Advances in Olericulture

Francesco Tei · Silvana Nicola
Paolo Benincasa *Editors*

Advances in Research on Fertilization Management of Vegetable Crops

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Preface

In the last decades, research on fertilization management in vegetables aimed at producing economical yields with reduced fertilizer inputs by the development and implementation of cropping systems, nutrient management approaches and crop varieties. Examples of the interventions in cropping systems include adequate crop rotations, intercropping, double cropping and other strategies for a better soil organic matter management; nutrient management approaches include modelling, decision support systems, crop nutritional status testing and precision agriculture technologies; amelioration of crop varieties has been directed towards higher nutrient/fertilizer use efficiency. Hence, the aim of this book is to review the recent literature on the key scientific and technical subjects of fertilization management in vegetable crops.

The book consists of ten chapters.

Chapter "The Role of Research for a Sustainable Fertilization Management in Vegetables: Future Trends and Goals", by the editors of the book, is the introduction to the book, presenting the importance of the fertilization as one of the agricultural practices in vegetable production and the rationale of the need for enhancing efficient fertilization strategies for the twenty-first century.

Chapter "Tools and Strategies for Sustainable Nitrogen Fertilisation of Vegeta ble Crops", by Thompson et al., presents and discusses the tools and strategies for sustainable nitrogen fertilization, including methods for soil analysis or estimation of the soil N supply, N balance calculations, methods based on plant analysis, methods based on monitoring crops with optical sensors and the use of computerized decision support systems based on simulation models.

Chapter "Organic Matter Mineralization as a Source of Nitrogen", by De Neve, is focused on the organic matter mineralization as a source of nitrogen. It provides details on the biotic and abiotic factors governing the process, introducing simple empirical equations that allow making rapid estimates of N mineralization, describing the different types of organic materials with respect to expected N availability and pointing out the importance of synchronizing N mineralization with crop N demand.

Chapter "Fertilizers: Criteria of Choice for Vegetable Crops", by Sambo and Nicoletto, reviews the main mineral fertilizers and traditional and innovative organic materials (i.e. compost, sewage sludge, anaerobic digestion residues and spent mushrooms compost) and the criteria of choice for vegetable crops.

Chapter "Crop Rotation as a System Approach for Soil Fertility Management in Vegetables", by Benincasa et al., deals with crop rotation as one of the key strategies of conservative agriculture, aimed at guaranteeing the long-term productivity and sustainability of vegetable cropping systems. Mineral and organic fertilization, crop residue management, cover cropping and green manuring and intercropping are examined in the frame of crop rotations in conventional and organic systems for either specialized or non-specialized vegetable production.

Chapter "Localized Application of Fertilizers in Vegetable Crop Production", by Simonne et al., focuses on principles and practices of the localized application (i.e. modified broadcast method, banding application method, fertigation method) in vegetable crop production in order to increase the uptake rate of applied nutrients, thereby reducing the application rates, the fertilization cost and the environmental impact of vegetable production.

Chapter "Water and Nutrient Supply in Horticultural Crops Grown in Soilless Culture: Resource Efficiency in Dynamic and Intensive Systems", by Pignata et al., analyses fertilization management for the different soilless culture systems for efficient and effective control of product quality and environmental sustainability in vegetable crop production. The chapter presents the characteristics and the controls of the substrate-based and liquid-based soilless culture systems in relation to irrigation and fertigation applications, both in open-cycle and closed-cycle hydroponic systems.

Chapter "Plant Breeding for Improving Nutrient Uptake and Utilization Efficiency", by Ferrante et al., deals with physiological, biochemical and molecular traits affecting nitrogen uptake by roots and new plant breeding approaches for improving nutrient uptake and utilization efficiency in plants.

Chapter "Water Management for Enhancing Crop Nutrient Use Efficiency and Reducing Losses", by Gabriel and Quemada, covers water management strategies oriented towards improving nutrient use efficiency, reducing nutrient losses and maintaining farm profitability in horticultural systems.

Chapter "An Economic Analysis of the Efficiency and Sustainability of Fertilization Programmes at the Level of Operational Systems, with Case Studies on Table Tomato, Carrot and Potato in Central Italy", by Martino et al., presents an economic analysis of the efficiency and sustainability of fertilization programmes conducted at the farm level and framed into a conceptualization of the relationship between the decisional and operational systems.

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The Role of Research for a Sustainable Fertilization Management in Vegetables: Future Trends and Goals

Francesco Tei, Silvana Nicola, and Paolo Benincasa

Abstract Global vegetable production amounts to 1.13 billion tonnes from about 58 million of hectares; in the last decade global vegetable production increased at an average annual rate of around 3% although significant variability can be found in function of the region and the country. Beyond their monetary value, vegetables are important dietary sources of micronutrients so sustainable fertilization management should be aimed to produce healthy and environmentally sustainable vegetables by taking into considerations peculiarities of the vegetable production. Vegetables represent about 9% of the world market in fertilizer consumption (i.e. about 16 Mt, of which 9.1% of N, 9.4 of P_2O_5 and 10.0% of K_2O). In the twenty-first century the research would be aimed at producing economical yields with reduced fertilizer inputs by the development and implementation of cropping systems, nutrient management approaches and crop varieties both showing higher nutrient/fertilizer use efficiency.

Keywords Vegetable production • Fertilizer consumption • Fertilization management • Sustainability • Trends • Research

1 Vegetable Production in the World

Global vegetable production amounts to 1.13 billion tonnes from about 58 million of hectares (FAO 2013). Asia produces about 77% of the world's vegetables (about 876 Mt from 43 Mha) followed by Europe (96 Mt, 4 Mha), Americas (82 Mt, 4 Mha with Northern America 36 Mt, 1.1 Mha – Central America 16 Mt, 0.8 Mha – South America 26 Mt, 1.3 Mha) and Africa (74 Mt, 7 Mha).

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Table 1 Top 20 countries for vegetable production in the world

Country	Tonnes	%	Country	ha	%
China	583,321,399	51.5	China	24,422,301	42.1
India	121,015,200	10.7	India	8,649,190	14.9
USA	34,279,961	3.0	Nigeria	1,897,003	3.3
Turkey	28,280,809	2.5	Turkey	1,117,618	1.9
Iran	23,651,582	2.1	USA	1,050,648	1.8
Egypt	19,590,963	1.7	Indonesia	1,015,293	1.8
Russia	15,485,353	1.4	Vietnam	939,214	1.6
Vietnam	14,975,501	1.3	Iran	868,475	1.5
Mexico	13,238,236	1.2	Russia	791,516	1.4
Italy	13,049,171	1.2	Egypt	753,942	1.3
Spain	12,701,300	1.1	Philippines	726,009	1.3
Nigeria	11,923,961	1.1	Mexico	671,764	1.2
Brazil	11,458,208	1.0	Ukraine	575,920	1.0
Japan	11,314,562	1.0	Cameroon	535,311	0.9
Republic of Korea	10,435,325	0.9	Thailand	513,219	0.9
Indonesia	10,243,856	0.9	Italy	509,557	0.9
Uzbekistan	10,042,155	0.9	Brazil	468,698	0.8
Ukraine	9,872,600	0.9	Ethiopia	425,520	0.7
Algeria	6,788,809	0.6	Japan	391,184	0.7
Philippines	6,367,844	0.5	Spain	336,400	0.6
World	1,132,599,514			57,992,483	

Source: FAOSTAT (2013)

China is the world's largest vegetable producer (about 580 Mt from 24 Mha) followed by India (121 Mt, 9 Mha), USA (35 Mt, 1.1 Mha), Turkey (28 Mt, 1 Mha), Iran (24 Mt, 0.9 Mha) and Egypt (20 Mt, 0.8 Mha) (Table 1). Italy (13 Mt, 0.51 Mha) is the largest producer in the European Union (64 Mt, 2.3 Mha) followed by Spain (12,7 Mt, 0.34 Mha). Mexico (13 Mt, 0.67 Mha) is the largest vegetable producer in the Latin America, followed by Brazil (11 Mt, 0.47 Mha) (Table 1). In Africa, the leading producing countries are Egypt (20 Mt, 0.75 Mha), Nigeria (12 Mt, 1.9 Mha) and Algeria (6.8 Mt, 0.33 Mha) followed by Morocco (5.6 Mt, 0.19 Mha), Tunisia (3.3 Mt, 0.14 Mha), South Africa (2.8 Mt, 0.16 Mha), Tanzania (2.6 Mt, 0.38 Mha), Cameroon (2.6 Mt, 0.54 Mha), Kenya (2.4 Mt, 0.17 Mha) and Ethiopia (1.9 Mt, 0.43 Mha).

In the last decade global vegetable production increased at an average annual rate of around 3% but significant variability can be found in function of the region and the country (FAO 2013):

- in Asia and the Pacific region vegetable production increased on average at the rate of about 6% per year with the fastest progress in India (13.7%) and Malaysia (7.9%) (FAO 2014b);
- Central Asia registered the fastest growth over the period, with 8.4% per year on average, with Uzbekistan that expanded production at the annual rate of 9.4%,

Kazakhstan at the rate of 7% and Tajikistan of almost 13%, but from a significantly smaller production base (FAO 2014c); growth was more contained in the Caucasus and Turkey (1.3% per year), but this area produced almost twice as much as Central Asia;
- Near East recorded an average rate of 4.5% with the Islamic Republic of Iran recording the highest annual growth rates (6.7%, FAO 2014e);
- in Africa growth in vegetable production was 3.4% per year with Algeria showing annual growth rate of 7.3% (FAO 2014a);
- Latina America recorded low annual rates (2.3% on average) but with a very good perfomance in Honduras (6.2%) and Brazil (4.4%) (FAO 2014d);
- In Europe (FAO 2014c) the increases of the vegetable production recorded in South Eastern Europe (2.8% per year) and CIS Europe (3.6% annual growth) have been offset by a stagnation or negative growth in the European Union countries: in CIS Europe, Ukraine surged ahead at 5.6% per year, while the Russian Federation grew at 2.5%; Central and Eastern EU showed zero production growth over the decade and reduced its vegetable planting area by 2.4% per year; production slowed by 0.3% in Poland, but expanded at the annual rate of 1.3% in Romania; Italy and Spain, the biggest producers in the group, saw their output cut over by 1.3% and 0.3% per year, respectively (planted area also receded).

2 Health and Economic Benefits from Vegetables

Beyond their monetary value, vegetables (and fruits) are important dietary sources of micronutrients and their sufficient daily consumption could help prevent major diseases, such as cardiovascular diseases and certain cancers. The World Health Organization (WHO) estimates that approximately 16.0 million (1.0%) disability adjusted life years (DALYs, a measure of the potential life lost due to premature mortality and the years of productive life lost due to disability) and 1.7 million (2.8%) of deaths worldwide are attributable to low fruit and vegetable consumption. Moreover, insufficient intake of fruit and vegetables is estimated to cause around 14% of gastrointestinal cancer deaths, about 11% of ischaemic heart disease deaths and about 9% of stroke deaths globally.

WHO and FAO recommend a minimum of 400 g of fruit and vegetables per day (excluding potatoes and other starchy tubers) for the prevention of chronic diseases such as heart disease, cancer, diabetes and obesity, as well as for the prevention and alleviation of several micronutrient deficiencies, especially in less-developed countries (FAO/WHO 2005).

Meeting the rising global demand for fruits and vegetables can create opportunities for poor farmers in developing countries but improvements in supply chain efficiency, reduction of post-harvest losses, improvement of small farmers technical knowledge and investments in infrastructure are deemed necessary throughout the world (FAO 2009).

3 Peculiarities of Fertilization in Vegetable Crops

A sustainable fertilization management is perfectly in line with the aim to produce healthy and environmentally sustainable vegetables (FAO 2009) but it should take into considerations some peculiarities of the vegetable production:

1. a high number of grown species (more than 50 species catalogued; European Commission 2016);
2. a very limited acreage of each vegetable crop, both at global and regional level, in comparison with maize, wheat, rice, oilseed, root and tuber crops (FAOSTAT 2013);
3. a small extension of farm producing vegetables;
4. a large variability of farming systems (e.g. large farm to smallholding; specialised vegetable production to urban and peri-urban vegetable farming) characterised by a large variability of technological level, marketing and trade ability;
5. different growing systems (i.e. open field, protected cultivation), planting time, destination (i.e. fresh market, frozen, canned, minimally processed) often within a single species;
6. frequent intensive cropping systems with high cropping intensity (i.e. number of vegetable crops grown in a piece of land per annum) and/or short crop rotation;
7. a relatively low nutrient use efficiency shown by vegetable crop species (Benincasa et al. 2011; Bindraban et al. 2015; Greenwood et al. 1989; Janssen 1998; Schenk 2006);
8. scientific and public concern about environmental sustainability of vegetable cropping systems (Agostini et al. 2010; Cordell et al. 2011; Rahn 2002) due to the amount of fertilisers applied in vegetable crops, often higher than the actual crop demand;
9. a complex interaction between the fertilization and the irrigation (Dukes et al. 2010; Farneselli et al. 2015);
10. a large impact of the fertilization on the vegetable quality (Maynard et al. 1976; Singh and Ryan 2015).

4 Fertilizer Consumption in Vegetable Production

Fertilizer consumption is increasing throughout the world: a recent FAO study (FAO 2015) on the world fertilizer trends and outlook to 2018 pointed out the following aspects:

- total fertilizer nutrient ($N + P_2O_5 + K_2O$) consumption at global level is estimated at about 187 Mt in 2014; with a successive growth of 1.8% per year, it is expected to reach more than 200 Mt by the end of 2018;

- the demand for nitrogen (113 Mt in 2014), phosphate (43 Mt), and potash (31 Mt) is forecast to grow annually by 1.4, 2.2, and 2.6%, respectively, during the period; the global capacity of fertilizer products, intermediates and raw materials will increase further;
- the global potential nitrogen balance (i.e. the difference between N potentially available for fertilizers and N fertilizer demand) as a percentage of N fertilizer demand is expected to steadily rise during the forecast period (3.7% in 2014, 5.4% in 2015, 6.9% in 2016, 8.8% in 2017, 9.5% in 2018);
- the global potential balance of phosphorous is expected to rise from 2.7 Mt in 2014 (i.e. 6.4% of total demand) to 3.7 Mt in 2018 (i.e. 8.5% of total demand);
- the global potential balance of potassium is expected to rise significantly from 8.7 Mt in 2014 (i.e. 25% of total demand) to 12.7 Mt in 2018 (i.e. 33% of total demand).

In 2011, when the total world fertilizer consumption was 172 Mt (of which 104 Mt N, 41 Mt P_2O_5 and 27 Mt K_2O), vegetables (Table 2) represented 9.3% of the world market (i.e. 16 Mt, of which 9.5 Mt N, 3.8 Mt P_2O_5 and 2.8 Mt K_2O, corresponding to 9.1, 9.4 and 10.0% of total consumption of each single fertilizer, respectively) (Heffer 2013). China concentrated about 66% (i.e. 11 Mt) of fertilizer world consumption in vegetables (Table 3) followed by India (6.7%), EU-27 (3.4%) and USA (1.8%). Within each country the percentage of fertilizer used in vegetables broadly varied in relation to the importance of vegetables in the national agricultural system and the development of crop fertilization management: data ranged from about 21% in China to 3.8% in India, 3.4% in EU-27 and 1.4% in USA.

5 Making Fertilization Sustainable in Vegetables: Trends and Goals of Research

The first 75 years of the twentieth century were a period of fruitful research on the development of fertilizer use in vegetables mainly focused on the optimization of fertilizer rates, scheduling, and placement for best crop productivity (Maynard and Lorenz 1979). Hochmuth (2003) remarked that in the last 25 years of the twentieth century much of the research has turned from "*the era of fertilizer materials development and application for vegetable crop growth*" to fertilization management mainly aimed at crop quality and environmental sustainability and so he focused his review on the advances in fertilizer formulations, sources and mode of action, soil and tissue testing, fertigation, relationship of fertilization and vegetable quality and the development of nutrient best management practices. Hochmuth also foresaw that in the twenty-first century the research would be aimed at producing economical yields with reduced fertilizer inputs by the development and implementation of cropping systems (e.g. adequate crop rotations, inter-cropping, double cropping, and other strategies for a better soil organic matter management), nutrient management approaches (e.g. models,

Table 2 Fertiliser consumption by all the crops and vegetables in 2011 at global level

	All the crops		Vegetables		
Fertilizer	Mt	% of total	Mt	% of total within veg	% within nutrient
N	104.25	60.5	9.52	59.1	9.1
P_2O_5	40.52	23.5	3.82	23.7	9.4
K_2O	27.44	15.9	2.75	17.0	10.0
$N + P_2O_5 + K_2O$	172.21	100	16.09	100	9.3

Source: Heffer (2013; modified)

Decision Support Systems, crop nutritional status testing, precision agriculture technologies…) and crop varieties both showing higher nutrient/fertilizer use efficiency. Indeed, research on fertilization management in vegetables developed according to Hochmuth prediction.

Several tools for soil analysis or estimation of the soil N supply are now available, as well as methods for N balance calculations, methods based on monitoring crops by plant analysis, and methods based on remote or proximal sensing. All these information can be used to develop computerised decision support systems based on simulation models. Several studies on organic matter mineralization as a source of nitrogen have deepened knowledge on the biotic and abiotic factors governing the process, introducing simple empirical equations that allow making rapid estimates of N mineralization with the aim of synchronizing N mineralization from different types of organic materials with crop N demand. Mineral fertilizers and traditional and innovative organic materials (i.e. compost, sewage sludge, anaerobic digestion residues and spent mushrooms compost) have been studied in detail and this helped define criteria of choice for vegetable crops.

Crop rotation has undergone renewed consideration as one of the key-strategies of conservative agriculture, aimed at guaranteeing the long term productivity and sustainability of vegetable cropping systems; numerous researches have investigated on mineral and organic fertilisation, crop residues management, cover cropping and green manuring, and intercropping in the frame of crop rotations in conventional and organic systems for either specialised or non-specialised vegetable production.

A lot of literature is available dealing with principles and practices of localized application (i.e. modified broadcast method, banding application method fertigation) in vegetable crop production in order to increase the uptake rate of applied nutrients, thereby reducing the application rates, the fertilization cost and the environmental impact of vegetable production. Also fertilization management in soil-less culture systems has been thoroughly investigated to develop efficient and environmentally sustainable production systems. Increased knowledge is available on Physiological, biochemical and molecular traits affecting nitrogen uptake by roots and new plant breeding approaches have been exploited for improving nutrient uptake and utilization efficiency in plants. On the other hand improvement in nutrient use efficiency has been achieved also by developing and studying

Table 3 Fertilizer use by vegetable crops in selected countries in 2011

	All the crops	Vegetables					
		$N + P_2O_5 + K_2O$		% of the total consumption within country			
Country	$N + P_2O_5 + K_2O$ (000 t)	(000 t)	% of country on world consumption	NPK	N	P_2O_5	K_2O
China	49,899	10,565	65.6	21.2	20.1	20.7	29.0
India	28,122	1076	6.7	3.8	3.0	3.7	8.0
USA	19,725	285	1.8	1.4	1.2	1.9	1.7
EU-27	16,165	545	3.4	3.4	2.5	4.8	5.4
Brazil	10,133	316	2.0	3.1	4.0	2.5	3.0
Indonesia	4795	241	1.5	5.0	5.5	6.0	3.5
Pakistan	3942	79	0.5	2.0	2.0	2.0	4.0
Canada	3025	18	0.1	0.6	0.6	0.5	0.8
Russia	2364	50	0.3	2.1	1.1	2.8	5.4
Vietnam	2300	205	1.3	8.9	9.0	8.0	10.0
Malaysia	1972	18	0.1	0.9	1.1	1.8	0.6
Australia	1967	38	0.2	1.9	1.7	1.5	5.5
Turkey	1943	138	0.9	7.1	7.0	6.0	16.0
Thailand	1922	195	1.2	10.2	10.0	10.0	11.0
Bangladesh	1761	53	0.3	3.0	3.0	3.0	3.0
Mexico	1750	148	0.9	8.5	5.5	12.0	17.0
Iran	1449	152	0.9	10.5	11.0	8.0	17.0
Belarus	1437	6	0.0	0.4	0.3	0.6	0.4
Argentina	1429	19	0.1	1.3	1.1	1.0	12.1
Egypt	1360	195	1.2	14.3	13.0	21.0	25.0
Japan	1100	205	1.3	18.6	19.7	17.5	18.7
Ukraine	930	7	0.0	0.8	0.5	1.2	1.6
South Africa	674	42	0.3	6.3	5.1	7.0	9.5
Uzbekistan	650	41	0.3	6.3	6.1	7.1	7.5
Philippines	615	39	0.2	6.3	4.2	10.0	13.0
Chile	493	21	0.1	4.2	3.4	3.0	8.0
Morocco	366	36	0.2	9.7	8.0	9.0	19.0
ROW	9921	1364	8.5	13.7	13.0	14.0	16.0
World (Mt)	172,209	16,096	9.3				

Source: Heffer (2013; modified)

advanced water management strategies aimed at reducing nutrient losses and maintaining farm profitability in horticultural systems.

Finally the efficiency and sustainability of fertilization programmes need to be defined by an economic analysis at the farm level and framed into a conceptualization of the relationship between the decisional and operational systems.

This book is aimed at reviewing the recent literature on the above mentioned key scientific and technical subjects of fertilization management in vegetable crops.

