vric.ucdavis.edu/veginfo/topics/fertilizer/tissueanalysis.pdf Accessed on August 2009

Ma CH, Kalb T (2006) Development of starter solution technology as a balanced fertilization practice in vegetable production. Acta Hortic 700:173–185

Macdonald AJ, Poulton PR, Howe MT, Goulding KWT, Powlson DS (2005) The use of cover crops in cereal-based cropping systems to control nitrate leaching in SE England. Plant Soil 273:355–373
MAFF (2000) Fertiliser recommendations for agricultural and horticultural crops. MAFF reference book 209. HMSO, London
Makowsky D, Guichard L, Beaudoin N, Aveline A, Lurent F (2005) A method to compare the accuracy of inidators of water pollution by nitrates. In: Schroder JJ, Neeteson JJ (eds) N management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 33–35
Mantovani P, Soldano M, Moscatelli G, Tabaglio V (2005) Nitrification inhibitors addition to summer and autumn-applied pig slurry: effects on soil, water and atmosphere. In: Schroder JJ, Neeteson JJ (eds) N Management in Agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 152–157
Marcelis L-FM, Heuvelink E, Goudriaan J (1998) Modelling biomass production and yield of horticultural crops: a review. Sci Hortic 74:83–111
Mastrorilli M (1999) Modellizzazione. Sviluppo di modelli idrologici per ambienti mediterranei. Boll SISS 48(1):245–250
Matthaus D, Gysi E (2001) Plant sap analysis in vegetables a tool to decide on nitrogen top dressing. Acta Hortic 506:93–102
Maynard DN, Barker AV, Minotti PL, Peck NH (1976) Nitrate accumulation in vegetables. Adv Agron 28:71–117
Meinardi CR, Beusen AHW, Bollen MJS, Klepper O, Willems WJ (1995) Vulnerability to diffuse pollution and average nitrate contamination of european soils and groundwater. Water Sci Tech 31:159–165
Mempel H, Meyer J (2002) Environmental system analysis for horticultural crop production. Acta Hortic 638:45–51
Meynard JM, Guichard L, Jeuffroy MH, Makowsky D (2002) Which decision support tools for the environmental management of nitrogen? Agronomie 22:817–829
Mills HA, Jones JB (1996) Plant analysis handbook II. Macro-Micro Publishing, Athens, GA
Mohammad MJ (2004) Squash yield, nutrient content and soil fertility parameters in response to methods of fertilizer application and rates of nitrogen fertigation. Nutr Cycl Agroecosyst 68:99–108
Moreno F, Cayuela JA, Fernandez JE, Fernandez-Boy E, Murillo JM, Cabrera F (1996) Water balance and nitrate leaching in an irrigated maize crop in SW Spain. Agric Water Manage 32:71–83
Müller T, Thorup-Kristensen K (2001) N-fixation of selected green manure plants in an organic crop rotation. Biol Agric Hortic 18:345–363
Narayan MS (2002) Effect of sugar and nitrogen on the production of anthocyanin in cultured carrot (*Daucus carota*) cells. J Food Sci 67(1):84–86
Neeraja G, Reddy KM, Reddy IP, Reddy YN (1999) Effect of irrigation and nitrogen on growth yield and yield attributes of rabi onion (*Allium cepa*) in Andhra Pradesh. Veg Sci 26:64–68
Neeteson J, Langeveld J, de Haan J (2003) Nutrient balances in field vegetable production systems. Acta Hortic 627:13–23
Neeteson JJ, Carton OT (2001) The environmental impact of nitrogen in field vegetable production. Acta Hortic 563:21–28
Neeteson JJ, Booij R, Dijk W van, Haan J de, Pronk A, Brinks H, Dekker P, Langeveld H (2001) Projectplan Telen met toekomst. Appl Plant Res, Publicatie nr. 2, Lelystad
Neeteson JJ (1995) Nitrogen management for intensively grown arable crops and field vegetables. In: Bacon PE (ed) Nitrogen fertilization in the environment. Marcel Dekker, New York, Chapter 8, pp 295–325
Neeteson JJ (1989) Evaluation of the performance of three advisory methods for nitrogen fertilisation of sugar beet and potatoes. Neth J Agric Sci 37:143–155
Neurkirchen D, Lammel J (2002) The chlorophyll content meter as an indicator for nutrient and quality management. Fertiliz Fert 2:89–109