Glossary

FAO Food and Agriculture Organization of the United Nations
WHO World Health Organization
DALYs Disability adjusted life years

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Tools and Strategies for Sustainable Nitrogen Fertilisation of Vegetable Crops

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Abstract In intensive vegetable production, N fertiliser applications often contribute to a supply of N that appreciably exceeds crop N requirements resulting in the loss of N to the environment which can result in NO_3^- contamination of water bodies. There is a range of tools and strategies that can assist vegetable growers to improve N management. These include various methods based on soil analysis or estimation of the soil N supply, N balance calculations, methods based on plant analysis, methods based on monitoring crops with optical sensors, and the use of computerised decision support systems based on simulation models or data bases. Use of these tools has been demonstrated to appreciably reduce fertiliser N application and N losses while maintaining production. The selection of tools to be used by a grower will be influenced by factors such as availability, the grower's technical level, and economic considerations. For fertigation systems with high frequency N application, a combination of a planning method such as a decision support system with a monitoring method is recommended. Additional tools that can assist in demonstrating to stakeholders the benefit of improved N management are simulation models that provide scenario analysis. Fundamental strategies for improving N fertiliser management are to consider all N sources such as root zone soil mineral N and N mineralised from organic materials, and to partition N application so that it coincides with crop N demand.

Keywords Fertiliser • Nitrogen losses • Nitrate leaching • Soil testing • Crop testing • Sap analysis • Optical sensors • Simulation models • Decision support systems • Nitrification inhibitors • Slow release fertilisers • Controlled release fertilisers

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1 Introduction

Intensive vegetable production systems are commonly associated with appreciable loss of nitrogen (N) to the environment. Significant nitrate (NO_3^-) leaching loss often occurs (e.g. Min et al. 2011; Ramos et al. 2002; Thompson et al. 2007a; Vázquez et al. 2006; Zotarelli et al. 2007) as a consequence of the common practices of excessive N fertiliser and irrigation application (Fereres et al. 2003; Meisinger et al. 2008; Pratt 1984; Thompson et al. 2007b). In addition, vegetable crops often have shallow rooting systems and short periods of high N demand, both of which favour NO_3^- leaching.

Substantial NO_3^- contamination of underlying aquifers can result from NO_3^- leaching loss from vegetable production systems (e.g. Harter and Lund 2012; Ju et al. 2006; Kraft and Stites 2003; Pulido-Bosch et al. 2000). Excessive N fertiliser application of vegetable crops is also associated with enhanced emissions of the greenhouse gas nitrous oxide (N_2O) (e.g. Min et al. 2012; Xiong et al. 2006). Also, N enriched drainage water can contribute to eutrophication of surface waters. In addition to the environmental consequences of N losses from vegetable production, excessive N application represents a repeated, appreciable and unnecessary expense to vegetable growers.

Concerns over human health (Follett and Follett 2001) and environmental consequences have prompted social and political pressure to reduce NO_3^- contamination of aquifers and eutrophication of surface water with NO_3^- originating from agriculture and horticulture. For example, in the European Union (EU), two pieces of legislation, the Nitrates Directive (Anon. 1991) and the Water Framework Directive (Anon. 2000) are forcing the imposition of improved management of N fertiliser. These directives require all farmers, in areas where there are environmental problems caused by N fertiliser use, to adopt improved N management practices. Regions within the EU where there is aquifer NO_3^- contamination or surface water eutrophication, or a high risk of either occurring, are designated as being Nitrate Vulnerable Zones (NVZ) as stipulated by the Nitrates Directive. These regions must then demonstrate improved water quality. Currently, these pieces of legislation have been most strongly implemented in The Netherlands, Belgium (Flanders), Denmark and Germany; it is considered to be a matter of time before there is strong implementation throughout the rest of the EU.

Vegetable growers generally apply N on the basis of experience, either their own or that of technical advisors (Chen et al. 2004; Thompson et al. 2007b; Tremblay and Bélec 2006). The adoption of science-based procedures to determine N fertiliser rates will contribute to reducing the large N losses to the environment that often occur in intensive vegetable production. Procedures to assist with the N management of vegetable crops must be adapted to the characteristics of the cropping systems. Some relevant characteristics are the variation in planting dates and cropping seasons, multiple cropping within a year, the diversity of species and the considerable differences in morphology between species, climatic requirements, the lengths of growing season between species, and the variety of cultivars of a species. Some characteristics of vegetable production favour the adoption of improved management procedures such as the intensity of crop management, the high value of the crops, and the generally small field sizes. A consideration is the tendency for increased adoption of fertigation in combination with drip or sprinkler irrigation; with these combined systems, high frequency N application often occurs. High frequency N application opens up possibilities for adaptive management (Granados et al. 2013) compared to the traditional approach of a pre-planting application and one to three side-dress application/s. Frequent N application has implications for the type of recommendation systems that can be used.

A wide variety of approaches have been developed to assist with the N management of vegetable crops. These include methods based on soil analysis, plant analysis, computer-based decision support systems, the use of proximal optical sensors to rapidly assess crop nutrient status, the use of nitrification inhibitors, and the use slow and controlled release fertilisers. This chapter will review the various methods that are in use on commercial farms or that have been the subject of recent research programs.

2 Nature of Output from Tools for N Management of Vegetable Crops

Methods to assist in N fertiliser management provide either: (a) a recommendation of the quantity of mineral fertiliser N to apply, or (b) an assessment of the N status of the crop or of the N supply from the soil. Methods based on soil testing and N balance calculations generally provide estimates of the quantity of fertiliser N to apply. Methods that assess crop N status such as plant analysis and the use of proximal optical sensors require interpretation procedures to inform users of whether, at the time of assessment, a crop has deficient, sufficient or excessive N status. To make such an assessment, generally either sufficiency values or sufficiency ranges are commonly used. Some methods of assessing the immediate soil N supply such as the Pre Side-dress Nitrate Test (PSNT; Sect. 3.4) and soil solution analysis (Sect. 3.8) also generally require interpretation procedures regarding sufficiency or otherwise.

A sufficiency value distinguishes between deficiency (below the value) and sufficiency (above the value). Sufficiency values are also referred to as reference or threshold values. A sufficiency range consists of lower and upper limit values; the lower limit value distinguishing between deficiency and sufficiency, and the upper limit value between sufficiency and excess. Sufficiency values and ranges are often determined for phenological (development) phases for a given species. They can also be expressed on the basis of thermal time. The use of phenological phases or thermal time provides flexibility to deal with the differences in planting dates and growing seasons that occur with vegetable cropping.

To determine sufficiency values and ranges, different approaches have been used such as experience, yield analysis or the use of indicators of crop N status. Two indicators that have been used, particularly with proximal optical sensors, are the Nitrogen Nutrition Index (NNI) (Lemaire et al. 2008) and the Sufficiency Index (SI) (Samborski et al. 2009). These are explained in Sects. 5.2 and 6.1, respectively, of this chapter. With methods that assess crop N status, and in some cases the immediate soil N supply, the subsequent decision on the rate of N fertiliser application is generally an adjustment to a previously-determined rate or standard plan of N fertilisation. These approaches are well-suited to where frequent small N applications are made because applications made after testing can be adjusted thereby ensuring optimal N management throughout the crop.

3 Methods Based on Soil Analysis or Soil N Supply

With soil testing approaches, the N fertiliser rate is adjusted in response to the amount of soil mineral N in the root zone. These can be considered as site specific approaches, in which the N supplied by the soil is taken into account using either relationships derived from (a) fertiliser trials or experience, or (b) mathematical calculations.

3.1 Nmin System

An approach used with field-grown vegetable crops in North-western and Central Europe is the Nmin system that was described originally by Wehrmann and Scharpf (1979) for use with cereals, and later by Wehrmann and Scharpf (1986) and Scharpf (1991) for use with vegetables. “Nmin” refers to mineral N, and not to N mineralised from organic material. In this approach, the recommended amount of mineral N fertiliser is influenced by the amount of soil mineral N in the root zone at planting. Field trials are used to obtain “N target values” which represents the required total supply of mineral N to ensure that the crop does not experience a N limitation. The total mineral N supply is the sum of applied mineral fertiliser N and soil mineral N in the root zone. To estimate the recommended mineral N fertiliser application rate, for a given crop, soil mineral N in the root zone, determined at the beginning of the crop is subtracted from the N target value. Hereafter, this procedure is referred to as the basic Nmin system.

Individual N target values are required for all crops, and are determined from a number of fertiliser trials conducted for a given species in a given region (Feller and Fink 2002). The root zone depth varies between crops, ranging from 15 cm for lamb’s lettuce to 90 cm for some cabbage cultivars and Brussels sprouts (Feller et al. 2015).The basic Nmin system is described by:

$$\text{N fertiliser recommendation} = \text{N target value} - \text{soil mineral N in root zone} \quad (1)$$

Soil mineral N in the root zone (Nmin) refers to the sum of NO_3^-–N plus NH_4^+–N. In practice, however, generally just NO_3^-–N is measured because normally almost all soil mineral N is in the form of NO_3^-–N because of rapid nitrification of NH_4^+–N. The additional measurement of NH_4^+–N is recommended when appreciable amounts are expected such as after recent application of organic fertilisers or mineral NH_4^+ fertilisers. The Nmin system does not explicitly consider N mineralisation, because it is implicitly considered in the experimental determination of the N target value. Without calling it the Nmin system, Neeteson (1994) suggested a very similar approach. Using numerous field trials, inverse linear relationships were derived between the optimal fertiliser N rate and root zone soil mineral N for each species within a region (Neeteson 1994).

The Nmin system uses experimentally-determined N target values, which are derived from fertiliser trials conducted in representative field sites. Given the large number of combinations of vegetable species, cultivars, locations, and distinct soil types, very large numbers of field trials would be required to develop a comprehensive set of N target values for all the commercially-grown vegetable species within a region (Feller and Fink 2002). The requirement for experimentally-determined target values is a major practical limitation of the Nmin system. Where active and well-funded Extension services exist, it is likely that N target values could only be determined for a number of major species. However, many regions lack Extension services with the funding and means to conduct numerous fertiliser trials. Another general limitation of the Nmin system is that the recommendations are made for average crops in a region. The N target value cannot readily be adapted to field specific conditions, such as variations in expected yield or expected N mineralisation from soil organic matter. The Nmin system provides a single N fertiliser recommendation for a crop; it does not provide information on the partitioning of the fertiliser application.

3.2 The KNS System

The KNS (Kulturbegleitende-Nmin-Sollwerte) system developed by Lorenz et al. (1989) is a development of the basic Nmin system and also uses the concept of the N target value. The N target value, used by the KNS system, is calculated for an individual crop using a very simple modelling approach. The KNS system does not require comprehensive fertiliser trials to experimentally determine N target values and does not assume fixed yields. This N recommendation system is used in parts of North-western and Central Europe, and is the most commonly used system in Flanders, Belgium. The KNS system considers root zone mineral N at planting and also during crop growth. The method allows calculation of N target values at any time during crop growth. This potentially enables the grower to adapt the fertilisation plan after unforeseen events, such as very high rainfall events that leach N from the root zone, high N mineralisation or unexpected changes in crop growth or development because of weather fluctuations. For most crops, N recommendations are made for two periods during crop growth; for crops with long growing cycles, three periods are recommended. The essential idea of the KNS system is to improve the accuracy of N fertiliser recommendations by applying part of the total N requirement at the beginning and to adjust the subsequent N top dressing according to a very recent soil mineral N analysis. It should be noted that this approach works only if two (or three) soil mineral N analyses are made for each crop. In practice, growers can be reluctant to make even one analysis per crop unless obliged to do so.

The KNS system considers a buffer value for root zone soil mineral N (N buffer) below which production is N limited (Ziegler et al. 1996); the buffer value is sometimes referred to as the required "residual" amount of soil mineral N in the root zone. The buffer value (in kg N ha^{-1}) is added to the anticipated crop N uptake (N crop) for a given period (e.g. several weeks) to calculate the N target value for that period (Eq. 2).

$$\text{N target value} = \text{N crop} + \text{N buffer} \tag{2}$$

where N crop is crop N uptake during the specified period, N buffer is the buffer value of required soil mineral N at the end of the specified period.

The N target value in the KNS system is the amount of mineral N that should be made available to the crop to ensure there is no N limitation during the specified period. The procedure used in the KNS system is described subsequently. An example is provided in Text Box 1 and Table 1; this is an adapted example of that described by Ziegler et al. (1996).

The N crop value, used to calculate the N target value, is the sum of weekly or daily crop N uptake values for the specified period. The N crop values are provided to users in tables or graphs and are derived from results of local fertiliser trials, surveys on growers' fields and published studies. The number of field trials to establish the KNS system is appreciably less than required for the basic Nmin system. To accommodate higher or lower yields than the average yields considered by the KNS system, manual adjustment to consider site specific features can be used to increase or lower crop N values.

The required soil mineral N buffer values are derived empirically. In general, N buffer values at final harvest are relatively high if there is a high risk of insufficient N causing a reduction in yield or in product quality. For example, for broccoli and cauliflower, a soil mineral N buffer of 80 kg N ha^{-1} is used to ensure marketable head sizes. Very low N buffer values (e.g. 0 kg N ha^{-1}) are applied if excessive N supply at harvest may cause marketing problems, such as high NO_3^- content in carrots grown for baby food. For most crops, the N buffer value is set to 40 kg N ha^{-1}. Crop specific properties may be considered such as with leek where low root density and low potential nitrate uptake per root length are considered to justify a higher buffer value of 60 kg N ha^{-1}.

Text Box 1 Example of KNS system (Adapted from Ziegler et al. 1996)
Determination of N fertiliser recommendation using the KNS system for a spring lettuce crop, with following characteristics:

- Total crop N uptake of 100 kg N ha^{-1}
- Rooting depth of 30 cm
- N fertiliser applied at planting and at 6 weeks
- Soil mineral N determined at planting and at 6 weeks to be 25 and 40 kg N ha^{-1}, respectively
- Assumed N mineralisation of 5 kg N ha^{-1} $week^{-1}$

Table 1 Information used to calculate N fertiliser recommendation

Weeks after planting	1	2	3	4	5	6	7	8	9
Crop N uptake (kg N ha^{-1} $week^{-1}$)	0	1	3	6	10	15	20	30	15
Soil mineral N buffer (kg N ha^{-1})	60					40			40
N target value at planting and for side dressing in week 6 (kg N ha^{-1})	80					120			
N mineralisation from soil organic matter (kg N ha^{-1} $week^{-1}$)	5	5	5	5	5	5	5	5	5
Soil mineral N determined in 0–30 cm soil (kg N ha^{-1})	25					40			
Recommended N fertiliser rate at planting and side dressing in week 6 (kg N ha^{-1})	30					60			

Whereas N mineralisation is implicitly considered in the experimentally-derived N target values used by the basic Nmin system, N mineralisation should be explicitly considered in the KNS system. Lorenz et al. (1989) suggested for the Rhineland Palatinate region in Germany a fixed value of 5.5 kg N ha^{-1} $week^{-1}$ for N mineralisation from soil organic matter. The full calculation for the N fertiliser recommendation in the KNS system is made according to Eq. 3.

$$\begin{aligned}\text{N fertiliser recommendation} = {} & \text{N crop} \\ & + \text{N buffer} - \big(\text{N mineralised from soil organic} \\ & \quad \text{matter} \\ & + \text{soil mineral N in the root zone}\big)\end{aligned} \tag{3}$$

where N fertiliser recommendation, N crop and N mineralised from soil organic matter are for the specified period; N buffer is for the end of the specified period; and soil mineral N is determined at the start of the specified period. The specified period may be from planting or from a later date during the crop.

Calculation of N target values:

1. N target value at planting $= (\text{Anticipated N uptake for weeks } 1 - 5) + \text{soilminN buffer}$
$= (0 + 1 + 3 + 6 + 10) + 60 = 80 \text{ kg N ha}^{-1}$
2. N target value week 6 $= (\text{Anticipated N uptake for weeks } 6 - 9) + \text{soilminN buffer}$
$= (15 + 20 + 30 + 15) + 40 = 120 \text{ kg N ha}^{-1}$

Calculation of recommended N fertiliser rates: = N target value – soil mineral N – N mineralisation

1. N fertiliser at planting $= 80 - 25 - (5 * 5) = 30$ kg N ha^{-1}
2. N fertiliser at week 6 $= 120 - 40 - (4 * 5) = 60$ kg N ha^{-1}

3.3 The N-Expert System

The N-Expert system, originally published by Fink and Scharpf (1993) is a further development of the KNS system. Fink and Scharpf (1993) observed a systematic difference between N target values, calculated according to the KNS system (Eq. 2), and experimentally-derived N target values. To overcome these systematic differences they included a general N loss term for the calculation of N target values. There are several specific N loss pathways; some such as NO_3^- leaching or gaseous N losses are “real N losses” in that N is physically lost from the field, whereas other pathways are “apparent N losses” in that they temporarily make N unavailable for the crop, e.g. N immobilisation. Based on the study of Fink and Scharpf (2000), a N recovery of 80% of total N supply is used in the N-Expert system. The estimated unrecovered N (that is assumed to be lost) and the estimated mineralisation from soil organic matter are combined in a term called “apparent N net mineralisation” (Eq. 4) (Feller and Fink 2002).

$$\text{N target value} = \text{N crop} + \text{N buffer} - \text{apparent net N mineralisation} \tag{4}$$

Using this calculated approach (Eq. 4), Feller and Fink (2002) obtained good agreement between calculated N target values and experimentally-determined N target value for 24 different vegetable crops, as presented in Fig. 1.

The calculation of N fertiliser recommendation with the N-Expert system is the same as with the KNS system, the only difference being that the term “N mineralised from soil organic matter” in Eq. 3 is substituted by “apparent net N mineralisation” which considers the net effect of N mineralisation and of both real and apparent N losses, during crop growth.

In view of the expense of soil mineral N analyses and the reluctance of growers to undertake soil analyses, the authors of the N-Expert system suggest only one analysis per crop (Feller et al. 2015). For crops that are grown from transplants, soil sampling and subsequent fertiliser application are recommended shortly before

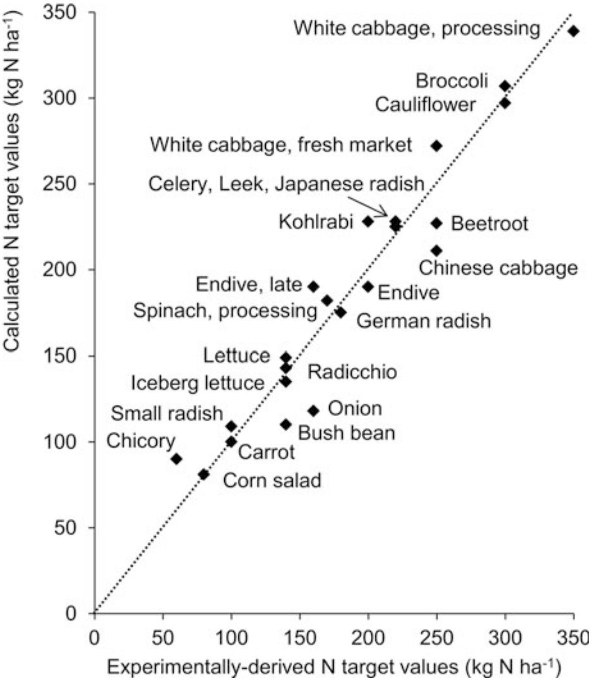

Fig. 1 N target values experimentally-derived by Scharpf (1991) related to N target values calculated with N-Expert. *Dashed line* is y = x (Reproduced with permission from Feller and Fink 2002. Nmin target values for field vegetables. Acta Horticulturae 571, 195–201 published by the International Society of Horticultural Science)

planting. For sown crops with a long germination period and slow early development, soil sampling and fertiliser application are recommended 4 or 6 weeks after sowing. A comprehensive, up-to-date table comprising N-Expert's N target values for all commercially relevant field vegetables in northern Europe is available as a free download at Feller et al. (2015).

The recently revised (September 2015) N-Expert 4 decision support software (in German and English), together with support (in German and English) and explanatory information (in German), is available at http://www.igzev.de/n-expert/?lang=en. The N-Expert decision support system is further discussed in Sect. 8.2 on Decision Support Systems. A modified, previous version of the N-Expert system was used in China with amaranth, spinach and cauliflower; compared to conventional management, yields were similar, less N was applied and there was less residual soil mineral N (Chen et al. 2005).

3.4 *The Pre Side-Dress Nitrate Test (PSNT)*

The Pre Side-dress Nitrate Test (PSNT) measures root zone soil NO_3^-–N, during the crop cycle, immediately prior to the main side-dressing N application that precedes the period of rapid vegetative growth (Hartz 2006; Heckman 2002; Meisinger et al. 2008). Only NO_3^-–N is determined because generally almost all soil mineral N is in the form of NO_3^-–N. The PSNT is primarily used to assess whether side-dress N application is required (Hartz 2006; Meisinger et al. 2008). It was developed for maize in North America and has been proposed as a N management system for grain maize in numerous US states and provinces of Canada. For maize, soil is sampled to 30 cm when the crop is 15–30 cm tall; when the soil NO_3^-–N content is >25 mg kg^{-1}, the soil N supply is considered to be sufficient and fertiliser N is not required (Meisinger et al. 2008).

The use of the PSNT with different vegetable crops such as tomato, lettuce, cabbage, celery, pepper and pumpkin has been evaluated (e.g. Bottoms et al. 2012; Breschini and Hartz 2002; Hartz 2006; Hartz et al. 2000; Heckman 2002). Breschini and Hartz (2002) demonstrated that use of the PSNT appreciably reduced N fertiliser applications in commercial lettuce crops. As general Extension guidelines for a wide range of vegetable crops including cabbage, cauliflower, broccoli, lettuce, cucumber, muskmelon, pepper, tomato and eggplant, Heckman (2002) recommended sampling to 30 cm and the use of limits of 25–30 mg NO_3^-–N kg^{-1} above which fertiliser N was not required. Hartz (2006) recommended general limits for vegetable crops of 20–25 mg NO_3^-–N kg^{-1}. The lower reference value of 20 mg NO_3^-–N kg^{-1} was specifically recommended for lettuce and celery by Hartz et al. (2000). The PSNT has been shown to be effective for identifying whether or not to apply side-dress N for field-grown vegetable crops.

The PSNT is primarily used to assess whether side-dress N application is required, and there is general agreement on the reference values for making this assessment. In commercial practice with grain maize, there are generally few cases where some side-dress N is not required, and these can often be suspected without the use of the PSNT, which limits the usefulness of the PSNT in practice. A major general limitation of the PSNT is the very limited availability of relationships between the results of the test and N fertiliser recommendations that are species and region specific There have been some derivations of relationships for determining N fertiliser recommendations from PSNT results. Schmidt et al. (2009) reported relationships for calculating N fertiliser recommendations for maize in Pennsylvania for PSNT values of <26 mg NO_3^-–N kg^{-1}. Breschini and Hartz (2002) reported a simple general procedure to calculate recommended N fertiliser applications for vegetable crops using the PSNT; the amount of fertiliser N to be added being that which increased the soil NO_3^-–N content in the root zone to the reference value, which was 20 mg kg^{-1} in their study. These authors presented a table that provided recommended rates of fertiliser N for soil NO_3^-–N contents of <20 mg kg^{-1}.

The use of the PSNT is restricted to field-grown crops receiving pre-plant and side dress N applications. As its name indicates, the PSNT is intended to assist with single side-dress N applications. For use with vegetable crops receiving frequent N application through fertigation, frequent soil sampling, extraction and analysis would be required.

3.5 Root Zone N Management

The root zone N management system reported in several Chinese studies, with greenhouse-grown tomato (He et al. 2007; Ren et al. 2010) and cucumber (Guo et al. 2008), is based on the KNS system and aims to maintain a buffer amount of root zone soil mineral N throughout the crop. The KNS system and the concept of the buffer amount of root zone soil mineral N were defined in Sect. 3.2 of this chapter. With root zone N management, fertiliser N recommendations for several side-dress applications are based on the difference between N target value and the sum of root zone (generally 0–30 cm) soil mineral N and NO_3^-–N applied in irrigation water according to Eq. 5.

$$\begin{aligned}\text{Recommended fertiliser N} = {} & \text{N target value} - \text{root zone soil mineral N} \\ & - NO_3^- - \text{N from irrigation water.}\end{aligned} \tag{5}$$

In China, irrigation water commonly has a sufficient $[NO_3^-]$ to contribute appreciable amounts of readily available N to crops. Therefore, the amount of NO_3^-–N added in irrigation water was included in Eq. 5 to calculate the N fertiliser requirement.

In the studies of He et al. (2007), Guo et al. (2008) and Ren et al. (2010), for each of the several N side-dress applications used, the amount of root zone mineral N was determined in order to calculate the corresponding N fertiliser recommendation. The N target value, as used in the KNS system, is crop N uptake plus the buffer value (see Sect. 3.2 of this chapter). For tomato, both He et al. (2007) and Ren et al. (2010) used fixed N target values of 200–300 kg N ha^{-1} which were most commonly 200 kg N ha^{-1} for each side dress application. For both of these studies, the derivation of the N target values was not clearly explained. For cucumber, Guo et al. (2008) calculated N target values as the sum of (a) buffer values of 200 kg N ha^{-1} for 0–30 cm soil, and (b) crop N uptake which was estimated using simple equations based on time since transplanting. These authors used different crop N uptake equations for autumn-winter and winter-spring growing seasons. Compared to conventional N management practices in Chinese greenhouse vegetable production, in which very excessive amounts of N are generally applied (Chen et al. 2004), the use of the root zone N management system consistently resulted in considerable reductions in N fertiliser application while maintaining fruit production (He et al. 2007; Guo et al. 2008; Ren et al. 2010). Nevertheless, appreciable apparent N losses still occurred with the use of root zone N management in these studies suggesting that further improvements in N use efficiency could be obtained by additional approaches such as improved irrigation management and improved estimation of N mineralisation from manures (He et al. 2007; Ren et al. 2010).

As experimental studies in the context of the massive N surpluses generally associated with Chinese greenhouse vegetable production (Chen et al. 2004; Ju et al. 2006), these studies (Guo et al. 2008; He et al. 2007; Ren et al. 2010) demonstrate that science–based management can substantially reduce N addition and apparent N loss while maintaining production. In the studies of He et al. (2007), Guo et al. (2008) and Ren et al. (2010), soil was extracted with a dilute calcium chloride solution and the extract was analysed in the laboratory for NH_4^+–N and NO_3^-–N. He et al. (2007) and Ren et al. (2010) also analysed the extracts for NO_3^-–N with test strips as a rapid analysis procedure. The willingness of growers to conduct and pay for soil analyses is discussed in Sect. 3.10 of this chapter.

3.6 Soil N Supply Indices

Soil N supply (SNS) indices provide an approach in which the soil N supply is estimated rather than measured. In England and Wales, an index system is used to estimate the "Soil N Supply" (SNS) where soil sampling and analysis have not been conducted. The "Fertiliser Manual RB209" (AHDB 2015), which is presented as a booklet, enables SNS Index values to be estimated, by using a series of look-up tables, for a given field and to provide the recommended N fertiliser rate for a given crop in that field. The SNS Indices estimate soil mineral N available to the crop which includes estimated N mineralised from organic material during the crop. SNS indices are determined for a specific field by considering average annual rainfall, soil texture and residues from the preceding crop. The SNS indices have values of 0–6, and each index value corresponds to a different incremental supply of soil mineral N in the root zone (in kg N ha^{-1}). Measurements of soil mineral N, at planting, can be incorporated into the recommendation procedure and are suggested for certain situations such as when there are high or uncertain amounts of residue from the preceding crop (Rahn 2012).

The use of SNS indices to determine N fertiliser recommendations takes place in two stages. Firstly, the SNS Index is determined for the site, and then for a given crop grown on that site, the corresponding N fertiliser rate is determined. For example, in a low rainfall zone (500–600 mm) with a medium-textured soil, the SNS Indices of 1, 3 and 4 correspond to estimated low, medium and high amounts of N in the residues of the previous vegetable crop. The estimated amounts of crop residue N are a function of the previous species the three previously-referred to residue classes are: low (e.g. carrot, onion), medium (e.g. lettuce, leek) and high (e.g. Brussels sprouts). The SNS indices of 1, 3 and 4, in this example, correspond to estimated soil N supply values of 61–80, 101–120, and 121–160 kg N ha^{-1}, respectively. For a lettuce crop, for SNS indices of 1, 3 and 4, the corresponding recommended N fertiliser rate are 180, 150 and 125 kg N ha^{-1}. Rahn (2012) described the use of the RB209 Fertiliser Manual to determine N fertiliser recommendations.

As described in Sect. 8.3 of this chapter, the software program PLANET (DEFRA 2014) provides recommendations based on estimated SNS Index values (as done using the RB209 Fertiliser Manual) and also enables record-keeping. Both the RB209 Fertiliser Manual (as a PDF file) and the PLANET software are freely available on Internet. Many growers in England and Wales have a copy of RB209 or PLANET. While it is difficult to know how many growers actually regularly use these recommendations; it seems many growers do so (C. Rahn, University of

Warwick, United Kingdom, personal communication). A revision of the RB209 Fertiliser Manual, the AHDB (Agriculture and Horticulture Development Board) Nutrient Management Guide is scheduled for release in 2017.

3.7 Dutch 1:2 Volume Soil:Water Extract Method

This method was developed for soil-grown crops in high technology greenhouses in The Netherlands where fertigation with frequent nutrient application is the standard practice. Species specific fertigation programs have been developed in which a standard nutrient solution is adjusted in response to the results of the analysis of extract obtained from a 1:2 volume, soil:water extraction that is conducted periodically throughout the crop (Sonneveld and Voogt 2009). The species specific standard nutrient solution is also adjusted for cropping conditions such as water quality, crop development stage, and soil type. In this system, all mineral N fertiliser is supplied by fertigation.

Because of frequent nutrient addition by fertigation, interest is in the immediately available nutrients in the soil, rather than the nutrient supply over longer time periods. To optimise the management of frequent nutrient addition, relatively frequent testing is necessary which requires simple and quick procedures to obtain and prepare samples. Composite soil samples are taken regularly, and extracted and analysed using the 1:2 volume (soil:water) extract method (Sonneveld and van den Ende 1971; Sonneveld and Voogt 2009; Sonneveld et al. 1990) which provides a good estimate of the [NO_3^-] in the soil solution and of total amount of immediately available soil mineral N per unit area. Additionally, information on the soil electrical conductivity (EC) and on the availability of other nutrients is provided (Sonneveld and Voogt 2009; Sonneveld et al. 1990). The analytical results of the extract solution are compared with target values and limits for individual nutrients. These results are used to adjust the nutrient concentrations and the EC of the applied nutrient solution.

This method has been used by commercial growers in greenhouses in The Netherlands for a number of years (W. Voogt, University of Wageningen, personal communication), and recently has been adapted to greenhouse conditions in Italy (L. Incrocci, University of Pisa, personal communication) and Greece (De Kreij et al. 2007). The sufficiency range values determined for crops in Italy are somewhat lower than those used in The Netherlands (L. Incrocci, University of Pisa, Italy, personal communication).

Unlike the previously described soil testing approaches, the 1:2 volume (soil: water) extract method was developed specifically for fertigated crops receiving high frequency nutrient application. The use of a composite soil sample, overcomes the issue of spatial variability that has been reported with localised measurements such as ceramic cup suction soil solution samplers (Sect. 3.8 of this chapter). While most use of the 1:2 volume (soil:water) extract method in The Netherlands, Italy and Greece has been with soil-grown greenhouse crops, it can be used with fertigated vegetable crops grown in open fields (W. Voogt, Wageningen University and Research, The Netherlands, personal communication).

3.8 Nitrate Concentration of the Soil Solution in the Root Zone

The NO_3^- concentration ($[NO_3^-]$) of the soil solution in the root zone, sampled regularly during a crop with ceramic cup suction samplers, has been used as a method to assist in the N management of vegetable crops. Conceptually, this method provides control over the immediately available N (both in form and location) in the root zone. This method is best suited for use with vegetable crops receiving frequent N addition through combined fertigation and drip irrigation, with the sampler providing samples of soil solution from within the drip irrigation bulb where most roots are located.

In Israel, soil solution samplers are commonly used in commercial vegetable production using a sufficiency value of 5 mmol NO_3^- L^{-1} (S. Kramer, Israeli Ministry of Foreign Affairs, personal communication). Burt et al. (1995) and Hartz and Hochmuth (1996) suggested the use of the root zone soil solution $[NO_3^-]$ to assist in the N management of vegetable crops, also using a sufficiency value of 5 mmol NO_3^- L^{-1}. Burt et al. (1995) commented that with frequent N application by combined fertigation/drip irrigation systems, the sufficiency values may be lower. Hartz (2003) commented that the high spatial variability of soil solution $[NO_3^-]$ may limit the practical value of this approach. In greenhouse-grown vegetable crops with very frequent nutrient application through combined fertigation/drip irrigation, excessive N application was associated with increasing soil solution $[NO_3^-]$ (Fig. 2; Gallardo et al. 2006; Granados et al. 2013; Peña-Fleitas et al. 2015). These results suggest that an on-going tendency of increasing soil solution $[NO_3^-]$ is an indicator of excessive N application with fertigated/drip irrigated vegetable crops, particularly where little drainage and therefore NO_3^- leaching occurs. The use of tendencies overcomes two issues: (1) the uncertainties associated with spatial variation of individual point measurements, and (2) the identification of sufficiency values and ranges (as discussed subsequently). Spatial variation may be a more important issue with commercial growers than in research studies because of grower reluctance to have a sufficient number (e.g. three or more) of replicated samplers within a field.

In a pepper crop grown in a greenhouse in south-eastern (SE) Spain, Granados et al. (2013) maintained soil solution $[NO_3^-]$ within a range of 8–12 mmol L^{-1} as part of an improved management system that appreciably reduced NO_3^- leaching and N fertiliser use. Subsequent studies, in this system, suggested that sufficiency values may be lower (R. B. Thompson, unpublished data). Through replication and careful selection of representative locations, the average coefficients of variation (CV) of measurements of soil solution $[NO_3^-]$ reported by Granados et al. (2013)

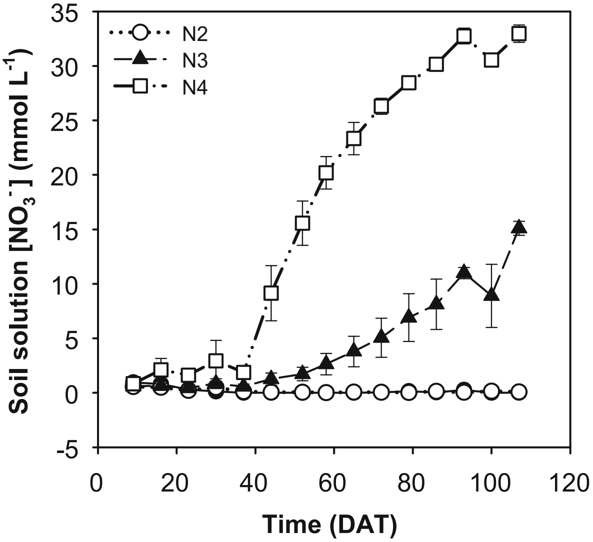

Fig. 2 [NO_3^-] of root zone soil solution during a fertigated tomato crop grown in a greenhouse in SE Spain. The average N concentrations applied by fertigation/drip irrigation were 5, 13 and 22 mmol L^{-1} for treatments N2, N3 and N4, respectively. Values are means ± SE ($n = 4$). DAT is days after transplanting (Reproduced with permission from Peña-Fleitas et al. (2015) Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques, Annals of Applied Biology 167, 387–405, published by John Wiley and Sons)

were relatively low, being only 27%. Without careful selection of representative sites in the same greenhouse system (e.g. avoiding where rainfall entered the greenhouse), CV values were appreciably higher (Granados 2011). These observations suggest that the high spatial variability reported by Hartz (2003) can be reduced by increasing the number of replicates and by careful site selection.

Small portable "quick test" systems (Parks et al. 2012; Thompson et al. 2009) enable on-farm determination of the [NO_3^-] in samples of soil solution. With rapid analysis systems, considerable care must be taken and results should be periodically checked against laboratory analysis. Combining the use of the suction samplers with on-farm analysis with "quick test" systems enables rapid assessment of the immediately available N supply in the root zone.

Ceramic cup suction soil solution samplers appear to be a useful approach for identifying excessive N fertilisation of fertigated vegetable crops through the observation of tendencies of increasing soil solution [NO_3^-]. Given the current uncertainties associated with definition of sufficiency ranges and the issue of spatial variability of soil solution [NO_3^-], it is suggested that other approaches (e.g. crop/plant testing) be used to accurately determine N insufficiency. As a general rule for the use of soil solution [NO_3^-], with values of >5 mmol L^{-1}, in the immediate root zone, it is unlikely that the immediate N supply will limit crop growth.

3.9 Use of Limits of Residual Soil Mineral N

In the region of Flanders in Belgium, there is a legal limit on the amount of residual soil mineral N in the autumn/early winter period after open field cropping (S. de Neve, University of Ghent, Belgium, personal communication). The limit is 90 kg N ha^{-1} in 0–90 cm soil; samples are taken between 1 October and 15 November. If there is $>$90 kg N ha^{-1}, growers are penalised.

With the increasingly strict implementation of legislation to reduce contamination of water bodies with N from agriculture, this approach may be implemented elsewhere. It is one of the few means by which the net result of a grower's N management can be evaluated. However, care should be exercised when interpreting residual soil mineral N data, as they are the result of numerous interacting factors including climatic conditions.

3.10 General Observations on Soil Testing Approaches

Most of the methods based on soil analysis or soil N supply require sampling of soil or the soil solution and subsequent analysis. Soil sampling requires firstly an extraction procedure, which is generally conducted with water, or with potassium chloride or calcium chloride solutions, and subsequently requires analysis of the extractant solution. Quick test procedures, such as those described by Thompson et al. (2009) and Parks et al. (2012) can be used (e.g. He et al. 2007), but given that extraction will normally be conducted in a laboratory, laboratory analysis can also be conducted which is more accurate and reliable than quick test procedures.

A fundamental issue with soil analysis is the willingness of growers to take soil samples and to pay for analysis. Experience in Germany has been that growers are generally reluctant to take samples. Often, the limiting factor is not costs, but the difficulty to integrate the whole process associated with sampling (timely sampling, sample preparation, sending the sample to the laboratory, calculating fertiliser demand based on the analysis) into the typically hectic daily routine on a vegetable farm. However, it has been seen that growers were more motivated when the costs of the analyses were subsidised (K. Rather, State Horticultural College and Research Institute, Heidelberg, Germany, personal communication). In The Netherlands, growers in high technology greenhouses regularly use the 1:2 soil:water extract method during a crop (W. Voogt, Wageningen University & Research, The Netherlands, personal communication). It appears in these high technology production systems where growers are accustomed to a high level of monitoring, that they are willing to regularly sample soil and to pay for the analyses. It appears that grower reluctance to sample soil and to pay for analysis can be at least partially overcome by increasing their technical knowledge. The provision of efficient support services to rapidly conduct analyses and provide recommendations is essential. The imposition of recommended practices through legislation will presumably contribute to increasing adoption of soil testing approaches.

4 Nitrogen Balance Method

The determination of N fertiliser application rate using N balance calculations generally considers all major N inputs, thereby ensuring that the most significant N sources are considered when determining mineral N fertiliser recommendations. Essentially, the N balance subtracts the supply of N (from sources other than mineral fertiliser) from the crop demand for N; the difference being the amount of mineral N fertiliser required. Traditionally, the N balance has been calculated for the duration of a crop, resulting in an estimation of the total amount of N to be applied as fertiliser. With the use of computer-operated Decision Support Systems (DSS; see Sect. 8 of this chapter), N fertiliser requirements can be calculated daily or weekly using a N balance approach enabling crop, site and season specific N management. As discussed in Sect. 8 of this chapter, when done frequently by a DSS, these N balance calculations can be either "static", when they are used as a fixed plan considering expected yield and average climatic conditions, or "dynamic" when a series of short-term plans are prepared with real time or forecast climatic data so that the plan is continually adapted in response to actual cropping conditions. Additional soil analyses can be used as feed-back to adjust parameters, as is done in the KNS system (Sect. 3.2 of this chapter) which is essentially a simplified N balance method.

The inputs and outputs considered in the N balance are listed in Table 2. For each given time period, the sum of N inputs equals the sum of N outputs. Variations exist on the individual terms used in N balance calculations, and on the approaches used to solve the calculation of the N_{fert} term (e.g. Gianquinto et al. 2013; Meisinger et al. 2008; Tremblay et al. 2001). For example, the general N losses term (N_{loss}) in Table 2 can be fully expressed as the various N loss pathways of NO_3^- leaching, denitrification and NH_3 volatilisation, plus immobilisation. Estimating each N loss pathway is very difficult given the dynamic nature of each pathway, the difficulties of measurement, and the shortage of reliable field data. Consequently, a generalised N loss term is commonly used, as in Table 2. Two or all three of the N mineralisation terms may be combined. The German N-Expert system, another method based on the N balance (see Sects. 3.3 and 8.2 of this chapter), combines all N mineralisation terms and the general N losses term into the term Apparent Nitrogen Mineralisation which is the combined N mineralisation from all sources minus all N losses and immobilisation. Depending on site management and history, some N input terms will not be relevant, e.g. if manure or irrigation are not used.

As previously mentioned, there are variations between authors in the details of N balance calculations and in the terms and approach used. However, a consistent feature is that all major N sources are considered. There are two main approaches: (1) the efficiency factor approach, or (2) the safety margin approach. With the

Table 2 N inputs and outputs considered for developing a N balance. Note: the subscript "min" refers to mineral N and the subscript "mins" to mineralised N

N inputs	N outputs
Initial soil mineral N ($N_{\text{min-ini}}$)	Crop N (N_{crop})
N mineralised from soil OM ($N_{\text{mins-OM}}$)	N losses (N_{loss})
N mineralised from crop residues ($N_{\text{mins-crop res}}$)	Final soil mineral N ($N_{\text{min-fin}}$)
N mineralised from manure ($N_{\text{mins-man}}$)	
N applied in irrigation (N_{irr})	
Mineral N fertiliser (N_{fert})	
Total N Inputs (∑Inputs)	Total N Outputs (∑Outputs)

efficiency factor approach, the N_{loss} and $N_{\text{min-fin}}$ terms are removed and instead are implicitly considered by either applying efficiency factors to each of the N inputs considered (Gallardo et al. 2014; Meisinger et al. 2008) or by the use of a single efficiency factor for the combined N inputs (Thompson et al. 2013a) as in Eq. 6.

$$N_{\text{fert}} = (1/E) * \left[N_{\text{crop}} - \left(N_{\text{min-ini}} + N_{\text{mins-OM}} + N_{\text{mins-res}}\right)\right] \tag{6}$$

where E is the efficiency of use N supplied to the crop, and $N_{\text{mins-res}}$ is the combination of $N_{\text{mins-crop res}}$ and $N_{\text{mins-man}}$ (Table 2).