Normand B, Recous S, Vachaud G, Kengni L, Garino B (1997) Nitrogen-15 tracers combined with tensio-neutronic method to estimate the nitrogen balance of irrigated maize. Soil Sci Soc Am J 61:1508–1518
Oenema O, Kros H, de Vries W (2003) Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur J Agron 20:3–16
Olivier M, Goffart JP, Ledent JF (2006) Threshold value for chlorophyll meter as decision tool for nitrogen management of potato. Agron J 98:496–506
Olson SM, Simonne EH (eds) (2006) Vegetable production handbook for Florida. University of Florida, IFAS Extension, Gainesville, FL
Osborne SL (2006) Starter nitrogen fertilizer impact on soybean yield and quality in the Northern Great Plains. Agron J 98:1569–1574
Owen J, Scharpf HC, Weier U, Laurence H, Tremblay N (2003) Extension of practical solutions for efficient nitrogen management of vegetables crops: a comprehensive guide developed using a unique approach. Acta Hortic 627:161–163
Paschold J, Artelt B, Hermann G (2003) Influence of N-nutritional and catch crops on the yield of asparagus (*Asparagus officinalis* L.) and N-leaching. Acta Hortic 627:57–64
Paschold J, Artelt B, Hermann G (2001) Influence of N_{min} target values on Fertilisers need, yield and N_{min} residues in Asparagus. Acta Hortic 563:53–58
Paschold J, Scheunemann Ch (1989) Controlling output level in the white cabbage by assessing N-fertilization on the basic of soil and plant analyses. Acta Hortic 260:313–328
Pasda G, Hahndel R, Zerella W (2001) Effect of fertilizers with the new nitrification inhibitor DMPP (3.4 Dimethylpirazole phosphate) on yield and quality of agricultural and horticultural crops. Biol Fertil Soils 34:85–97
Pavlou GC (2007) Effect of organic and inorganic fertilizers applied during successive crop seasons on growth and nitrate accumulation in lettuce. Sci Hortic 111(4):319–325
Peltonen J (1994) Effect of nitrogen fertilizers differing in release characteristics on the quantity of storage proteins in wheat. Cereal-Chem 71:1–5
Phene CJ (1999) Efficient irrigation systems and irrigation scheduling for processing tomato: the challange. Acta Hortic 487:479–485
Piekielek WP, Fox RH (1992) Use of a chlorophyll meter to predict sidedress nitrogen requirements for maize. Agron J 84:59–65
Pimpini F, Gianquinto G, Sambo P (2005) Organic vegetable production: evolution, base principles and quality of products. Italus Hortus 12(4):31–44
Prasad M, Simmons P, Maher MJ (2004) Release characteristics of organic fertilisers. Acta Hortic 644:163–170
Rabbinge R, Rossing W (2000) Meeting the demand for ecological modernization in horticulture: the role of systems approaches. Acta Hortic 525:115–121
Radersma S, van Evert F (2005) Crop related indicators: is the crop able to tell the farmers what to do? In: Schroder JJ, Neeteson JJ (eds) N management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 247–249
Radersma S, van Geel W, Smit A, van Wess N (2005) Decision support systems for nitrogen fertilization to maintain production and reduce potential N-Losses: main questions ad answers in the Netherlands. In: Schroder JJ, Neeteson JJ (eds) N management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N Workshop, 2005, Maastricht, The Netherlands, pp 266–269
Rahn CR, Bending GD, Lillywhite RD, Turner MK (2003) Novel techniques to reduce environmental N pollution from high nitrogen content crop residues. Acta Hortic 627:105–111
Rahn C (2002) Management strategies to reduce nutrient losses from vegetables crops. Acta Hortic 571:19–25
Rahn C, DeNeve S, Bath B, Bianco V, Dachler M, Cordovil C, Fink M, Gysi C, Hofman G, Koivunen M, Panagiotopoulos L, Poulain D, Ramos C, Riley H, Setatou H, Sorensen J, Titulaer H, Weier U (2001) A comparison of fertiliser recommendation systems for cauliflowers in Europe. Acta Hortic 563:39–45