Given the difficulty of obtaining reliable efficiency factors, the "safety margin" approach is a practical alternative (Gianquinto et al. 2013; Tremblay et al. 2001), and is used in practical manuals prepared for farmers and advisors (e.g. Tremblay et al. 2001). The safety margin is the equivalent of the buffer soil mineral N defined for the KNS system (Sect. 3.2 of this chapter), which is the minimum amount of soil mineral N that must be present in the root zone to avoid a yield reduction. Tremblay et al. (2001) used the equation:

$$N_{\text{fert}} = \left(N_{\text{crop}} + N_{\text{Safety margin}} + N_{\text{Immobilisation}}\right) - \left(N_{\text{min-ini}} + N_{\text{mins-OM}} + N_{\text{mins-crop res}}\right) \tag{7}$$

where $N_{\text{Safety margin}}$ is the safety margin or buffer amount of soil mineral N and $N_{\text{Immobilisation}}$ is an estimate of immobilisation calculated as (N_{crop} + $N_{\text{Safety margin}}$) × 0.15.

Tremblay et al. (2001) used Eq. 7 for various species and scenarios under the conditions of Germany, and Quebec, Canada. In doing so, $N_{\text{mins-OM}}$ was assumed to be 5 kg N ha^{-1} week^{-1} for these conditions (similar to the value assumed by the KNS system described in Sect. 3.2 of this chapter), and formulas were provided to calculate $N_{\text{mins-crop res}}$. N_{crop} (for the entire crop) can be estimated by multiplying expected yield by crop N uptake per unit of yield. Tabulated values of the latter were provided by Tremblay et al. (2001) for common vegetable crops in Germany and Canada, and by Gianquinto et al. (2013) for the Mediterranean Basin. Commonly, local values are available.

Gianquinto et al. (2013) presented a simplified practical solution of the N balance. Firstly, N_{crop} is estimated by multiplying expected yield by N uptake per unit of yield. Then Eq. 8 is solved:

$$N_{fert} = N_{crop} - N_{min\text{-}ini} \tag{8}$$

The N_{fert} value is then adjusted to an "adjusted value of fertiliser N" ($N_{adj\text{-}fert}$) to consider the inefficiency of N fertiliser use because of N losses and residual soil mineral N. This is done using either the: (a) efficiency factor approach (Eq. 9) or (b) the safety margin approach (Eq. 10), which were both described previously.

$$N_{adj\text{-}fert} = N_{fert}/E \tag{9}$$

$$N_{adj\text{-}fert} = N_{fert} + N_{Safety\ margin} \tag{10}$$

5 Methods Based on Crop/Plant Analysis

5.1 Crop and Plant Monitoring Approaches – General Considerations

Monitoring of crop or plant N status potentially integrates crop N demand and the soil N supply, providing an overall assessment of whether the two are in balance or not (Schröder et al. 2000). Imbalances can occur despite an apparently adequate soil N supply, such as when very rapid crop N uptake follows measurement of soil mineral N, when there is very low N supply in the immediate root zone, or the crop has a poorly developed root system. Many of the more recently developed crop/plant N monitoring approaches enable rapid *in-situ* assessment of crop N status. Supplementing soil analyses with crop/plant monitoring can provide a comprehensive assessment of the N status of a given crop. Important issues when dealing with crop/plant monitoring approaches are the interpretation of the results, firstly to inform users of whether a crop has deficient, sufficient or excessive N status, and secondly the transformation of the results into fertiliser recommendations. These comments are relevant to the monitoring methods based on crop/plant analysis described subsequently in this Section, and those using proximal optical sensors described in Sect. 6.

5.2 Tissue Analysis

Measurement of leaf N content, also known as N tissue analysis, is a long established method of assessing crop N status of vegetable crops (Burt et al.

1995; Geraldson and Tyler 1990; Hartz and Hochmuth 1996). Most commonly, the most recently fully expanded leaf is sampled. Generally, sufficiency ranges (with maximum and minimum values) for different phenological phases are used to interpret the results, with a progressive reduction in sufficiency ranges with crop growth as the crop N content declines (e.g. Hartz and Hochmuth 1996; Hochmuth et al. 2015). Hartz and Hochmuth (1996) and Hochmuth et al. (2015) published values of sufficiency ranges for numerous vegetable species grown in Florida, USA; Hartz and Hochmuth (1996) suggested that sufficiency ranges for crops grown California are likely to be similar. In general, it is preferable that locally-determined sufficiency ranges and values be used. For example, in Almeria, SE Spain, Casas and Casas (1999) determined local reference values for a range of greenhouse-grown vegetable species.

There are mixed reports of the nature of the relationships between leaf N with overall crop N content and crop status. Leaf N content was strongly and consistently correlated with total crop N content (Bottoms et al. 2012; Peña-Fleitas et al. 2015) throughout tomato crops suggesting that leaf N content can be used as a surrogate of crop N content. However, the correlation was not consistent over time in muskmelon (Peña-Fleitas et al. 2015) or lettuce (Bottoms et al. 2012). Peña-Fleitas et al. (2015) observed on-going changes in the relationship of leaf N content with crop N status, assessed using the Nitrogen Nutrition Index (NNI; Lemaire et al. 2008) in tomato and muskmelon, which is consistent with the reduction in sufficiency values with crop growth. The NNI is an effective and established indicator of crop N status (Lemaire et al. 2008; Padilla et al. 2014, 2015, 2016). The NNI is the ratio between actual crop N content and the critical crop N content (i.e. the minimum N content necessary to achieve maximum growth of a crop) (Greenwood et al. 1990). Values of NNI of <1 indicate N deficiency, values of >1 indicate N excess, and values of ≈ 1 indicate N sufficiency (Lemaire et al. 2008).

Olsen and Lyons (1994) reported that leaf N is a relatively insensitive measure in sweet pepper because of its limited response to short-term periods of inadequate N supply. This insensitivity was attributed to there being only relatively small changes in leaf protein which constitutes most of the leaf N content (Olsen and Lyons 1994).

The availability of suitable sufficiency values is an important consideration. Sufficiency values for a given species may vary with differences in climate, region, crop management and cultivar. Where local sufficiency values are not available, they should be determined or values from a similar cropping system and region should be validated before being recommended. Practical considerations are the logistics of sending samples to a laboratory, the time delay to obtain results, and the cost of laboratory analyses. For routine testing, it appears to be best suited to where infrequent side-dress N applications are made. Given its relative unresponsiveness and the time delay to obtain results, it is not suitable for frequent N application with fertigation.

5.3 NO_3^- Analysis of Dried Petiole or Mid-Rib Tissue

Nitrate analysis of dried petiole or mid-rib tissue has been available for a number of years (Burt et al. 1995; Goffart et al. 2008). Burt et al. (1995) published detailed tables of sufficiency values for numerous vegetable species for the USA. Inconvenient aspects are the time to obtain and prepare the samples and to obtain laboratory results. In recent years, there has been little work on this method.

5.4 Petiole Sap NO_3^- Analysis

Petiole sap NO_3^- analysis measures the $[NO_3^-]$ in the conducting tissue of leaf petioles, and is considered to be a sensitive indicator of crop N status at the time of sampling (Burt et al. 1995; Goffart et al. 2008; Olsen and Lyons 1994). The sensitivity of sap $[NO_3^-]$ to crop N status has been demonstrated in various vegetable crops, including processing tomato (Farneselli et al. 2014; Hartz and Bottoms 2009), pepper (Olsen and Lyons 1994) and potato (Goffart et al. 2008).

Normally, the most recent fully expanded leaf is sampled; it is recommended that >20 petioles be sampled from different representative plants to overcome variation between individual plants (Goffart et al. 2008). Strict protocols need to be followed for leaf selection, petiole removal, handling and storage, and for the extraction and storage of sap samples (Farneselli et al. 2006; Hochmuth 1994, 2015). Analysis can be made on farm using small portable rapid analysis systems (Hochmuth 1994, 2015; Parks et al. 2012; Thompson et al. 2009), some of which can measure sap $[NO_3^-]$ without dilution. With rapid analysis systems, considerable care must be taken with the calibration, use of and maintenance of the equipment, and results should be periodically checked against laboratory analysis.

Most reports are that the petiole sap $[NO_3^-]$ declines notably as crops grow (e.g. Hartz and Bottoms 2009; Hochmuth 1994, 2015). Recommendations are generally made as sufficiency ranges for phenological phases; the reported sufficiency ranges commonly decline as crops grow and develop (e.g. Hochmuth 1994, 2015). However, in tomato and muskmelon grown in soil in a greenhouse and which received N every 1–4 days in complete nutrient solutions through a combined fertigation/drip irrigation system, petiole sap $[NO_3^-]$ remained relatively constant for each of four different treatments in which different applied N concentrations were maintained throughout the crops (Peña-Fleitas et al. 2015) (Fig. 3). Farneselli et al. (2014) did not observe an on-going decline in sap $[NO_3^-]$ of fertigated open field tomato, whereas Hartz and Bottoms (2009) did. These results suggest that fertigated vegetable crops receiving very frequent N applications may not exhibit the appreciable decline in sap $[NO_3^-]$ that has been commonly reported for crops receiving pre-plant and side-dress N applications. This may be related to the observation of Goffart et al. (2008) that individual N applications and the form of N can influence sap $[NO_3^-]$. Further work is required to elucidate the evolution

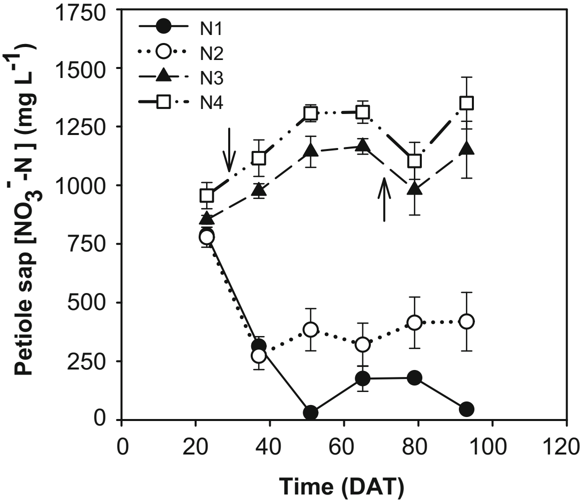

Fig. 3 Petiole sap [NO_3^-] during a fertigated tomato crop grown in a greenhouse in SE Spain. The average applied N concentration was 1, 5, 13 and 22 mmol L^{-1} for treatments N1, N2, N3 and N4, respectively. Values are means ± SE ($n = 4$). Arrows in each graph indicate the commencement of N treatments (↓) and the day of topping (↑). DAT is days after transplanting (Reproduced with permission from Peña-Fleitas et al. (2015) Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques, Annals of Applied Biology 167, 387–405, published by John Wiley and Sons)

of sap [NO_3^-] in fertigated vegetable crops and to explain the different general tendencies reported by Peña-Fleitas et al. (2015) and Farneselli et al. (2014) compared to those of Hartz and Bottoms (2009).

Peña-Fleitas et al. (2015) obtained a very strong linear relationship between sap [NO_3^-] and NNI (described in Sect. 5.2 of this chapter) for an indeterminate tomato crop grown with fertigation in a greenhouse (Fig. 4). Re-analysing data of Farneselli et al. (2014) of two field-grown determinate tomato crops, Peña-Fleitas et al. (2015) obtained nearly identical linear relationships between sap [NO_3^-] and NNI as was obtained for the greenhouse-grown tomato crop (Fig. 4). Using a common linear relationship for these three tomato crops (Fig. 4), Peña-Fleitas et al. (2015) derived a unique sufficiency value of 1050 mg L^{-1}, for NNI = 1, for the three tomato crops. In greenhouse-grown, fertigated muskmelon there was also a relatively constant and strong linear relationship between sap [NO_3^-] and NNI throughout much of the crop (Peña-Fleitas et al. 2015). The strong linear and relatively constant relationships with NNI observed in these crops suggest that in fertigated vegetable crops sap [NO_3^-] is a sensitive indicator of crop N status. Further work is required to explore the relationship between sap [NO_3^-] and crop N status in fertigated vegetable crops.

As a general assessment, petiole sap NO_3^- analysis can provide useful information on the N status of vegetable crops. However, petiole sap [NO_3^-] values can be affected by factors such as cultivar, amount and timing of N previous application,

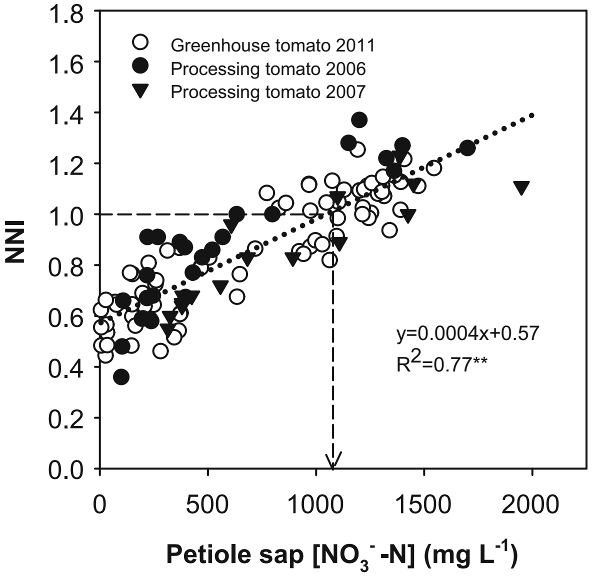

Fig. 4 Linear relationship of petiole sap [NO_3^-–N] to Nitrogen Nutrition Index (NNI) for tomato combining all data from a greenhouse-grown, indeterminate, fresh market tomato crop in 2011 (Peña-Fleitas et al. 2015) and from two determinate, processing tomato crops grown in open fields in 2006 and 2007 (Farneselli et al. 2014). Data excluded in processing tomato were from the first sampling date at 30 days after transplanting (DAT) in both the 2006 and 2007 crops and from the last sampling dates of 84 DAT in 2006 and of 71 and 84 DAT in 2007 (see Peña-Fleitas et al. (2015). The derivation of a general sufficiency value of 1050 mg NO_3^-–N L^{-1} that corresponds to NNI = 1 is shown (Reproduced with permission from Peña-Fleitas et al. (2015) Assessing crop N status of fertigated vegetable crops using plant and soil monitoring techniques, Annals of Applied Biology 167, 387–405, published by John Wiley and Sons)

crop water status and of rainfall events stimulating N mineralisation (Goffart et al. 2008). It has been demonstrated that petiole sap [NO_3^-] is a good indicator of crop N status for a given vegetable species in a given region, e.g. processing tomato in central Italy (Farneselli et al. 2014). In general, it appears that sap [NO_3^-] can potentially provide information on the adequacy of crop N status for a given species within a given region, and that consistent N management practices (e.g. timing, pre-plant applications) and similarity of cultivars and general crop management are likely to improve its viability both within and between regions. Recent results with fertigated vegetable crops suggest that frequent N and irrigation application (Peña-Fleitas et al. 2015) may reduce the influence of crop management and climatic factors such that similar sufficiency values can be used with the same species in different regions.

As with all crop/plant monitoring procedures to assess N crop status, the issues of (a) detecting excess crop N status and (b) relating measurements to fertiliser recommendations have generally received insufficient attention and require further work.

6 Use of Proximal Optical Sensors

There has been a tremendous amount of recent research with proximal optical sensors to assess crop N status and to assist in determining N fertiliser application rates for various agricultural crops (e.g. see reviews by Fox and Walthall 2008; Samborski et al. 2009; Tremblay et al. 2012). Proximal sensors are a form of remote sensing in which the sensors are positioned either in contact or close to the crop. These sensors do not directly measure N content in plant tissue, but provide measurements of optical properties that are indicative of crop N status, thereby indicating N sufficiency or the degree of N deficiency. The issue of detecting N excess with crop monitoring approaches is discussed in Sect. 7 of this chapter. Measurements with proximal optical sensors can be made quickly and periodically throughout a crop; and the results are usually very rapidly available. Some sensors are limited to individual spot measurements while others have continuous "on-the-go" capabilities that enable large representative surface areas of foliage to be measured and mapped.

To date, most of the evaluations of proximal optical sensors have been with cereals for single side-dress N fertiliser applications at a given crop development stage or age. For vegetable crops, more frequent measurement is likely to be required when N is applied frequently by fertigation. A key issue for the use of proximal optical sensors, as with all forms of crop monitoring, is the requirement for sufficiency values or ranges (as defined in Sect. 2 of this chapter). For practical use in vegetable production, where planting dates and cropping cycles can vary appreciably, sufficiency values or ranges should be related to phenological stages or thermal time. The effects of different cultivars or classes of cultivars need to be assessed.

6.1 Interpretation of Data from Proximal Optical Sensors

Proximal optical sensors measure optical properties of plants, such as light transmittance, canopy reflectance or chlorophyll fluorescence. Sensor measurements usually involve 2–3 simultaneous measurements of a property at different wavelengths, which are integrated using equations known as vegetation indices. To relate sensor measurements or indices to crop N status, a calibration or normalisation procedure is required. Two broad approaches are used: (a) absolute values and (b) Sufficiency Index (SI) values. The use of absolute values is based either on yield response functions (Fox and Walthall 2008; Gianquinto et al. 2004; Padilla et al. 2017) or is related to measures of crop N status such as the Nitrogen Nutrition Index (NNI; described in Sect. 5.2 of this chapter) (Mistele and Schmidhalter 2008; Padilla et al. 2015, 2016, 2017) or to crop or leaf N content (e.g. Chen et al. 2010; Gianquinto et al. 2011a; Padilla et al. 2014, 2015).

In the SI approach, the sensor measurement or the derived vegetation index of a crop is divided by a measurement or equivalent index value obtained from a small area of the same crop (N reference plot) managed so that N is not limiting (Samborski et al. 2009; Tremblay and Bélec 2006; Tremblay et al. 2011). The rationale of the SI approach is that effects of various factors on optical measurements, that are common to both the measured area and the N reference plot, such as abiotic and water stress, disease incidence and cultivar are normalised, thereby isolating the difference in N status (Samborski et al. 2009; Tremblay and Bélec 2006). The SI approach provides a relative value that indicates the degree of N deficiency; it enables such assessment to be made at different growth stages and with different cultivars. Sufficiency Index values that have been recommended for different crops in different locations, generally range from 0.90 to 0.96 (Samborski et al. 2009). These SI values represent sufficiency values; lower values are regarded as indicating that N fertiliser application is required. An alternative to the establishment of a non-N limiting reference plot is the virtual-reference concept (Holland and Schepers 2013) where an area within the field with good growth is assumed not to be N limited and is used as a reference. The SI approach assumes that there is a plateau response due to sensor saturation when N is not limiting, because either (a) luxury N uptake does not occur or (b) if luxury N uptake does occur, it will not be reflected in a saturated sensor reading.

It is commonly regarded that the plateau response occurs. However, differences between vegetable species have been reported (see Sect. 7 of this chapter); appreciable luxury N uptake reflected in sensor readings occurred in muskmelon (Padilla et al. 2014) but was moderate in cucumber (Padilla et al. 2016). Where luxury N uptake occurs and sensor readings do not saturate, the SI approach will not be suitable. The issue of luxury N uptake and crop monitoring is discussed more fully in Sect. 7.

Where the SI approach is not suitable, an alternative procedure is required to relate the absolute values measured by the sensor to crop N status. Padilla et al. (2015) reported a procedure to determine sufficiency values for absolute values of optical sensor readings, with vegetable crops, that can be used to derive sufficiency values for frequent measurement (e.g. each 1–2 weeks) and for individual phenological phases. This procedure is based on the relationships between optical sensor measurements and NNI. Procedures to relate absolute values measured directly by the sensor to crop N status have to consider issues such as standardisation of tissue measured, selection of crop growth stages, and the various possible issues that are normalised when using the SI approach.

Where deficient crop N status is identified, the N fertiliser requirement must be determined. The N fertiliser requirement can be quantitatively and directly related to SI values or to absolute sensor readings by use of an algorithm (e.g. Holland and Schepers 2013; Solie et al. 2012) or this can be done semi-quantitatively by making adjustments to a previous plan of N fertiliser applications.

6.2 Chlorophyll Meters

Chlorophyll meters (CMs) are small, hand-held, clip-on optical sensors that indirectly measure leaf chlorophyll content. Leaf chlorophyll content is correlated to leaf N content (Fox and Walthall 2008). There are currently several commercially available sensors, including the SPAD-502 (Konica-Minolta, Japan) and Hydro N-tester (Yara International, Norway) which are almost identical, and the more recent atLeaf sensor (FT Green LLC, DE, USA; Zhu et al. 2012) and Apogee chlorophyll meter (Apogee Instruments, Inc., UT, USA; Parry et al. 2014). The atLeaf sensor is much cheaper than the established SPAD-502 and Hydro N-tester sensors. Most research work has been done with the SPAD-502. Chlorophyll meters generally measure leaf chlorophyll content in their own units (SPAD, HNT or atLeaf units); the Apogee CM measures in μmol of chlorophyll per m^2 of leaf surface or in SPAD units. For each individual measurement, the measured area is generally $<10\ mm^2$. Consequently, there is a requirement for appreciable replication e.g. 20–40 measurements on different plants per field or experimental treatment, and for strict measurement protocols (e.g. leaf selection, position on leaf).

Chlorophyll meters such as the SPAD and Hydro N-tester estimate leaf chlorophyll by the differential transmission of red and near infra-red (NIR) radiation (Fig. 5).

There are many research publications on the use of CM to evaluate crop N status, mostly with field crops which have been reviewed by Fox and Walthall (2008), Goffart et al. (2008), Meisinger et al. (2008), and Samborski et al. (2009). These reviews also describe interferences, protocols and data interpretation. A number of studies have been done with various vegetable species and potato (e.g. Farneselli et al. 2010; Gianquinto et al. 2006; 2011b; Goffart et al. 2008; Padilla et al. 2014, 2015; Westerveld et al. 2004). The variety of leaf forms of vegetable species has implications for CM measurement. For example, finely-dissected leaves of carrot can be difficult to measure and leaf veins must be avoided (Westerveld et al. 2004). Composite (e.g. tomato) and large leaves (e.g. melon, cucumber) require well-defined and consistent measurement points as considerable variability in readings can occur within leaves.

Numerous studies with different vegetable species have generally reported significant relationships between CM readings and crop/leaf N content or crop NNI for given sampling times throughout a crop. These relationships differ between species and change during a given crop (e.g. Gianquinto et al. 2006, 2011b; Padilla et al. 2014, 2015). Relationships between CM readings and crop N status are generally linear (Gianquinto et al. 2006; Padilla et al. 2014, 2015; Zhu et al. 2012); sometimes plateau responses occur at relatively high N contents suggesting saturation (e.g. Goffart et al. 2008). It is not clear exactly what are the conditions (e.g. species, chlorophyll and N contents) when saturation occurs; this requires further elucidation. Protocols for using CMs to aid vegetable crop N management have been developed (Gianquinto et al. 2004, 2011b; Olivier et al. 2006; Samborski et al. 2009). CM sensors are robust, sensitive and easy to use; however, despite this and the considerable amount of research conducted with CMs, there appears to have

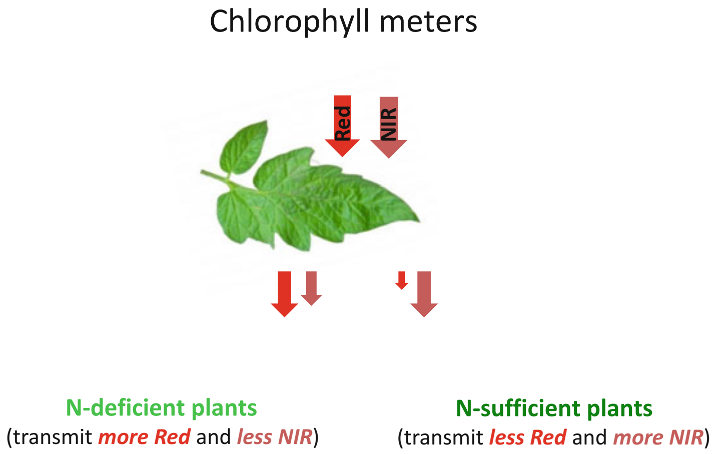

Fig. 5 Schematic representation of the differential transmission of red and infra-red light used to estimate leaf chlorophyll content with leaf chlorophyll meters

been little adoption into crop N management with vegetable or other types of crops. Problems include lack of sensitivity and specificity, the intensity of the sampling effort needed, and the absence of stable relationships with actual N fertiliser requirements.

6.3 Reflectance Sensors

There has been substantial recent research on the use of proximal reflectance sensors to assist with crop N management (e.g. Fox and Walthall 2008; Meisinger et al. 2008; Samborski et al. 2009; Schmidt et al. 2009, 2011). These optical sensors are commonly positioned 0.4–3.0 m from the crop canopy. Much of the recent research has been conducted with cereal crops where they are used commercially to control variable rate application of N fertiliser (Fox and Walthall 2008; Meisinger et al. 2008; Samborski et al. 2009). Most, particularly the newer reflectance sensors, are active sensors e.g. the various Crop Circle (Holland Scientific, Inc, Lincoln, NE, USA), and Greenseeker sensors (Trimble Navigation Ltd., Sunnyvale, CA, USA), and the Yara N Sensor ALS (Yara International ASA, Oslo, Norway) that have their own light source so that they can be used in any light conditions. Many reflectance sensors can be mounted on a tractor to automatically control N fertiliser application rates; most can be used for manual measurement. Both the Crop Circle and Greenseeker ranges have simpler, cheaper, hand-held models that are well-suited to manual use with vegetable crops.

A big advantage of most proximal reflectance sensors is that because of their on-the-go capabilities they can measure large representative areas of the crop canopy. Canopy reflectance measurements are based on the interaction of different light

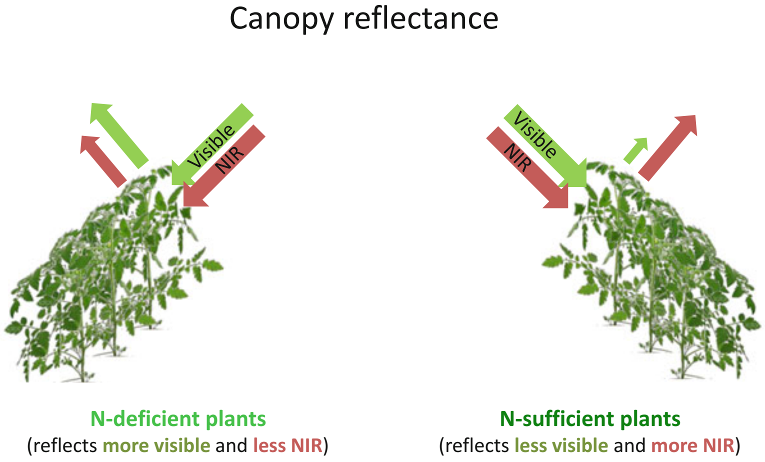

Fig. 6 Differential reflectance of visible and near-infra red radiation used to calculate vegetation indices with canopy reflectance sensors

wavelengths, in the visible and near infra-red (NIR) spectrum, with the crop canopy. This interaction is influenced by crop N status (Fox and Walthall 2008; Samborski et al. 2009). The reflectance of 2–3 individual wavelengths such as green, red, far-red, and NIR are used in mathematical equations to derive vegetation indices. Among the numerous indices that have been proposed, the most commonly-used is the NDVI (Normalised Difference Vegetation Index). A detailed list of relevant indices and their calculation is provided by Bannari et al. (1995) and by Li et al. (2010). Commonly, the selected indices are interpreted for N management using the Sufficiency Index (SI) discussed in Sect. 6.1 of this chapter, or by establishing relationships with measures of crop N status such as the Nitrogen Nutrition Index (Mistele and Schmidhalter 2008; Padilla et al. 2015, 2017). A schematic representation of the differential reflectance of visible and near-infra red radiation used to calculate reflectance indices is presented in Fig. 6.

For vegetable crops, studies with tomato (e.g. Gianquinto et al. 2011a; Padilla et al. 2015), muskmelon (Padilla et al. 2014) and cucumber (Padilla et al. 2017; Wei et al. 2010) have demonstrated the sensitivity of canopy reflectance measurements throughout crops. As yet, unlike with cereals, there appears to be little use of canopy reflectance sensors for N fertiliser management in commercial vegetable production.

6.4 *Fluorescence Measurement of Polyphenols*

Polyphenolic compounds, in particular flavonols, are produced in plant leaves under stress conditions so that their content is usually inversely related to crop N

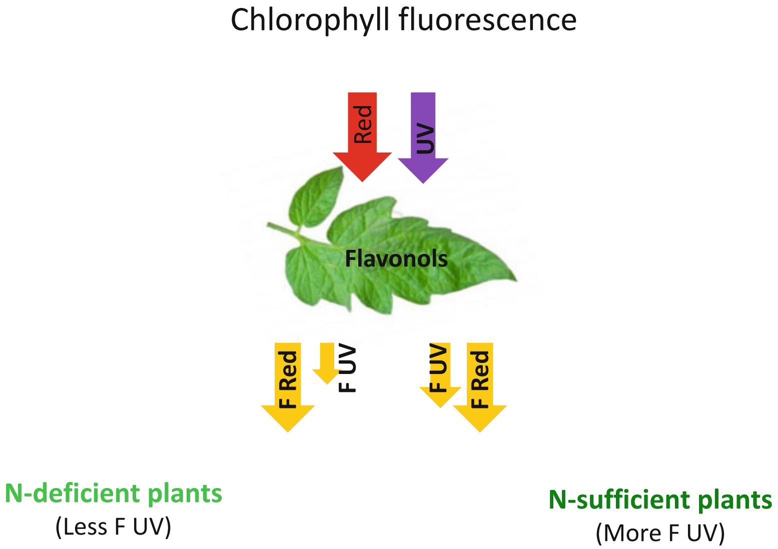

Fig. 7 Schematic representation of the differential emission of chlorophyll fluorescence under red and UV wavelengths that is used to estimate leaf flavonols content. "F" refers to fluorescence

status. The ratio of chlorophyll to flavonols (or polyphenols), known as the Nitrogen Balance Index (NBI), has been reported to be very sensitive to crop N status because chlorophyll decreases and flavonols (or polyphenols) increase when N becomes increasingly limiting (Padilla et al. 2016; Samborski et al. 2009; Tremblay et al. 2009, 2012). Optical sensors based on measurement of fluorescence properties have been developed to estimate the contents of both flavonols (or polyphenols) and chlorophyll. The two most-commonly used fluorimeters are the Dualex Scientific+$^{\mathrm{TM}}$ which is a clip-on sensor and the Multiplex which is a proximal sensor, both are produced by Force-A, Orsay, France.

The measurement principle used by these sensors is that mesophyll chlorophyll emits fluorescence in the red to far-red region of the light spectrum after being illuminated with ultraviolet (UV) and red light. Flavonols that accumulate in the leaf epidermis absorb appreciable amounts of UV light while transmitting most of the red light; the transmitted red light is subsequently absorbed by the chlorophyll in mesophyll chloroplasts. Flavonols reduce far red chlorophyll fluorescence under UV illumination without altering far red chlorophyll fluorescence under red illumination, so the flavonols content is estimated by comparing far red chlorophyll fluorescence under red and UV wavelengths (Fig. 7).

A number of studies have suggested that leaf flavonols and the ratio of chlorophyll to flavonols (NBI) are earlier, more sensitive and more specific indicators of crop N status (Tremblay et al. 2009, 2012) than chlorophyll estimation. Padilla et al. (2014, 2016) reported that these measurements were sensitive to crop N status in muskmelon and cucumber, respectively. This is a relatively recent and promising line of research.

6.5 Hyperspectral Proximal Sensors

In recent years, there has been an increased availability of, and interest in the use of, high resolution hyperspectral (HS) field radiometers. Hyperspectral proximal sensors measure reflectance in small wavelength intervals across a broad and nearly continuous spectrum, including the visible (400–700 nm), NIR (700–1350 nm) and short wavelength infrared (1350–2500 nm) ranges. This provides the potential for appreciable improvement of the assessment of biophysical and biochemical characteristics of agricultural crops compared to canopy reflectance sensors that measure only a small number of pre-selected wavelengths (Jain et al. 2007; Thenkabail et al. 2012). The use of indices that exploit reflectance measurements in narrowband intervals, especially those involving the red-edge region, have produced good results in characterising plant nutrient status (Perry and Roberts 2008; Thenkabail et al. 2012). Although promising results have been observed in studies combining multivariate analysis of HS data and field mapping of plant characteristics, their transformation into fertiliser recommendations requires more research particularly for vegetable crops where little research work has been conducted. Moreover, in their current formats, hyperspectral proximal sensors require intensive data processing after field measurement, which appreciably diminishes their utility for practical use. The integration of HS data with crop simulation models is a promising approach to optimise N management (Baret et al. 2007).

7 Luxury N Consumption and Responses of Monitoring Approaches at Excessive Crop N Status

Given that excessive N application is a common occurrence in intensive vegetable production, the ability of plant/crop monitoring approaches to detect excessive N supply is an important practical consideration. Under excessive N supply, the amount of N taken up by the crop can exceed the minimum amount necessary to achieve maximum growth (the critical N uptake amount) resulting in luxury N uptake (Lemaire and Gastal 1997). There appears to be differences among vegetable species in the occurrence of luxury N uptake, and, where it does occur, in the degree of luxury N uptake. Appreciable and moderate luxury N uptake was observed in muskmelon (Padilla et al. 2014) and cucumber (Padilla et al. 2016), respectively. The EU-Rotate_N model considers that there are differences among species in the occurrence and degree of luxury N uptake (Rahn et al. 2010). Of the 32 vegetable crops considered by the EU-Rotate_N model, 18 are indicated as having varying degrees of luxury N uptake, and 14 as not having luxury N uptake

(Rahn et al. 2010). These assessments of luxury N uptake were based on a mixture of experience and agronomic trials (C. Rahn, University of Warwick, United Kingdom, personal communication).

Species that have little or no luxury N uptake will not accumulate appreciable additional N once N sufficiency has been achieved even when increasingly excessive N is applied. In species, where little or no luxury N uptake occurs, monitoring approaches related to crop N content will generally not be able to distinguish excessively fertilised from adequately N fertilised crops. In such species, the Sufficiency Index (described in Sect. 6.1 of this chapter), which assumes that measurements exhibit a plateau response with an increasingly excessive N supply after N sufficiency, could be used to identify and characterise N deficiency.

Where luxury N uptake does occur, crop monitoring may respond to an excessive N supply. In a muskmelon crop with appreciable luxury N uptake, Padilla et al. (2014) reported that sensor readings of a chlorophyll meter and canopy reflectance indices increased with an increasingly excessive N supply and crop N status. In such species, where monitoring measurements do not exhibit a plateau response when crops increasingly accumulate excessive N, the Sufficiency Index may not be suitable. Where the Sufficiency Index is not suitable, sufficiency values and ranges based directly on absolute values may be more appropriate.

It appears that there may be two factors that influence the response of monitoring approaches to excessive N supply: (1) the occurrence or not of luxury N uptake, and (2) the response of the monitoring approach to the component being measured e.g. chlorophyll readings made with a SPAD meter that saturate at very high leaf chlorophyll contents associated with very high N contents (Cartelat et al. 2005). The limited available data suggest (a) that plateau sensor responses sometimes occur and that the mechanism maybe one or both of the factors previously mentioned, and also (b) that plateau sensor responses do not always occur (e.g. Padilla et al. 2014). Further work is required to identify and understand crops where plateau sensor responses do not occur. In these cases, there may be diminishing sensor responses to increasing crop N status which could influence the sensitivity of the monitoring approach to distinguish excessive crop N status. Further discussion on the interpretation of data from optical sensors is presented in Sect. 6 of this chapter.

In relation to the capacity of other monitoring approaches such as tissue analysis and petiole sap analysis to detect excess crop N status, there are limited data. Where appreciable luxury N uptake does not occur or does so in a limited manner, it is unlikely that the leaf sampled for tissue analysis will respond differently to the entire plant. Therefore, in such species, it seems unlikely that tissue testing will be capable of clearly detecting excess N status. It may be able to do so in species where appreciable luxury N uptake occurs. Regarding petiole sap analysis, there are insufficient published studies with excessively fertilised vegetable crops to assess the capacity of this approach to detect excessive crop N status.

8 Use of Simulation Models and Decision Support Systems for N Management

For N management, simulation models can be used: (a) to estimate crop fertiliser N requirements and/or (b) for scenario analysis to demonstrate the impact of N management on crop response and N losses to the environment. Given that irrigation is commonly used in vegetable production and that fertigation is being increasingly adopted, a number of simulation models that deal with N management of vegetable also consider irrigation.

Simulation models that estimate crop fertiliser N requirements may be incorporated into user-friendly Decision Support Systems (DSSs) with the aim of providing practical tools for growers and technical advisors to develop N fertiliser plans. These DSSs consider crop N demand, usually for short time intervals throughout a crop, and other N sources; they calculate N fertiliser requirements as supplemental N required to optimise crop N status.

The use of models for scenario analysis is very useful for demonstration purposes for example with growers, advisors, administrators and policy makers. Generally, relatively simple models, with few and readily available inputs are used for practical DSSs while more complex models with more inputs tend to be used for scenarios analysis.

8.1 Simulation Models for Scenarios Analysis of N Management

Many of the simulation models developed to evaluate crop N management and its environmental impact are complex scientific models and their use has generally been restricted to scientific studies in which they are used as a means of aggregating knowledge or to conduct scenario analysis. Scenario analysis commonly takes two forms, being either: (a) demonstration of management consequences to stakeholders, or (b) as an alternative to costly experimental field trials with multiple treatments.

Generally, these models simulate N and water dynamics in the crop-soil system. Numerous such models have been developed, some examples are EPIC (Williams et al. 1984) one of the first such models developed and the basis for some subsequent models, STICS (Brisson et al. 2003), CropSyst (Stöckle et al. 2003), and the DSSAT group of models (Dayan et al. 1993; Jones et al. 2003). These are large and complex models which require numerous inputs, and which were generally developed for cereal crops. There have been a very small number of adaptations of these models to simulate aspects of N dynamics in vegetable crops (e.g. Cavero et al. 1998; Onofri et al. 2009; Rinaldi et al. 2007), but generally their use for practical N management of vegetable crops has been limited.

The comprehensive EU-Rotate_N model (Rahn et al. 2010) was developed as result of an EU funded research project to optimise N management in a wide range of vegetable and arable crops and rotations throughout Europe (Rahn et al. 2010). For many vegetable species, EU-Rotate_N simulates crop growth and marketable yield, crop N uptake and crop evapotranspiration. It considers N supplied by various sources such as soil mineral N, fertiliser N and N mineralised from soil organic matter, manures and crop residues, and water supplied by rain and various forms of irrigation. It can be used to conduct economic analyses and to assess negative environmental impacts through nitrate leaching and gaseous N losses. EU-Rotate_N has been used to simulate growth, production, and N and water dynamics in numerous diverse vegetable production systems such as various cool season species grown in open field conditions in Germany (Nendel 2009), open field vegetable crops in Mediterranean conditions (Doltra and Muñoz 2010) and in greenhouse-grown tomato and cucumber crops in SE Spain and China (Guo et al. 2010; Soto et al. 2014; Sun et al. 2012). The EU-Rotate_N model has been demonstrated to be an effective scenario analysis tool of N and irrigation management for different vegetable crops grown in diverse environments. By comparing scenarios, EU-Rotate_N can also be used to identify optimal N management. A feature of EU-Rotate_N is that the model considers crops grown in rotations, by considering rotation effects such as those of crop residues, residual soil mineral N throughout the profile, different rooting depths etc.

8.2 Decision Support Systems Based on Simulation Models

Computer-based Decision Support Systems (DSS) can be used to calculate crop N fertiliser recommendations, and also crop irrigation requirements. The term "computer" here refers to all computing devices including smart phones and tablets. These DSSs can be stand-alone (i.e. installed directly on the device) or web-based programs (that can be consulted wherever there is an Internet connection). The use of computer technology enables numerous and frequent calculations to be made, various inputs to be considered, the use of stored data records for individual fields, access to data bases, and use for record keeping. Frequent calculation of N fertiliser requirements is essential for fertigated vegetable crops with frequent nutrient application. Relatively simple DSS with few data requirements are well-suited for on-farm use (Gallardo et al. 2014; Parneaudeau et al. 2009; Rahn et al. 1996).

Two broad modelling approaches are used for simulation models that are incorporated into DSSs. They are either "static" in that standard conditions are assumed such as expected yield and average climatic conditions, or they are "dynamic" in that they respond to real time or forecast conditions. Static approaches require less input data; data bases of long term average climatic data can also incorporated into the DSS so that there is no requirement to input climate data. Dynamic models simulate growth and production in the context of actual cropping conditions and have the capacity to respond to unseasonal weather and to weather fluctuations. Some DSS use both approaches, giving the user the option of either using a data base of average long term climatic data or entering real time climatic data as with the VegSyst-DSS (Gallardo et al. 2014). The use of long term average climatic data considerably simplifies the process of data entry, and is most suited to where there is small inter-annual climate variability such as in Mediterranean climates. With the rapid developments in Information and Communication Technology (ICT) it should be feasible to automatically enter forecast climate data (e.g. from 5 to 7 day forecasts). Where high frequency N application is employed (e.g. with fertigation/drip irrigation), this would enable N fertiliser planning for weekly periods to be based on forecast climate conditions. It would also enable adjustment of provisional plans based on long term average climatic data.

Several DSSs based on simulation models have been developed in Europe to assist with N fertilisation of vegetable crops e.g. N-Expert (Feller 2015; Fink and Scharpf 1993), Azofert (Machet et al. 2007; Parneaudeau et al. 2009) and WELL_N (Rahn et al. 1996, 2001). The French DSS, Azofert was developed for cereals and vegetables, whereas WELL_N and N-Expert were developed primarily for N recommendations of vegetable crops, but also include cereals when grown in rotation with vegetables. The development of and the general procedures used by N-Expert were described in Sect. 3.3 of this chapter. N-Expert has been recently thoroughly revised and updated to produce N-Expert 4 (released in September 2015) for which information and free downloads in either English or German are available at: http://www.igzev.de/n-expert/?lang=en. The program is executable on all computer operating systems (as at September 2015). The N-Expert software assists growers and fertiliser advisers to calculate the N (and also P, K and Mg) fertiliser requirement of vegetable crops and also to prepare nutrient balances for N, P, K and Mg as required by German Law. N-Expert 4 contains an updated database of nutrient uptake for all relevant field vegetable crops and for many other crops that are grown in crop rotations with vegetables. When compared with grower management in intensive vegetable rotations over 5 years, N-Expert reduced N leaching losses by 150 kg N ha^{-1} $year^{-1}$ on average, with no significant effects on crop yield and quality (Armbruster et al. 2013).

The WELL_N DSS (Rahn et al. 1996, 2001) was developed as a practical DSS to determine N fertiliser recommendations in the United Kingdom. It has been used in commercial vegetable production by growers and advisors. WELL_N is based on routines of the previously developed research model N_ABLE (Greenwood 2001). It considers average climate, soil mineral N, crop residues and N mineralisation from soil organic matter to calculate the minimum total amount of mineral N fertiliser required for maximum production of 25 different crops (Rahn et al. 2001). A default rate of N mineralisation from soil organic matter of 5 kg N ha^{-1} $week^{-1}$ is assumed (Rahn et al. 1996).

The VegSyst-DSS, based on the VegSyst simulation model was developed to calculate daily irrigation and N fertiliser requirements and nutrient solution N concentrations [N] for fertigated vegetable crops grown in greenhouses in SE Spain (Gallardo et al. 2014). In this greenhouse-based vegetable production system, most crops are grown in soil, and all crops are grown with combined fertigation/drip irrigation; most receive N in all irrigations (every 1–4 days), which is applied on the basis of concentration (Thompson et al. 2007b).