Rahn CR, Greenwood DJ, Draycott A (1996) Prediction of nitrogen fertilizer requirement with HRI WELL_N Computer Model. Progress in Nitrogen Cycling. Proceedings of the8th nitrogen fixation workshop, University of Ghent, Belgium, 5–7 Sept 1994 Kluwer, Dordrecht, pp 255–258

Rahn CR, Paterson C, Vaidyanatha LV (1993) Improving the use of nitrogen in brassicae rotations. Acta Hortic 339:207–218

Rahn CR, Vaidyanathan LV, Paterson CD (1992) Nitrogen residues from *Brassica* crops. Aspects Appl Biol 30:263–270

Rajput TBS, Patel N (2006) Water and nitrate movement in drip-irrigated onion under fertigation and irrigation treatments. Agric Water Manage 79:293–311

Ramos C, Agut A, Lidon A (2002) Nitrate leaching in important crops of the Valencian community region (Spain). Environ Pollut 118:215–223

Randall GW, Goss MJ (2001) Nitrogen losses to surface water through subsurface, tile drainage. In: Follet RF, Hatfield JL (eds) Nitrogen in the environment: sources, problems and management. Elsevier Science, Amsterdam, pp 95–122

Remie B, Groenwold K, Rovres J, Clevering O, Pijnenburg H, Hekkert M, Lagenveld H (2003) Nutrient management on vegetables farms: what will be the future? Acta Hortic 627:275–282

Riley H, Guttormsen G (1999) Alternative equations for critical N-concentration in cabbage. Acta Hortic 506:123–128

Romic D, Romic M, Borosic J, Poljak M (2003) Mulching decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. Agric Water Manage 60(2):87–97

Rühlmann J (1999) Calculation of net nitrogen mineralization from the decomposable soil organic matter pool. Acta Hortic 506:167–174

Salo T, Raisio R, Tiilikkala K (2001) Effectiveness of fertilizer recommendation in Finnish carrot and pea production. Acta Hortic 506:37–40

Schaller RG (2000) Nitrogen nutrition and flavour compounds of carrots (*Daucus carota* L) cultivated in Mitscherlich pots. J Sci Food Agric 80:49–56

Scharpf HC (1991a) Dungenfenster: Fruhwarnsysteme fur dien-VersotgungLnad Und Forst, Heft, 10:S.24

Scharpf HC (1991b) Stickstoffdünung im Gemüsebau., AID-Heft 1223. Bonn; Auswertungs-undInformationdienst für Ernährung, Landwirstschaft und Forsten e.V

Schenk MK (2006) Nutrient efficiency of vegetable crops. Acta Hortic 700:25–38

Schroder J, Neeteson J, Oenema O, Struik P (2000) Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crop Res 66:151–164

Scudlark JR, Russell KM, Galloway JN, Church TM, Keene WC (1998) Organic nitrogen in precipitation at the Mid-Atlantic U.S. coast – methods evaluation and preliminary measurements. Atmos Environ 32:1719–1728

Seddaiu G, Iezzi G, Roggero PP (2007) Fissazione e trasferimento dell'azoto fissato dal favino al frumento duro in successione. Atti del "XXXVII Convegno Nazionale della Società Italiana di Agronomia", 13–14 Settembre 2007, Catania, Italy

Sexton P, Carroll J (2002) Comparison of SPAD chlorophyll meter readings vs. petiole nitrate concentration in sugarbeet. J Plant Nutr 25:1975–1986

Shaffer MJ, Delgado JA (2002) Essentials of a national nitrate leaching index assessment tool. J Soil Water Conserv 57:327–335

Shaffer MJ, Halvardson DA, Pierce FC (1991) Nitrate leaching and economic analysis package (NLEAP): model description and application. In: Follet RF, Keeney DR, Cruse RM (eds) Managing nitrogen for groundwater quality and farm profitability. ASA, SSA and CSSA, Madison, WI, pp 285–322