The VegSyst simulation model is a relatively simple model that calculates daily values of crop biomass production, crop N uptake and crop evapotranspiration (ETc). The model has been calibrated and validated for the major vegetable crops grown in greenhouses in SE Spain (tomato, sweet pepper, muskmelon, cucumber, zucchini, egg-plant, watermelon) (Gallardo et al. 2011, 2014, 2016; Gimenez et al. 2013). It is assumed that there are no water or N limitations of crop growth. The VegSyst-DSS calculates N fertiliser requirements, based on crop N uptake, by considering soil mineral N, and N mineralised from both the most recent manure application and from soil organic matter, and the efficiency with which N from each N source is used (Gallardo et al. 2014). Irrigation requirements are calculated based on ETc and by considering irrigation water salinity and the application uniformity (Gallardo et al. 2014). Irrigation is a determinant of the amount of applied N when N is applied on the basis of concentration. DSSs that calculate N requirements for fertigated vegetable crops, such as the VegSyst-DSS, should also calculate irrigation requirements.

The Veg-Syst DSS considers the planting date, length of cropping season, and climatic conditions of each crop; using either real time or long term average climate data, from an internal data base. Within greenhouses in the Mediterranean climate of SE Spain, there is little inter-annual climate variability, and long term average climate data show little deviation from real time data (Bonachela et al. 2006). When the database of long term average climatic data is used, the only required inputs for the Veg-Syst DSS are the species, the dates of the crop, some details of the soil and irrigation system, and information on the timing and amount of whitewashing used to limit excessive heat within the greenhouse. For the combined fertigation/drip irrigation systems used in SE Spain, VegSyst DSS prepares daily plans of the recommended irrigation volume and of the recommended N concentration. For practical purposes, the recommended N concentration is also averaged over 4 weeks to reduce the number of adjustments to the composition of the fertigation solution. A stand-alone version of VegSyst DSS that operates with Windows operating systems is available at http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml.

Decision Support Systems for N management have been developed for leafy vegetables grown in open fields in California and Italy. In the Central Coast region of California (e.g. the Salinas Valley), the on-line DSS software CropManage (https://ucanr.edu/cropmanage/login/offline.cfm, click on “About CropManage”) has been developed to aid in the adoption of more efficient practices of N management to reduce NO_3^- leaching into underlying aquifers (Cahn et al. 2013). The CropManage software estimates N fertiliser and irrigation requirements on a field-by-field basis. The N fertiliser algorithm generates recommendations based on crop N uptake, current soil NO_3^-–N status, and estimated soil N mineralisation. The irrigation scheduling algorithm uses real-time reference evapotranspiration data from the Californian CIMIS (California Irrigation Management Information System) climate station network (http://www.montecitowater.com/Cimis.htm), crop coefficients based on the planting configuration, and soil water holding characteristics to estimate irrigation intervals and volumes. Nitrogen management is based on adding sufficient N in periodic (e.g. weekly) applications to maintain root zone soil mineral N at a maximum threshold value of 15–20 mg NO_3^-–N kg^{-1}, based on the philosophy of the PSNT (described in Sect. 3.4 of this chapter). To improve the functionality of CropManage, an earlier version was thoroughly evaluated by growers in commercial lettuce fields and their feedback was incorporated into the software (Cahn et al. 2013).

A DSS that calculates N fertiliser recommendations for leafy vegetables has been recently developed in Italy (Massa et al. 2013). The simulation model within this DSS calculates the optimal amount of mineral N in the root zone to ensure maximum production whilst avoiding an excessive N supply. The N fertiliser recommendations are the amounts required to maintain the optimal soil mineral N content in the root zone. The underlying approach of maintaining an optimal root zone soil mineral N content is the same general approach for root zone N management described in Sect. 3.5 of this chapter. This DSS is based on the daily simulation of crop N uptake and a daily N balance calculation. The DSS was successfully tested in spinach (Massa et al. 2013).

FERTIRRIGERE (Battilani et al. 2003) is a DSS based on a dynamic model that assists in irrigation and nutrient management of processing tomato grown in Mediterranean regions. The main inputs are daily climate data (average temperature and wind speed, rainfall), and basic soil parameters (texture, nutrient content). Outputs are daily irrigation and macro nutrient requirements. When compared with grower management in 56 different farms in Tuscany (Italy), FERTIRRIGERE reduced N application by 46% on average, with no important effects on production and quality (A. Pardossi, University of Pisa, personal communication). FERTIRRIGERE (in Italian) can be freely downloaded (after registration) at http://cloud.consorziocer.it/CerAcqueNET/Login.aspx.

Researchers at the University of Pisa, Italy (Drs A. Pardossi, L. Incrocci and D. Massa) have developed a family of DSSs for nutrient recommendations for vegetable crops in Tuscany, Italy. The CAL-FERT software (Incrocci et al. 2013) is a DSS that calculates fertilisation plans for N, phosphorus (P) and potassium (K) for various vegetable species by considering soil analysis, crop nutrient uptake and the mineralisation of nutrients from soil organic matter and decomposition of biomass of previous crops. It is available in Italian at http://www.cespevi.it/softunipi/calfert.html. The CAL-FERT software is an example of a static model that works with a target yield value, provided by the user, and a data base of long-term average climatic data. From the information of expected yield, cropping dates and climate conditions, CAL-FERT fits a crop N uptake curve which is then used with a daily N balance calculation to estimate daily N fertiliser requirements. Users can also input real time or forecast climate data.

The GREEN-FERT software is another DSS developed by the same researchers at the University of Pisa for managing fertilisation of various nutrients using the Dutch 1:2 volume soil:water extract method (Sonneveld and Voogt 2009; Sonneveld et al. 1990) for different vegetable species grown in soil in greenhouses in Italy. The Dutch 1:2 volume soil:water extract method was described in Sect. 3.7 of this chapter. This software (in Italian) can be freely obtained at http://www.cespevi.it/softunipi/greenfert.html. GREEN-FERT contains a database for interpretation of the aqueous extracts; users can modify the database according to their personal experience. These researchers also developed the “Nutrient Solution calculator” which is an Excel™ spreadsheet developed to assist growers and consultants with the preparation of nutrient solutions for fertigation to user-specified recipes of nutrient concentration, electrical conductivity (EC) and pH. This software is available in several different languages (EN, NL, ES, IT HU) at http://www.wageningenur.nl/en/Research-Results/Projects-and-programmes/Euphoros-1/Calculation-tools/Nutrient-Solution-Calculator.htm. Descriptions of the various nutrient management software programs developed by these researchers at the University of Pisa are available in Incrocci et al. (2013).

The NDICEA nitrogen planner (http://www.ndicea.nl/indexen.php) is a computer-based program developed by the Louis Bolk Instituut in The Netherlands that assists with N planning for vegetable and arable crops. It estimates N mineralisation from soil organic matter and different types of manures and organic residues, estimates N losses and performs weekly comparisons of crop N demand with net available N supply. This program has been in use for 15 years and is well known within the research community of organic agriculture. The latest version (from 2015) has The Netherlands, Flanders (Belgium), England, Denmark and Spain as pre-set country options, and has been used in several other countries. It offers a language choice of English, Dutch or Spanish. For use in other countries (with different soils, crops, manures, climate) the model can be adapted by changing the databases within the model and connecting it via Internet to obtain climate data from other weather stations.

The “Fertigation model” of Voogt et al. (2006) combines a crop evapotranspiration model with an empirical nutrient uptake model. It calculates on-going nutrient uptake concentrations (Thompson et al. 2013b) based on crop specific parameters such as cropping phase, plant height, LAI and real-time greenhouse climate data. Soil type, soil N-dynamics and the analytical results of regularly taken soil samples are used as parameters for adjustments (W. Voogt, Wageningen University and Research, The Netherlands, personal communication). The output is the composition of the nutrient solution which is used as input for a computer-controlled fertigation unit.

8.3 Decision Support Systems Based on Data Bases

A DSS that is currently used in the United Kingdom is PLANET (Planning Land Applications of Nutrients for Efficiency and the environmenT; http://www.planet4farmers.co.uk/Content.aspx?name=PLANET) a nutrient management decision support tool developed for use by farmers and advisers in England/Wales and Scotland. It has been developed for cereal and vegetable crops. PLANET incorporates computerised versions of both the RB209 Fertiliser Manual (described in Sect. 3.6 of this chapter) for England and Wales and Scotland's Rural College (SRUC) technical notes (http://www.sruc.ac.uk/downloads/120451/crop_technical_notes). It is essentially a database that contains and integrates all of the tables of the RB209 Fertiliser Manual and the relevant Scottish recommendations.

Additionally, it provides for detailed record keeping of individual fields and the capacity to update during cropping. Detailed records can be kept of cropping, soil analyses, and each fertiliser and manure application, and reports can be produced. PLANET also assesses compliance with the maximum N limit for individual crops and fields within Nitrate Vulnerable Zones (defined in Sect. 1 of this chapter).

9 Application Methods

9.1 Split Applications

Split N applications whereby the N is applied two or more times to a crop is a strongly recommended practice for vegetable production. Commonly, relatively small N applications are made immediately prior to planting and then one or more side-dress applications are made later during periods of rapid vegetative growth and fruit growth when the demand for N is much greater. Relatively small amounts of N are required for the period prior to the onset of rapid vegetative growth. Large single N applications at planting run the risk of appreciable N losses occurring, particularly when the amount of applied mineral N in the soil, mostly in the form of NO_3^-–N, appreciably exceeds the immediate crop N demand. The basic philosophy of split application is to partition N applications to coincide with crop demand. Most commonly, where split applications are made, one or two side-dress applications are made. The KNS system can be used to optimise side-dress N applications.

9.2 Fertigation

Fertigation is commonly used with drip irrigation, and is being increasingly used with sprinkler irrigation. In particular, combined fertigation and drip irrigation systems are being increasingly used in vegetable production systems e.g. throughout southern Europe and in the central coast of California. With fertigation, N can be applied with varying degrees of frequency depending on the irrigation schedule. Cahn et al. (2013) presented an example of five N applications by drip fertigation during a crop in California. In SE Spain, N applications to drip fertigated vegetable crops, grown in soil in greenhouses, are made every 1–4 days (e.g. Granados et al. 2013).

There are various types of fertigation systems in which nutrients are supplied to a crop through the irrigation system. These can be broadly categorised as being: (1) simple fertiliser tanks, (2) manually-operated multi-tank (i.e. two or more tanks) systems, and (3) computer-operated multi-tank systems. Generally, with category 1 systems, fertiliser is applied on the basis of rate, with category 2 systems as either rate or concentration, and with category 3 systems on the basis of concentration. With computer-operated multi-tank systems, nutrients are commonly applied in all or most irrigations; in combination with drip irrigation, there can be high frequency applications of both water and nutrients.

The combined use of fertigation and drip irrigation provides the technical capacity to spoon-feed N and irrigation as required by the crop. Applying frequent small N applications can appreciably reduce the risk of N loss associated with larger, more infrequent N applications such as with conventional split applications. However, growers generally lack the tools to take advantage of this advanced technical capacity for precise N management. To do so, both irrigation and N management have to be optimised. Excessive irrigation with an optimal concentration of N will result in the application of excessive N. Similarly, excessive N application with optimal irrigation can result in a large accumulation of soil mineral N that can subsequently be lost to the environment (Soto et al. 2015). The recommended approach for optimising both irrigation and N management of fertigated vegetable crops is a combination of prescriptive and corrective management for both irrigation and N (Granados et al. 2013). Prescriptive management is the preparation of detailed plans of recommendations for both irrigation and N fertiliser applications, which can be prepared using DSSs (see Sect. 8.2 of this chapter). Corrective management is the use of monitoring techniques to identify adjustments that ensure that the supply of water and N maintains the desired crop water and N status. Monitoring approaches for N management were discussed in Sects. 3.7, 3.8, 5.4 and 6 of this chapter. Monitoring methods for irrigation of vegetable crops were reviewed by Gallardo et al. (2013).

10 Specialised Fertilisers

10.1 Fertilisers with Nitrification Inhibitors

Nitrification inhibitors (NI) appreciably slow the otherwise generally rapid process of nitrification i.e. the transformation of ammonium (NH_4^+) to NO_3^-, in soil, over a period of time. By slowing and delaying nitrification, NIs reduce the possibility of losses of root zone mineral N by NO_3^- leaching and denitrification, and also reduce nitrous oxide (N_2O) emissions associated with both nitrification and denitrification. The most commonly used chemical nitrification inhibitors are 3,4-dimethylpyrazole phosphate (DMPP) and dicyandiamide (DCD) (Gilsanz et al. 2016; Pasda et al. 2001; Zerulla et al. 2001). Nitrification inhibitors are combined with NH_4^+ based fertilisers; commercial products are available, such as the widely distributed ENTEC® range which incorporates DMPP. ENTEC® fertilisers are distributed by the company EuroChemAgro (http://eurochemagro.com/products/entec/). There has been considerable interest in recent years in their use to reduce nitrous oxide (N_2O) emissions associated with nitrification and denitrification (e.g. Gilsanz et al. 2016; Zhang et al. 2015). A number of studies have demonstrated their capacity to appreciably reduce N_2O emissions from intensive vegetable production (e.g. Scheer et al. 2014; Cui et al. 2011; Pfab et al. 2012; Zhang et al. 2015).

For practical N management, NIs provide the possibility of a reduced number of N fertiliser applications in vegetable production. This can be particularly advantageous for conventional surface applications of N fertiliser, and for short season crops such as lettuce where their use may ensure that a single pre-planting N application provides sufficient N for the entire crop. Their use can reduce the number of N fertiliser applications and maintain yields of vegetable crops (Pasda et al. 2001). Other benefits that have been reported with vegetable production include less NO_3^- accumulation in leafy vegetables (Irigoyen et al. 2006; Pasda et al. 2001) and reduced NO_3^- leaching loss (Cui et al. 2011). From a commercial farming perspective, the benefits to be gained from the use of NIs must be balanced against the additional cost of NH_4^+ based fertilisers containing NIs.

The overall effect of nitrification inhibitors is to delay nitrification. If excessive N fertiliser with a NI is applied, the delayed formation of NO_3^- may simply result in delayed N losses to the environment. Additionally, for NIs to be effective, their rate of degradation and their possible movement in soil should be taken into consideration within the given cropping conditions.

An important consideration is the possible uptake of NIs, and their degradation products, by vegetable crops. Nitrification inhibitors are subject to extensive standard toxicology and ecotoxicology testing prior to commercial release (Zerulla et al. 2001). Nevertheless, consumers and retailers will be concerned about the presence of these compounds and/or their degradation products in edible vegetable products. Plant absorption of DCD by wheat and subsequent metabolism within the plant was reported by Marsden et al. (2015). Where NIs are used in vegetable production, the routine analysis of edible products for the NIs used and their metabolites, as occurs with pesticides, should be considered where it is not mandatory. Where NIs are present in edible vegetable products, there are established acceptable daily intake limits for the active compounds that are part of the toxicological evaluation in the registration process (Pasda et al. 2001).

Nitrification inhibitors may have a role to play in vegetable production for reducing the number of N fertiliser applications and/or reducing N_2O emissions and NO_3^- leaching loss. However, given the concern of consumers and sales outlets regarding the presence of agrochemicals and their derivatives in food, appreciable attention will need to be paid to ensure that there are no or at least minimal concentrations of NIs and their derivative compounds in edible vegetable products. Research will be required to better understand the uptake of NIs and metabolites by different vegetable species, and of the processes of the metabolism of NIs within vegetable plants. Where NIs are used in commercial farming, testing for NIs and their principal metabolites may need to be incorporated into the routine analysis of agrochemicals that is commonly associated with edible vegetable products.

10.2 Slow and Controlled Release Fertilisers

The terms "slow release fertilisers" and "controlled release fertilisers" have been used interchangeably and also separately. Slow release fertilisers (SRF) have been defined as those from which nutrient release is slower than from the commonly-used mineral fertilisers, and where the rate, pattern and duration of release are not well controlled (Shaviv 2001). Controlled release fertilisers (CRF) have been defined as those where the factors dominating the rate, pattern and duration of release are well-known and controllable during the preparation of the CRF (Shaviv 2001). Here these fertilisers will be considered collectively as "slow and controlled release fertilisers" (SCRF).

Slow and controlled release fertilisers are a very active and constantly evolving area of research. The current discussion will focus on the most important and established nitrogen SCRFs. Organic and processed organic fertilisers will not be considered, nor will fertilisers with urease inhibitors. The focus here will be on mineral nitrogen SCRF fertilisers. There are two broad categories of mineral nitrogen SCRF fertilisers.

The first broad category is of products in which the N source, generally urea, has been chemically reacted with a compound to slow the release of N; microbial and chemical decomposition processes in soil slowly release N into the soil solution (Guertal 2009; Shaviv 2001). There are two main sub-groups within this category: urea-formaldehyde products (UF) and isobutylidene diurea (IBDU). Urea-formaldehyde is formed by reacting urea with formaldehyde at varying temperatures and reaction times, both processes influence the length of chains produced of combined urea and carbon-hydrogen groups. The length of the chains negatively influences the rate and positively influences the duration of N release (Guertal 2009).

The second sub-group within this broad chemically-stabilised of urea products is IBDU (Isobutylidene diurea) which is a combination of urea and isobutyraldehyde (Guertal 2009). Nitrogen is released following hydrolysis of IBDU, N release is faster with smaller particle size and faster with warmer soil temperatures (Guertal 2009). This first broad category of SCRF is regarded as being slow release fertilisers (Shaviv 2001) because there is less control over the rate of N release than with other forms of SCRF.

The second broad category of SCRF is that of fertilisers that have a physical coating around a physical unit of mineral N fertiliser, which is most commonly a urea prill. Typical coating materials are sulphur, wax, resin, polymer or a combination of these materials (Guertal 2009). Sulphur coated urea has been used since the 1960s (Shaviv 2001), and more recently, resin or polymer coatings have been used (Guertal 2009; Shaviv 2001). Nitrogen release from coated products is influenced by coating thickness, orifice size in the coating, soil moisture, soil temperature, and soil microbial activity (Guertal 2009). An example of a resin coated SCRF is the commonly-used Osmocote® domestic fertiliser. Coated SCRFs are regarded as controlled release fertilisers because variations in coating material, coating thickness orifice size provide some control over the N release rate (Guertal 2009; Shaviv 2001). A comprehensive review of coating materials was provided by Shaviv (2001).

Slow and controlled release N fertilisers potentially enable a single N fertiliser application to provide the complete N requirement of a vegetable crop with an appreciably reduced risk of N losses during the crop. They are more expensive than conventional mineral N fertiliser per unit of N. Agronomic studies with vegetable crops have generally reported similar yields from single applications of nitrogen SCRF compared to conventional N management (Guertal 2009). One possible disadvantage in the context of vegetable production is ensuring sufficient crop available N when there is a rapid increase in crop N demand during the exponential growth phase (Guertal 2009).

Despite the considerable research activity with SCRF, they have a very small market share. Shaviv (2001) reported that they comprised about 0.15% of all fertiliser sales, but that their use had doubled in the preceding ten year period. The vast majority of SCRF were sold for non-agricultural markets (e.g., turf, golf courses, landscaping) (Shaviv 2001). Agriculture accounted for slightly more than 10% of total SCRF use, but the demand was increasing at an annual rate of about 10% (Shaviv 2001). In the USA, only a small proportion of total agricultural use occurs with vegetable crops (Morgan et al. 2009). In general, it seems that to date, there has been little use of SCRF in vegetable production.

Slow and controlled release fertilisers are well suited to situations where crops are present for prolonged periods (e.g. turf, golf courses, fruit trees), where their use confers an economic advantage by reducing fertiliser application. In the case of vegetable production, where crops are commonly of short duration, vegetable growers may not perceive sufficient economic advantage through reduced N applications, to justify the extra cost of SCRF (Morgan et al. 2009). An additional and important issue with vegetable cropping is to ensure the N supply during periods of peak N demand; SCRF may not always be able to provide sufficient amounts of readily available N. It is important that the rate of N applied in SCRF is not excessive; if it is, the use of SCRF may only delay N loss.

In general, research with SCRF in vegetable crops has shown similar but not higher production than with conventional N management (Guertal 2009), and until now the economics of reduced N fertiliser application have not convinced many vegetable growers. It is possible that for environmental reasons that legislation may encourage adoption of SCRF. If there is to be appreciably increased use of SCRF in vegetable production for environmental reasons, it should be based on sound scientific research demonstrating reduced N losses under diverse realistic cropping conditions. It is likely that the potential use of SCRF in vegetable production may be influenced by the characteristics of cropping systems. Hartz and Smith (2009) commented that the use of SCRF for environmental reasons may be most suitable where appreciable in-season NO_3^- leaching loss is likely and where this was beyond the control of the grower. These authors considered that this was not the case in the Mediterranean climate of California, which would also apply to vegetable crop grown in other regions with Mediterranean climates and also to greenhouse-grown crops. Examples of more suitable regions for the use of SCRF are areas with heavy rainfall events during cropping and on sandy soils.

11 Future Developments

The coming years will see an increasing availability of low-cost sensors that will potentially enable rapid in-field monitoring of crop and soil nutrient status, enabling in-season adjustment of fertilisation plans according to crop specific conditions. Additionally, tools (Apps, DSSs) will be developed for mobile computer devices (smart phones, tablets) that will provide the means to prepare crop specific fertiliser plans and to very rapidly interpret data from sensors.

These technologies individually provide appreciable potential to improve nutrient management. Together, the combination of planning and monitoring tools provides considerable potential for optimal nutrient management, particularly for N (e.g. Granados et al. 2013), as was outlined in Sect. 9.2 of this chapter. Following the preparation of a crop specific nutrient management plan that considers the site and season specific requirements of a given crop, monitoring tools can then be used to ensure that optimal nutrient status is maintained. The challenges facing researchers, developers, and Extension staff are to develop user-friendly and effective applications of these technologies, to demonstrate their practical value to vegetable growers, and to effectively support growers in using them.

It seems very likely that in the coming years, in many different regions, there will be strong political and social pressure on vegetable growers to adopt management practices that reduce N losses to the environment. Therefore, it also seems likely that there will be increasing adoption of the tools and strategies outlined in this chapter.

12 General Considerations

Optimal N management of vegetable crops is something that cannot be done in isolation; it must be part of a complete crop management package in which all aspects of crop management are optimised e.g. irrigation, other nutrients, pest, disease and weed management. Otherwise the effect of the improved N management practices may be limited.

The choice of which procedures to use will be influenced by numerous factors. A major determinant is what is on offer, that is which recommendation schemes or tools are available through local Extension services or other service providers. These schemes and tools should all be adapted to local cropping and general farming conditions. For a given region, the schemes and tools provided should be appropriate to the technological level of local growers, the nature of the crop (e.g. length of growing season, crop morphology), the number and frequency of N applications, economic considerations and very importantly, the level of available support. These same considerations are relevant for individual growers when selecting an approach or tool to use.

13 Conclusions

There is range of tools and strategies that can assist vegetable growers to improve N management. These include various methods based on soil analysis or estimation of the soil N supply, N balance calculations, methods based on plant analysis, methods based on monitoring crops with optical sensors, and the use of computerised decision support systems based on simulation models or data bases. Use of these tools has been demonstrated to appreciably reduce fertiliser N application and N losses while maintaining production. Basic strategies for improving N fertiliser management are to consider all N sources such as root zone soil mineral N and N mineralised from organic materials, and to partition N application so that N applications coincide with crop N demand.

Developments in planning approaches can provide site and crop specific nutrient plans for individual crops. On-going developments in monitoring approaches should, in the near to intermediate future, provide tools that ensure optimal crop N status. Combinations of planning and monitoring approaches, particularly when combined with both fertigation and drip irrigation, provide the potential for precise optimal N management of vegetable crops.

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Glossary

AHDB Agriculture and Horticulture Development Board
CIMIS California Irrigation Management Information System
CM Chlorophyll Meter
CRF Controlled Release Fertilisers

CV Coefficient of Variation
DCD Dicyandiamide
DMPP 3,4-dimethylpyrazole phosphate
DSS Decision Support System
E Efficiency of use of N supplied to the crop
EC Electrical Conductivity
EN English
ES Spanish
ETc Crop evapotranspiration
HS Hyperspectral
HU Hungarian
IBDU Isobutylidene diurea
ICT Information and Communication Technology
IT Italian
KNS system "Kulturbegleitende-Nmin-Sollwerte" system
LAI Leaf area index
$\mathbf{N_{adj\text{-}fert}}$ Adjusted value of fertiliser N to consider the inefficiency of N fertiliser use
NBI Nitrogen Balance Index
$\mathbf{N_{crop}}$ Nitrogen absorbed by the crop
NDVI Normalised Difference Vegetation Index
$\mathbf{N_{fert}}$ N fertilizer requirement
NI Nitrification inhibitors
$\mathbf{N_{Immobilisation}}$ Immobilised nitrogen
$\mathbf{N_{irr}}$ Nitrogen applied in irrigation water
NIR Near Infra-Red
NL Dutch
$\mathbf{N_{loss}}$ Nitrogen losses
Nmin Mineral nitrogen
$\mathbf{N_{min\text{-}ini}}$ Soil mineral N at the beginning of the crop
$\mathbf{N_{min\text{-}fin}}$ Soil mineral N at the end of the crop
$\mathbf{N_{mins\text{-}crop\ res}}$ N mineralised from crop residues
$\mathbf{N_{mins\text{-}man}}$ Nitrogen mineralised from manure
$\mathbf{N_{mins\text{-}OM}}$ Nitrogen mineralised from soil organic matter
$\mathbf{N_{mins\text{-}res}}$ Nitrogen mineralised from residue materials
$\mathbf{N_{Safety\ margin}}$ The safety margin or buffer amount of soil mineral N below which the soil supply of N is limited for optimal crop production
NNI Nitrogen Nutrition Index
NVZ Nitrate Vulnerable Zones
OM Organic matter
PLANET Planning Land Applications of Nutrients for Efficiency and the environmenT
PSNT Pre Side-dress Nitrate Test
SCRF Slow and Controlled Release Fertilisers

SE South-east
SCRUC Scotland's Rural College
SI Sufficiency Index
SNS Soil N Supply
SRF Slow Release Fertilisers
UF Urea-formaldehyde products
UV Ultraviolet

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Organic Matter Mineralization as a Source of Nitrogen

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Abstract The process of nutrient mineralization is crucial to nutrition of agricultural crops. Nitrogen is often the most critical plant nutrient and therefore this chapter focusses on mineralization of nitrogen (N) as crucial factor in N nutrition of crops. In horticulture N mineralization is often high as a result of frequent organic matter additions to soil. An in-depth knowledge of the process of N mineralization and the abiotic factors regulating it is essential in order to maximize N use efficiency and avoid unwanted losses to the environment. Therefore this chapter starts with a short description of the process of N mineralization, and then provides detail on the biotic (composition of the organic matter) and abiotic factors governing the process. The process is also treated mathematically by introducing simple empirical equations that allow making rapid estimates of N mineralization. Finally, the different types of organic materials are treated with respect to expected N availability, and the problem of synchronizing N mineralization with crop N demand is treated.

Keywords Nitrogen mineralization • Mineralization kinetics • Soil organic matter • Organic residues • Crop residues • Nitrogen use efficiency

1 Introduction

Soil organic matter (SOM) has traditionally been viewed as the main yield-determining factor in agriculture and even more so in horticultural production. Before the advent of synthetic fertilizers, organic material was the only applicable source of nitrogen. Perhaps more importantly, increasing SOM results in improved soil physical properties both in light-textured (mainly water holding capacity) and heavy textured-soils (workability, aeration). Some studies also indicate a positive effect from management-derived soil OM on the resis tance of soil to compaction (Holthusen et al. 2012; Schjønning et al. 2007). Large-scale application of mineral fertilizers resulted in a loss of attention for SOM content during a large part of the

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previous century, but the problems of global change (carbon sequestration in soils) and loss of (soil) biodiversity have placed SOM again at the top of the research agenda (e.g. the Soil Thematic Strategy in Europe that was launched in 2002 (Van-Camp et al. 2004), with much attention to soil organic matter).

Despite the availability and large-scale use of mineral fertilizers in horticulture, notably in vegetable production, SOM and organic materials remain crucial sources of nutrients and SOM alone typically supplies between 25 and 50% of the total N requirement of a vegetable crop (on highly fertile soil this can even be more than 100%). This supply of nutrients is possible through the process of mineralization, which will be discussed in detail in this chapter. While the process of mineralization obviously releases plant-available nutrients other than N (notably S and P) the chapter will focus on N mineralization because of its specific importance for crop production and its link with environmental issues.

2 The Process of N Mineralization

Mineralization of organic matter in soil is an almost exclusively biological process carried out primarily by heterotrophic bacteria and fungi (the role of fauna will be discussed later). These organisms use soil organic matter as building blocks for biomass assimilation and derive energy from the organic carbon (C) that is respired, under aerobic conditions, as CO_2. Any nutrients present in the organic substrate in excess of the metabolic needs will be released into the soil solution as mineral nutrients, which is the actual mechanism of N mineralization. The mineralization processes of C and N are thus completely coupled, and whether there is net release of N or not depends on the carbon-to-nitrogen (C:N) ratio of the substrates. If the substrate is low in N (high C:N ratio), mineral N present in the soil solution will be used for metabolic activity, i.e. resulting in N immobilization (Myrold and Bottomley 2008). The processes of N mineralization and immobilization occur simultaneously in soil at all times (Mineralization-Immobilization Turnover, MIT, Norton and Schimel 2012), and it is the result of these two processes which is termed net N mineralization and which can be measured by monitoring evolution of mineral N in soil. Mineralization of N occurs both under aerobic and anaerobic conditions, but given the focus on vegetable production, in the following sections we will focus on aerobic N mineralization only.

The process of net N mineralization can make a very significant contribution to overall crop N uptake (and in natural ecosystems it is practically the only source of plant available N). Net N mineralization depletes the soil organic N pool and thus this pool needs to be replenished for a sustained N mineralization in the long term. In agricultural ecosystems the soil organic N pool is replenished by a variety of N sources, e.g. immobilization of mineral fertilizer N not taken up by the crop, the N fraction of organic fertilizers/wastes that has not mineralized during the cropping season, the N in roots and root exudates.

Soil fauna are hypothesized to play a significant part in the process of N mineralization, and research has suggested that protozoa and nematodes in particular are important in this respect. However, the estimates of contributions of soil fauna have often been based on theoretical food web calculations (e.g. Hunt et al. 1987) or on simplified experimental setups in completely sterilized environments which fail to represent the natural soil conditions. Recent research using more realistic experimental conditions yielded highly variable contributions of e.g. nematodes to N mineralization ranging from 0 to 32%, depending on resource availability (fresh organic matter additions or not) and the presence or absence of plants (Buchan et al. 2013; Gebremikael et al. 2014).

3 Measurements and Mathematical Description of N Mineralization

3.1 Methods for Measuring N Mineralization

Given the importance of the process for plant nutrition, there exists a very large body of literature on measurement and prediction of N mineralization from SOM and from fresh organic materials.

Gross N mineralization or immobilization (and thus MIT) can only be measured using isotopes of N (^{15}N techniques), following two approaches, namely the tracer method (in which ^{15}N is added to the substrate pool of the studied process) and the pool dilution method (in which ^{15}N is added to the product pool of the studied process) (Norton and Schimel 2012). The pool dilution approach for estimating gross mineralization and NH_4^+ consumption rates has been used in numerous laboratory and field studies (e.g. Hooker and Stark 2008; Murphy et al. 2003). While the use of ^{15}N is the only way to fundamentally study N transformation processes in soils, the necessary assumptions with respect to recycling of the ^{15}N between the various pools prevent its applicability to practical situations. The process of net N mineralization can in principle be quantified by monitoring the evolution of soil mineral N over time, either in the field or under controlled conditions in the laboratory, and the further discussion is limited to measurements of the net process.

3.1.1 Field Measurements of N Mineralization

The most realistic estimates of N mineralization can probably be obtained from field measurements, where all possible interactions and sources of variation play, including the natural variations in soil moisture and temperature. The buried bag and soil core methods have been described as suitable methods for obtaining net N mineralization rates in the field (Hart et al. 1994) In principle, in situ net N mineralization in a given soil layer can be obtained simply by monitoring variations in soil mineral N concentration in that layer as a function of time, in case there are no gains or losses of N from that layer. The estimate of N mineralization may need to be rescaled to take into account variations in ambient conditions in order to come to a general estimate of N mineralization. However, in most situations there will be significant gains and losses of N from the soil by plant N uptake, leaching of nitrate, gaseous N losses by denitrification or ammonia volatilization. Therefore, in cropped fields the measurements of soil mineral N should be accompanied by measurements of N uptake by the crop, and if significant N losses occur, these too have to be measured or estimated. Also, the natural spatial variability may lead to very large variations both between replicated soil mineral N measurements and in time, which may well obscure the true mineralization pattern. Based on N balance calculations during the growing season, Willekens (2016) found a consistent pattern of net N mineralization in the first months in fields with an early-planted leek crop, followed by net N immobilization later in the growing season, pointing at a large within season variability. In conclusion, a onetime measurement (i.e. one season only) of N mineralization in the field may be highly inaccurate, and N mineralization needs to be assessed over different seasons to come to a reliable estimate. This makes accurate determinations of in situ N mineralization expensive and time-consuming.

3.1.2 Laboratory Measurements of N Mineralization

Incubations of soil in the laboratory under controlled environmental conditions are most commonly used to assess N mineralization rates both from SOM and from added organic materials. Many different methodologies and set-ups have been used to this end, and an exhaustive overview is not possible here. In essence, one can distinguish the different approaches based on the degree of disturbance of the soil prior to incubation. Undisturbed soil can be used by taking undisturbed soil cores in the field and incubating as such. Soils can be moderately disturbed, e.g. a bulk soil sample is collected in the field, homogenized and incubated either fresh or after drying to various extents. The soil can also be completely disturbed (dried, ground and sieved) and possibly mixed with inert material (quartz sand) before incubation. Another differentiation can be made based on whether soil cores are sampled destructively (usually with undisturbed or slightly disturbed soil) or non-destructively (e.g. the incubation leaching method following Stanford and Smith (1972), with completely disturbed soil) during the incubation. Using undisturbed or slightly disturbed soils with destructive sampling has the advantage of better reflecting field conditions and thus yielding realistic estimates of N mineralization (Cabrera and Kissel 1988). However, variability can be very large, especially with undisturbed soil. Care should also be taken to start incubations only with soils initially low in mineral N, because excessive mineral N contents affect the mineralization process and may obscure any possible trends in the measurements. The incubation leaching method has the advantage of low variability between replicates (fully homogenized) and no excessive accumulation of mineral N (leaching procedure). However, the experimental conditions are highly artificial and may produce unrealistic estimates of N mineralization.

3.2 Mathematical Description of Net N Mineralization Kinetics

Modeling of N mineralization is covered in detail in chapter "An Economic Analysis of the Efficiency and Sustainability of Fertilization Programmes at the Level of Operational Systems, with Case Studies on Table Tomato, Carrot and Potato in Central Italy". In this section, we merely reflect on equations that are fitted to measurements of net N mineralization, making abstraction of the underlying mechanistic considerations. The most commonly used equations assume zero or first order kinetics of N mineralization, or combinations of these (Table 1). An overview of different first order model approaches is given in de Oliveira Camargo et al. (2002).

Zero order equations are typically used for describing N mineralization from native SOM (because the N mineralized over the incubation period is often negligibly small compared to the total soil N pool) and for added organic materials where only a small portion of the N is mineralizable. First order equations are typically used when N mineralization is measured for prolonged periods at high temperatures and for organic materials with high and rapid N release, e.g. vegetable crop residues. Combined equations are rarely used in practice given the number of parameters that has to be estimated (3, 4 or more) based on data that exhibit inherent large variability. In case net N immobilization is observed, or net N immobilization followed by net mineralization, alternative equations need to be used, e.g. as in De Neve et al. (2004). However, in intensive vegetable growing organic materials applied shortly before or during the growing season will seldom lead to net N immobilization.

When fitting equations to N mineralization kinetics, one should be well aware of the large variability and uncertainty that is associated with measurements of N mineralization, both in situ and in controlled lab conditions. I.e. the complexity of the model should be matched to the quality, variability and/or uncertainty of the available data. For this reason, most often the simplest models (simple zero and first order kinetics) will be the wisest choice.

Table 1 Most commonly used kinetic models for N mineralization in soil

Type	Equation	Number of parameters to be estimated
0-order	$N_{\min}(t) = k\ t$	1
1-order	$N_{\min}(t) = N_A(1 - e^{-kt})$	2
Double 1-order	$N_{\min}(t) = N_{A,f}\left(1 - e^{-k_f t}\right) + N_{A,s}\left(1 - e^{-k_s t}\right)$	4
Combined 1- and 0-order	$N_{\min}(t) = N_{A,f}\left(1 - e^{-k_f t}\right) + k_s t$	3

4 Predicting N Mineralization

Laboratory or field measurements of N mineralization are labour-intensive and costly, but are highly needed to calculate fertilizer advices for vegetable crops. Therefore, much research has been dedicated to finding alternative methods that would predict N mineralization based on a onetime (bio)chemical characterization of the soil organic matter or the added organic materials. Conceptually there is an important difference between predicting N mineralization from SOM or from AOM, and therefore these will be discussed separately.

4.1 N Mineralization from SOM

The absolute amount of N mineralization from SOM is determined by a large number of controlling soil properties, the most important of which are the SOM content and the soil texture. Within a given soil textural class, there is a relationship between N mineralization and the SOM content, but this relationship is not very strong because many other controlling factors govern the mineralization and N release. The quality of organic matter is often related to its C/N ratio, but C:N ratios of agricultural soils are typically in a relatively small range of 8–15, making it a poor predictor of N mineralization. Other factors such as soil pH undoubtedly play a part in N mineralization (Curtin et al. 1998; Neale et al. 1997), with reduced N mineralization rates expected with decreasing pH (due to reduced biological activity). However, in vegetable soils pH is often adjusted and is expected not to drop below a point where it could negatively impact N mineralization. Soil texture exerts a very strong control on SOM content, with higher SOM accumulation in heavier textured soils as a result of physical and biochemical protection mechanisms. Accordingly, this leads to lower rates of N mineralization per unit soil organic carbon (SOC) at higher clay contents (Franzluebbers et al. 1996; Hassink 1994).

The use of simple indicators (total SOC or soil organic nitrogen (SON), C:N ratio) of soil N mineralization implicitly assume that SOM is one homogeneous pool, which clearly is a gross oversimplification. Given that recent (i.e. past years) and historical soil management (i.e. from decades to even centuries) may contribute to the build-up (or breakdown) of easily mineralizable N pools, these simple indicators therefore often fail to predict N mineralization. E.g. large and frequent inputs of animal manures over a period of years will result in the buildup of an easily mineralizable organic N pool and lead to N mineralization rates that are much higher than one would anticipate from the SOC or SON content. This is typically the case in regions of intensive livestock production, which are often also associated with intensive vegetable production areas (e.g. Brittany in France, West Flanders in Belgium, Brabant in The Netherlands).

Countless (bio)chemical extraction procedures of SOM and SON fractions have been tested as predictors of net N mineralization since many decades (e.g. Keeney and Bremner 1966; Stanford 1982) to account for the presence of variably available N pools. Recent examples of research to isolate kinetically different soil N fractions include the combination of soil physical and chemical fractionations (e.g. Jegajeevagan et al. 2013) and of subcritical water extraction (Sleutel et al. 2013). However, no method has found broad applicability because correlations with field-measured N availability are often low (Bundy and Meisinger 1994). The problem in correlating chemical extraction methods with lab or field estimates of N mineralization lays also in the uncertainty associated with these estimates, which may partly explain the lack of correlation often observed.

In conclusion, there is no single generally applicable method to predict N mineralization from SOM. A rule of thumb that can be used to obtain a rough estimate of N mineralization (in the absence of true measurements) is a mineralization rate of 2–3% of the soil organic N under temperate maritime climates (with the lower end for heavy soils and the high end for sandy soils), but this rule should be applied with much caution.

4.2 N Mineralization from Exogenous Organic Materials

To some extent the same principles for predicting N mineralization from SOM also apply to exogenous organic materials (EOM) (or added organic materials, AOM). However, the natural variation in composition of EOM is much larger than that of SOM, leaving much more scope for finding good predictors.

The most common predictor of N mineralization of EOM is the C:N ratio. When the C:N ratio of the material is large (or the N content is small), the microbial biomass will immobilize N during the decomposition process in order to fulfill its metabolic requirements. This may lead to a temporary shortage of mineral N for the crop. The C:N ratio that leads to neither net N mineralization nor immobilization, i.e. the C:N ratio at which the microbial demand for N is met exactly (Bloemhof and Berendse 1995), is called the critical C:N ratio and is typically between 20 and 40. The values at the higher end are found when the mineralization process is monitored for a longer time.

The C:N ratio cannot be used successfully in all cases and many alternative measures have been developed in trying to predict N mineralization. The most important ones are probably the sequential extraction methods yielding fractions that are increasingly more resistant to mineralization. The “Van Soest” fractionation (Van Soest and Wine 1967) is the most standardized method, which was developed in animal nutrition science to provide a measure of digestibility of fodders. It is based on a consecutive extraction using neutral and acid detergents yielding fractions of water-soluble compounds, hemicellulose, cellulose and lignin. Because digestion of fodders by animals is in some way comparable to degradation of organic materials in soil, the fractionation scheme developed for fodders has been applied extensively to characterize organic material with respect to C and N mineralization (e.g. Jensen et al. 2005; Lashermes et al. 2010; Morvan et al. 2006). An alternative scheme used to predict N mineralization (e.g. Chaves et al. 2005a; De Neve and Hofman 1996) is based on the sequential extraction of lipids, waxes, water-soluble compounds, hemicellulose, cellulose and lignin using ether, alcohol, water, dilute HCl and strong H_2SO_4, respectively. These fractionation schemes yield only operationally defined fractions and the distribution over the fractions is highly dependent on the fractionation method used, such that results from different experiments cannot be directly compared. Polyphenols have also been used as predictors of N mineralization, especially for tropical legumes which tend to have high polyphenol concentrations, often in composite factors such as lignin/N or (lignin + polyphenols)/N (e.g. Constantinides and Fownes 1994). The results of many of the above mentioned studies, however, are conflicting, and despite these efforts in developing alternative (better) predictors for N mineralization, it appears that C:N ratio is still to be preferred when trying to make predictions of N release from a broad range of materials.

Correlating (bio)chemical composition with N release measured after a fixed time does not allow to dynamically use such relations e.g. in simulation models. De Neve and Hofman (1996) used the biochemical composition of vegetable crop residues to predict the mineralization parameters of the first order model (amount of mineralizable N and mineralization rate). They incorporated this in a simple model that was successfully used to calculate N mineralization and nitrate leaching losses following field incorporation in autumn of vegetable crop residues (De Neve and Hofman 1998).