Sibley KJ (2008) Development and use of an automated on-the-go soil nitrate mapping system. Doctoral Thesis, Wageningen University, Wageningen, The Netherlands

Sidat Y, Upendra M, Bharat P (2000) Fresh market tomato yield and soil nitrogen as affected by tillage, cover cropping and nitrogen fertilisation. HortScience 35:1258–1262

Silber A, Xu G, Wallach R (2003) High irrigation frequency: the effect on plant growth and on uptake of water and nutrients. Acta Hortic 627:89–96

Silgram M, Hatley D, Gooday R (2007) IRRIGUIDE: a decision support tool for drainage estimation and irrigation scheduling. Proceedings of the 6th biennial conference of the European federation of IT in agriculture (EFITA)/world congress on computing in agriculture (WCCA) 2007 joint conference "Environmental and rural sustainability", Glasgow, UK, 2–5 July 2007

Silgram M (2005) Effectiveness of the nitrate sensitive areas scheme (1994–2003). Final report to UK Defra under project M272/56. 22pp. http://www.defra.gov.uk. Accessed on August 2009

Silgram M, Williams A, Waring R, Neumann I, Hughes A, Mansour M (2004) Effectiveness of the nitrate sensitive areas scheme in reducing groundwater concentrations. Q J Environ Geol Hydrogeol 38:117–127

Silgram M, Williams A, Waring R, Neumann I, Hughes A, Gaus I, Mansour M (2003) Assessment of the effectiveness of the nitrate sensitive areas scheme in reducing nitrate concentrations in groundwater. Technical report for UK Environment Agency R&D Project P2-267/2/TR. ISBN 1844320758. Environment Agency, Bristol, UK. 90 pp + 2 Appendices

Silgram M, Chambers BJ (2002) The effects of repeated straw incorporation on soil mineral nitrogen supply, fertiliser N requirements and nitrate leaching losses. J Agric Sci (Cambridge) 139(2):115–127

Silgram M, Shepherd M (1999) The effects of cultivation on soil nitrogen mineralisation. Adv Agron 65:267–311

Simonne EH, Hochmuth GJ (2006) Soil and fertilizer management for vegetable production in Florida. In: Olson SM, Simonne EH (eds) Vegetable production handbook for Florida, 2005/2006. Vance Publishing, Lenexa, KS, pp 3–15

Simonne EH, Studstill DW, Hochmuth RC (2006) Understanding water movement in mulched bed on sandy soils: an approach to ecologically sound fertigation in vegetable production. Acta Hortic 700:173–178

Simonne EH, Studstill DW, Hochmuth RC, Jones JT, Starling CW (2005) On-farm demonstration of soil water movement in vegetables grown with plasticulture. Electronic Database Info. System, HS 1008. http://edis.ifas.ufl.edu/HS251

Simonne EH, Studstill D, Hochmuth RC, McAvoy G, Dukes MD, Olson SM (2003) Visualization of water movement in mulched beds with injections of dye with drip irrigation. Proc Fla State Hortic Soc 116:88–91

Singandhupe RB, Rao GGSN, Patil NG, Brahmanand PS (2003) Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicon esculentum* L.). Eur J Agron 19:327–340

Smit A, Hann de J, Zwart K (2005) Farming for the future; can arable and horticultural on sandy soils comply with the EU nitrate directive. Results from the nucleus farms Vredepeel and Meterik. Telen net toekomst raposrt, Plant Research International, Wageningen, The Netherlands.

Smit AB, Stoorvogel JJ, Wossink GAA (2000) A methodology to support the decision to invest in spatially variable nitrogen fertilisation. Neth J Agric Sci 48(3–4):273–290

Smith FW, Loneragan JF (1997) Interpretation of plant analysis: concepts and principles. In: Reuter DJ, Robinson JB (eds) Plant analysis: an interpretation manual, 2nd edn. Commonwealth Scientific and industrial research organization, Collingwood, Victoria, pp 3–33

Soler-Rovira J, Aroyo-Sanz J, Soler-Rovira P (2005) Nitrogen flow analysis in the Spanish agriculture and flow production system. In: Schroder JJ, Neeteson JJ (eds) N Management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 36–39

Souza CF, Folegatti MV, Matsura EE, Or D (2006) Time domain reflectometry (TDR) calibration for estimating soil solution concentration. Engenharia Agricola 28(1):282–291

Stenger R, Priesack E, Barkle G, Sperr G (1999) A tool for simulating nitrogen and carbon dynamics in the soil-plant atmosphere system. In: Tomer M, Robinson, M, Gielen G (eds) Proceedings of the technical session No 20. New Zealand Land Treatment Collective, New Plymouth, NZ, pp 19–28

Stevens CJ, Quinton John N (2009) Pollution swapping in arable agricultural systems. Crit Rev Environ Sci Technol 39(6):478–520

Sulas L, Canu S, Muresu R (2007) Azotofissazione e sovescio di una coltura di favino per la gestione della fertilità in sistemi cerealicolo-foraggeri biologici mediterranei. 3rd Workshop GRAB-IT, Roma

Suprayago D, Van Noordwijk M, Hairiah K, Cadisch G (2002) The inherent 'safety-net' of an Acrisol: measuring and modelling retarded leaching of mineral nitrogen. Eur J Soil Sci 53(2):185–194

Sweeney D, Graetz D, Bottcher A, Locascio S, Campbell K (1987) Tomato yield and nitrogen recovery as influenced by irrigation method, nitrogen source and mulch. HortScience 22:27–29

Swiader J, Moore A (2002) SPAD-chlorophyll response to nitrogen fertilization and evaluation of nitrogen status in dryland and irrigated pumpkins. J Plant Nutr 25:1089–1100

Taber HG (2001) Petiole sap nitrate sufficiency values for fresh market tomato production. J Plant Nutr 24:945–959

Tei F, Benincasa P, Guiducci M (2003) Critical nitrogen concentration in lettuce. Acta Hortic 627:187–194

Tei F, Benincasa P, Guiducci M (2002) Critical nitrogen concentration in processing tomato. Eur J Agron 18:45–55

Tei F, Benincasa P, Guiducci M (2000) Effect of nitrogen availability on growth and nitrogen uptake in lettuce. Acta Hortic 533:385–392

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

Thompson RB, Granado M, Gasquez J, Gallardo M, Giménez C (2005) Nitrate leaching losses from a recently developed intensive horticultural system in a previously disadvantaged region. In: Schroder JJ, Neeteson JJ (eds) N management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 420–423

Thompson RB, Gallardo M, Giménez C (2002) Assessing risk of nitrate leaching from the horticultural industry of Almeria, Spain. Acta Hortic 571:243–245

Thorup-Kristensen K, Pedersen L (2006) Cropping systems with winter wheat or spring wheat? Root growth, catch crops, nitrogen leaching, and baking quality. Proceedings of European joint organic congress, 30–31 May 2006, Odense, DK.

Thorup-Kristensen K, Magrid J, Stroumann Jensen L (2003) Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv Agron 79:227–302

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

Thorup-Kristensen K, Van der Boogard R (1999) Vertical and horizontal development of the root system of carrots following green manure. Plant Soil 212:145–153

Thorup-Kristensen K, Sørensen JN (1999) Soil nitrogen depletion by vegetable crops with variable root growth. Acta Agric Scand, Sect B – Soil Plant Sci 49:92–97

Thorup-Kristensen K, Nielsen NE (1998) Modelling and measuring the effect of nitrogen catch crops on the nitrogen supply for succeeding crops. Plant Soil 203:79–89

Thorup-Kristensen K (1994) The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. Fertliz Res 37:227–234

Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D (2001) Forecasting agriculturally driven global environmental change. Science 292:281–284

Tosti G (2008) Green manure and nitrogen fertility management in organic farming systems. Doctoral Thesis, University of Perugia, Italy

Tosti G, Boldrini A, Benincasa P, Tei F, Guiducci M (2008) The N Nutritional Status of Processing Tomato Grown after Green Manures. Proceedings of the 10th congress of the European society for agronomy "Agriculture as resource for energy and environmental preservation-multifunctional agriculture", Bologna, Italy, 15–18 Sept 2008

Tremblay N, Belec C (2005) Strategies for environmental responsible N management using state of the art crop sensing tools. In: Schroder J.J. and Neeteson J.J (eds) N management in

agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 279–281
Tremblay N, Scharpf HC, Weier U, Laurence H, Owen J (2003) Nitrogen management in field vegetables. Ed Agriculture et Agroalimentaire Canada, Cat. No. A42-92/2001E-INISBN 0-662-30494-2
Uhte R (1995) Integration of ecological aspects within economical decision support models for vegetable crop production. Ber Landwirtsch 73:33–50
University of Minnesota (1996) Nitrate test offers economic, environmental benefits for potato farmers. News information, Minnesota's Future 64
US Environmental Protection Agency (1989). National Primary and Secondary Drinking Water Regulations, proposed Rule, Fedd. Reg., 54: 22077. USEPA, Washington, DC
Van Alphen BJ, Stoorvogel JJ (2000) A methodology for precision nitrogen fertilization in high-input farming systems. Precision Agric 2(4):319–332
Van Dijk W, Smit AL (2006) How to meet the EC-nitrate directive in Dutch vegetable growing? Acta Hortic 700:197–204
Vazquez N, Pardo A, Suso ML, Quemada M (2006) Drainage and nitrate leaching under processing tomato growth with drip irrigation and plastic mulching. Agric Ecosyst Environ 112:313–323
Vazquez N, Pardo A, Suso ML, Quemada M (2005) A methodology for measuring drainage and nitrate leaching in unevenly irrigated vegetables crops. Plant Soil 269:297–308
Vigil MF, Kissel DE (1991) Equations for estimating the amount of nitrogen mineralized from crop residues. Soil Sci Soc Am J 55:757–761
Visser de P, Voogt W, Heinen M, Assinck F (2005) Reduction of nitrate from intensive arable cropping y specific crop management. In: Schroder JJ, Neeteson JJ (eds) N Management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands
Vitosh ML, Silvia GH (1996) Factors affecting potato petiole sap nitrate tests. Commun Soil Sci Plant Anal 27:1137–1152
Vitosh ML, Silvia GH (1994) A rapid petiole sap nitrate–nitrogen test for potatoes. Commun Soil Sci Plant Anal 25:183–190
Vos J, Vereijken P, van der Werf A (2005) Managing N by catch crops and buffer strips. In: Schroder JJ, Neeteson JJ (eds) N Management in agrosystems in relation to the Water Frame Directive. Proceedings of 14th N workshop, 2005, Maastricht, The Netherlands, pp 225–227
Vos J, van der Putten P (2004) Nutrient cycling in cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. II Effect of catch crop on nitrate leaching in autumn and winter. Nutr Cycl Agroecosyst 70:23–31
Wehrmann J, Scharpf H (1986) The Nmin method-an aid to integrating various objectives of nitrogen fertilization. Z Pflanzenernaerh Bodenk 149:337–344
Weier U, van Riesen U, Scharpf HC (2001) Nmin-N-plots: a system to estimate the amount of nitrogen top dressing of vegetables. Acta Hortic 563:47–52
Westerveld SM, McKeown AW, Scott-Dupree CD (2003) Chlorophyll and nitrate meters as nitrogen monitoring tools for selected vegetables in Southern Ontario. Acta Hortic 627:259–266
Whitmore AP (1996) Modellling the release and loss of nitrogen after vegetable crops. Neth J Agric Sci 44:73–86
Wiesler F, Bauer M, Kamh M, Engels Th, Reusher S (2002) The crops as indicators for side-dress nitrogen demand in sugar beet production, limitations and perspectives. J Plant Nutr Soil Sci 165:93–99
Zhang YM, Hu CS, Zhang JB, Chen DL, Li XX (2005) Nitrate leaching in an irrigated wheat-maize rotation field in the North China Plain. Pedosphere 15:196–203