5 Environmental Factors Influencing N Mineralization

When (potential) mineralization rates have been measured under controlled environmental conditions, they need to be adjusted to take into account the effects of abiotic factors, of which soil temperature and moisture content are usually assumed to be most important. This is especially important when N mineralization needs to be implemented in simulation models.

5.1 Soil Temperature

Temperature effects on N mineralization have often been calculated using Q10 (temperature coefficient)/Arrhenius type equations (Hansen et al. 1995), but these lack biological significance. Therefore alternative measures should be used which include a maximum N mineralization rate at an optimum temperature, e.g. the Gauss type function proposed by De Neve et al. (1996):

$$k(T) = k_{opt} \cdot e^{\left(-\kappa\left(1-\frac{T}{T_{opt}}\right)^2\right)}$$

where k(T) is the mineralization rate as a function of temperature, k_{opt} the mineralization at optimum temperature T_{opt}, and κ a rate parameter reflecting the temperature sensitivity of k. Another example, biologically most realistic, is the asymmetric temperature function described by Thornley (1998) (Fig. 1):

$$k(T) = \frac{(T - T_{min})^{q(T)}.(T_{max} - T)}{\left(T_{opt} - T_{min}\right)^{q(T)}.\left(T_{max} - T_{opt}\right)}$$

where

$$q(T) = \frac{\left(T_{opt} - T_{min}\right)}{\left(T_{max} - T_{opt}\right)}$$

In first order kinetic models, it is then assumed that only the mineralization rate and not the amount of mineralizable N is influenced by temperature (De Neve et al. 1996). With this assumption the mineralization at any given temperature can be calculated.

5.2 Soil Moisture Content

Soil moisture content influences N mineralization by limiting the diffusion of substrates to the decomposer organisms (low moisture content range) or by limiting O_2 diffusion (high moisture content range). The influence of soil water content on microbial processes in soil is more important in dry (Mediterranean and (semi)arid) than in humid climates, also because of the large variability in rainfall events in comparison to humid climates (Fisher and Whitford 1995). However, in humid climates prolonged dry spells occasionally occur, and soil water content will limit process rates such as N mineralization at some periods of the year. The influence of soil water content on N mineralization has been expressed on the basis of gravimetric soil water content, water tension, % of water holding capacity (WHC), % of water filled pore space (%WFPS). Perhaps counter-intuitively, the use of water potential seems not the most appropriate measure. Skopp et al. (1990) indicated that

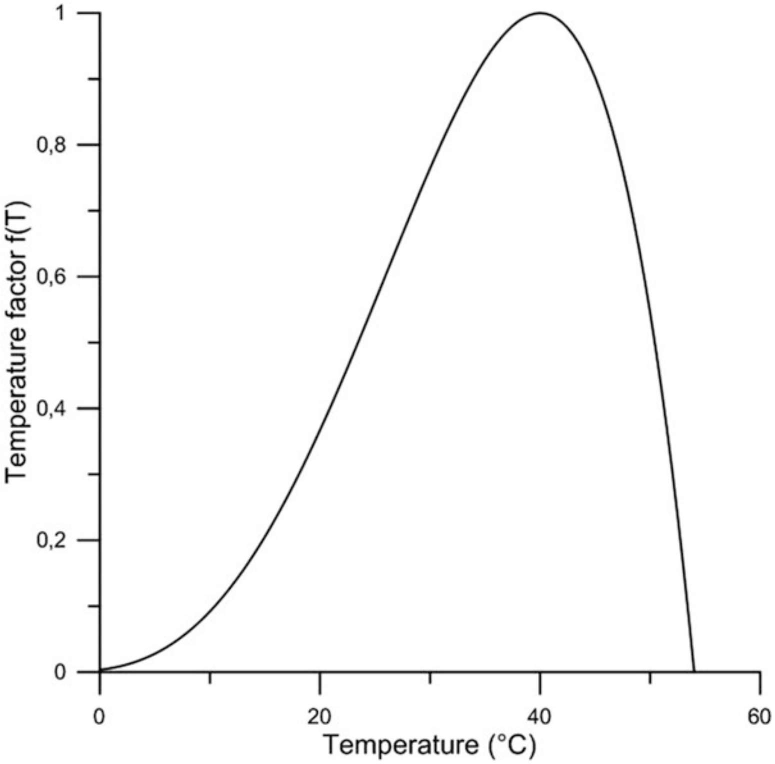

Fig. 1 Temperature correction factor according to Thornley (1998) with Tmin = −5 °C, Topt = 40 °C and Tmax = 54 °C

using soil water potential to describe soil water effects on microbial activity tends to emphasize the driest conditions (lowest water potentials). Especially in humid climates, the use of %WFPS seems to be the preferred method.

Many relationships between measures of soil moisture and N mineralization have been proposed, including linear (Stanford and Epstein 1974), parabolic (Myers et al. 1982), exponential (Singh and Singh 1994), logistic (Gonçalves and Carlyle 1994) and Gaussian (De Neve and Hofman 2002). However, to date there is no generally acceptable model for calculating the impact of soil moisture.

5.3 *Other Abiotic Factors*

Factors other than soil temperature and soil moisture, e.g. soil structure and compaction, are also important regulators of N mineralization kinetics. Degradation of soil structure leading to loss of macro porosity and compaction negatively impacts the decomposer community responsible for SOM degradation and thus affects N mineralization (De Neve and Hofman 2000). The effect of compaction on N mineralization strongly depends on soil texture (Schrama et al., 2013), with much larger negative impacts on heavy soils than on sandy soils. Despite this potentially important effect of soil structure on N mineralization, its quantification remains difficult because of the extreme spatial and temporal variability.

Strongly related to changes in soil structure is the change in N mineralization upon conversion from conventional tillage (CT) to reduced tillage (RT) or no-till (NT). Converting to RT/NT brings about complex changes in the soil structure which may result in more compacted soil, fundamental change in pore size distribution, increased protection of organic matter. In general, N mineralization is expected to decrease under RT/NT as compared to CT. However, this is not always the case E.g. in a comparison of CT and RT fields on similar soils and with similar rotations in the Belgian loess belt, D'Haene et al. (2008) found higher N mineralization rates in the RT fields, which was attributed to the higher SOC content and higher microbial biomass in RT.

6 Sources of Organic Matter

Sources of organic matter will be discussed in detail in chapter "Localized Application of Fertilizers in Vegetable Crop Production". Here we briefly touch upon the main categories of organic materials with specific reference to their N mineralization potential. The sources of organic matter can be categorized broadly as on-farm and off-farm. The on-farm types typically represent the organic materials that have traditionally been available, mainly crop residues, green manures and animal manures. In recent years there has been a massive increase in especially the off-farm types of organic matter available in agriculture and horticulture. Nowadays a variety of composts (green waste compost, municipal solid waste compost), by products from the agricultural industries (animal by-products such as blood meal, hair meal, bone meal), digestates from manure processing and from bio-energy production, etc. are available to vegetable growers. All these materials have specific properties with respect to N release, and for many of these "new" organic materials (e.g. digestates) the mineralization properties are poorly characterized.

6.1 Plant Materials

Unprocessed plant materials are on-farm organic materials including crop residues, green manures and catch crops. Vegetable crop residues are a potential major source of N for the subsequent crop. The harvesting index (ratio of harvested produce to the total biomass) is often small for vegetable crops, leaving more N in the residues than is removed with harvest (Table 2). Exceptionally high amounts of crop residues are sometimes reported, e.g. 80 ton fresh matter and 297 kg N ha^{-1} for processing cauliflower (Agneessens et al. 2014b). Proper management of vegetable crop residues and taking full account of these in fertilizer advices is

Table 2 Fresh matter and N content of vegetable crop residues compiled from various sources in Europe

Type of crop residues	Fresh matter (ton ha^{-1})	N content (kg N ha^{-1})
Brussels sprouts	50–60	140–200
White cabbage (processing)	40–50	170
Broccoli		180
Chinese cabbage		100
White cabbage (fresh market)	30–40	170
Cauliflower		130
Fennel		90
Peas		85
Beans		90
Carrots	20–30	90
Celery		110
Iceberg lettuce		85
Leek	10–20	60
Spinach		30
Lettuce	<10	35

Chaves (2006)
A comprehensive overview based on field experiments in Germany can be found in Fink et al. (1998)

crucial to avoid over-fertilization and N losses (see also Sect. 7). In a double cauliflower cropping system, the N demand of the second crop can sometimes be completely met by N mineralization from SOM and from the residues of the first crop (Rahn et al. 2001).

With the exception perhaps of tropical legumes with high polyphenol contents, N mineralization from plant residues can be predicted satisfactorily on the basis of the C:N ratio. For the specific case of vegetable crop residues, one can assume that between 60 and 80% of the N in the residues will be mineralized within the weeks following incorporation in summer or early autumn (De Neve and Hofman 1996). Obviously, this N needs to be duly taken into account when determining the fertilizer rate for the following crop, or measures need to be taken to avoid N losses when no crop follows the incorporation of the residues.

6.2 Animal Manures

Animal manures can be divided basically into liquid animal manures (slurries) and solid animal manures (farmyard manure). This subdivision is also highly relevant with respect to N mineralization and N availability. Liquid manures contain large amounts of mineral N (mainly ammoniacal, typically around 50% of the total N), and the organic N fraction releases additional N in soil by mineralization, resulting in a total available N fraction of about 70%. Solid manures are extremely variable, with less mineral N (around 20% of total N), and N availability within the growing season following application may vary greatly from 40% to less than zero (i.e. net N immobilization). This depends basically on the amount and type of bedding material added and the storage conditions and time before field application.

6.3 Off-Farm Materials

Within the concept of resource use efficiency and waste minimization, emphasis is put increasingly on recycling of organic matter. As a result, in recent years many organic waste streams from the agricultural industries are being redirected towards agriculture as a source of organic matter and nutrients. These include sludges from e.g. dairy factories, breweries, gelatin production, slaughterhouses, deepfreeze industry, paper industry, many types of municipal solid waste, etc. Some of these waste streams are transformed into much wanted and expensive organic fertilizers, e.g. animal by-products with high N concentrations (blood meal and feather/hair meal: approximately 13% N) and fast N mineralization. The problem here is that, despite the numerous studies that have been conducted (e.g. Sims and Stehouwer 2008), many organic waste streams remain poorly characterized with respect to N availability, and may lead to poor nutrient use efficiency and nutrient losses. Given that new waste streams are generated continuously, certainly more research will be needed in the future.

Special categories to be mentioned are municipal solid wastes (from non-selectively collected waste) and sewage sludge. While both these types of waste are rich in nutrients, land application is hazardous and prohibited in a number of countries because of potential high levels of contaminants.

6.4 Processed Organic Materials

All the materials mentioned above, both on- and off-farm, can be applied as such or be processed before land application, often in mixtures with other organic materials. Processing may include composting, digestion after various pretreatments (usually with generation of renewable energy) and pyrolysis. The feedstock materials for such processing are sometimes not very well characterized, but even much less is known about how the organic material resulting from the process (compost, digestate, effluent, biochar) behaves in soil. The efficient use of these processed organic materials is an important challenge for future research, notably with respect to predicting N availability.

7 Synchronization of N Mineralization with Crop N Demand

Ideally, N mineralization in soil should follow the N demand by the crop in order to maximize N use efficiency. Whether or not N mineralization follows N demand is mainly determined by the abiotic factors of soil temperature and moisture content. Lack of synchrony may occur e.g. in temperate humid climates in early spring, when soil temperatures are still low and hence N mineralization is limited, and in autumn, when crop N demand is low or zero while N mineralization rates may still be high due to high soil temperatures (Fig. 2).

The lack of synchrony in spring can easily be remediated by additional fertilization, but excessive N mineralization in autumn will potentially lead to high N losses. This is especially true with incorporation of N-rich vegetable crop residues in autumn. For instance, when crop residues of vegetables were incorporated in autumn (end of September) in a soil with initially low mineral N content (15 kg mineral N ha^{-1} to 120 cm depth), the N losses by nitrate leaching were very high, giving average NO_3^--N concentrations of 29 mg N L^{-1} in the drainage water for e.g. cauliflower leaves (De Neve and Hofman 1998) (Table 3 and Fig. 3).

Research has focused on manipulating the N mineralization from such crop residues by addition of immobilizing materials, and on stimulating the remineralization of immobilized N when crop N demand resumes. Various materials, including paper waste (Rahn et al. 2003; Vinten et al. 1998), straw, sawdust, immature green waste compost (Chaves et al. 2005b), tannic acid (De Neve et al. 2004) were found to be effective in reducing mineral N concentrations in soil upon crop residue incorporation under controlled conditions in the laboratory. However, when some of these materials were applied in the field at the time of incorporation of vegetable crop residues, they gave either no or only very limited reductions in

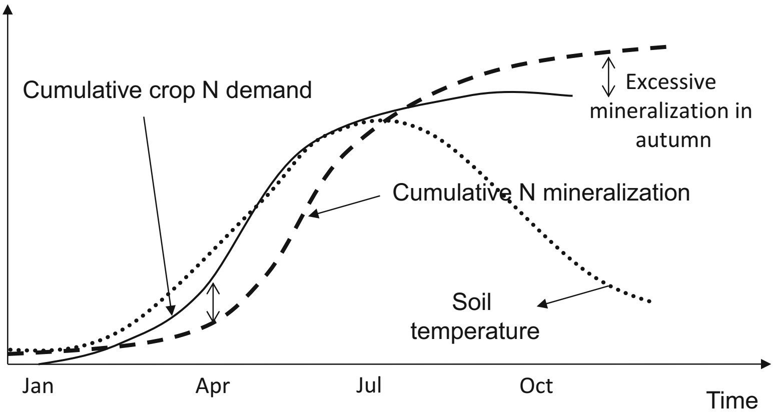

Fig. 2 (Lack of) synchronization between N mineralization in soil and the crop N demand. Excessive N mineralization in autumn is mainly the result of incorporation of high N crop residues

Table 3 Amounts of N mineralized, leached below 120 cm (model calculations) and left in the soil profile 4 months after incorporation of vegetable crop residues into a loamy sand soil

	Residue N released		N leached below 120 cm (kg ha^{-1})	N_{min} in soil 0–120 cm (kg ha^{-1})	N_{min} 60–120 cm (kg ha^{-1})
	% of total residue N	kg N ha^{-1}			
Control soil	n.a.[a]	n.a.[a]	26	43	26
Cauliflower leaves	60	88	66	95	75
Iceberg lettuce leaves	73	54	53	76	50
Red cabbage leaves	52	45	46	53	33
Broccoli stems	45	15	34	50	33
White cabbage stems	19	12	32	47	26

[a] Not applicable

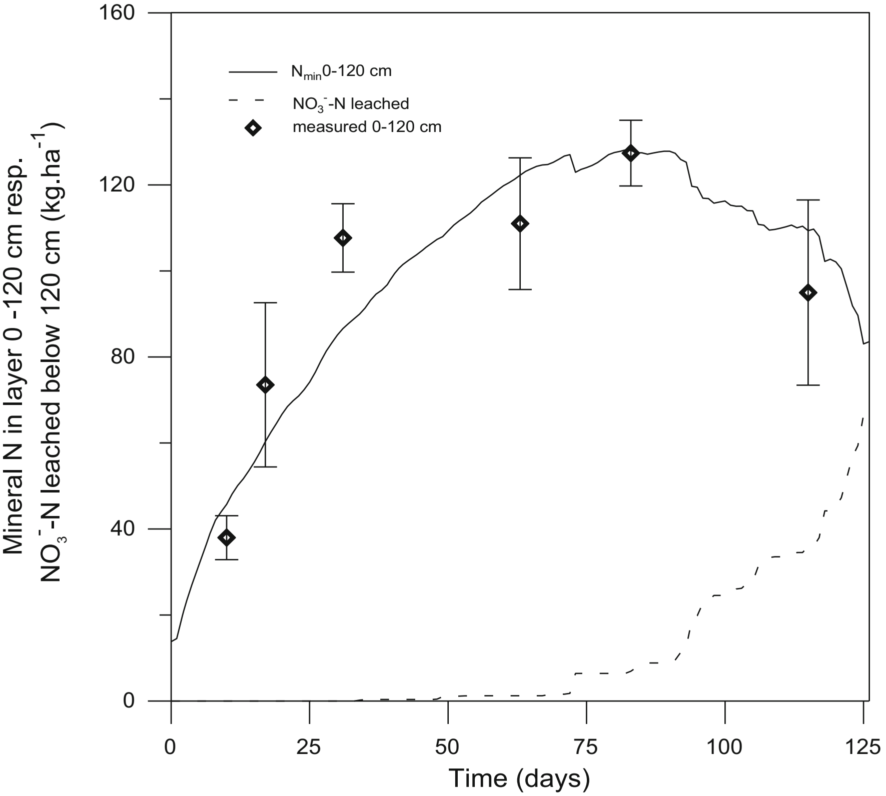

Fig. 3 Soil mineral N (0–120 cm depth) (*diamonds*: measured values ± st dev; *solid line*: simulations) and cumulative NO_3 leaching (kg N ha^{-1}) (*dashed line*) following incorporation of cauliflower leaves in autumn in a loamy sand soil

soil mineral N concentrations (Chaves et al. 2007). This was attributed to a small N immobilization potential because of decreasing temperatures in late autumn.

When N from organic materials has been immobilized as depicted above, remineralization of this immobilized N in the following spring should coincide with the onset of crop N demand. Various materials (vinasses, molasses, dairy sludge and malting sludge) have been tested for their potential to stimulate (re) mineralization of immobilized N, but with variable and limited success. Rahn et al. (2003) and De Neve et al. (2004) found a significant remineralization following the addition of molasses to soils previously amended with crop residues or crop residues plus green waste compost in laboratory incubations. However, Chaves et al. (2005b) either did not observe this effect, or the effect was only very short-lived. A recent in-depth literature review on management options of vegetable crop residues can be found in Agneessens et al. (2014a).

8 Conclusion

N mineralization is a key process governing N availability to crops, especially in intensive field vegetable production. Predicting N mineralization, in particular from native SOM remains a challenge, and there is no generally accepted method for this. Synchronization of N mineralization with crop N uptake is crucial to maximize N use efficiency and reduce N losses, and more research will be needed to improve this. Another challenge for N management in horticulture now and in the future will be the characterization of new organic materials derived from industrial by-products and municipal wastes after various processing steps with respect to their N release in soils under varying conditions.

Glossary

AOM Added organic materials
C Carbon
C:N Carbon-to-nitrogen
CT Conventional tillage
EOM Exogenous organic materials
MIT Mineralization immobilization turnover
N Nitrogen
Q10 Temperature coefficient
SOM Soil organic matter
$N_{min}(t)$ Nitrogen mineralized as a function of time
NT No-tillage
RT Reduced tillage
WFPS Water filled pore space
WHC Water holding capacity

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Fertilizers: Criteria of Choice for Vegetable Crops

Paolo Sambo and Carlo Nicoletto

Abstract The use of fertilizers in vegetable production is an essential element to achieve good production and high quality products. However, there are many alternatives in the choice of fertilizers not only in relation to the different vegetable crops, but also in relation to the new challenges that are posed by the increasing world population and environmental issues. In recent decades there has been a marked change in many countries linked to the increasing use of natural fertilizers and soil improvers in place of the classic mineral fertilizers. To better understand the effect that individual fertilizers or soil improvers may determine is necessary to know the main chemical and physical parameters of soil. Fertilizers often influence these parameters generally behaving in a positive way, but also negative if improperly managed.

Currently the range of fertilizers usable in horticulture is extremely wide and diversified. This chapter includes the main mineral fertilizers related to the macronutrients supply with regard to the various effects that can result at both production and quality level. Attention was also dedicated to traditional and innovative organic materials that are used with increasing interest such as compost, sewage sludge, anaerobic digestion residues and spent mushrooms compost. Matrices used in order to meet the nutritional needs of crops together with the organic matter supply and reducing the environmental impact.

Keywords Mineral nutrition • Macro-nutrients • Nitrogen • Phosphorous • Potassium • Compost • Sewage sludge • Anaerobic digestion residues • Spent mushrooms compost • Organic matrices

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1 Introduction

1.1 Fertility Management

Green plants constitute the first link in all the biological chains in the biosphere, having the capacity to transform solar energy into chemical energy, utilizable by all living beings. Indeed, thanks to chlorophyll, water, air and solar energy, plants are the only living things that can form organic matter from inorganic elements, which may thus be assimilated by animals and humans. In order to carry out this fundamental function vascular plants need an environment that can guarantee the availability of light, water and the chemical elements indispensable to organic synthesis. The soil is an essential constituent of this environment, as it provides plants with support, plus water and mineral nutrition. It also permits the conservation and transformation of plant and animal remains, guaranteeing the maintenance of nutrients, and above all energy, within the ecosystem.

These functions are carried out by the soil as it is a polyphase system, i.e. characterized by the presence of solid, liquid and gas phases, in which the development of an intense and complex biological activity takes place. The importance of this activity is obvious, given that more than 70% of the energy fixed by plants is consumed by soil microorganisms and that the living things in the soil easily reach 2000 kg ha^{-1} (Perelli et al. 2009).

1.2 Ecology of Fertilization

All microbes, animals and humans draw their primary source of energy from plants. Indeed, only green plants do not consume organic matter but create it using solar energy and a limited number of inorganic elements. Therefore, there is a cycle of organic matter among plants, soil and users, in parallel to which there are cycles of energy and mineral elements. In nature, these latter derive mainly from the mineral matrix of the soil and, in a small part, from the waters, atmospheric depositions and biological fixation, which only involves nitrogen and, minimally, sulphur. Once assimilated by the plants, minerals pass into the organisms of animals, fungi and bacteria that utilize them as food and return them to the soil with their feces and remains. Importantly, plants can only uptake the nutritional elements if they are in certain chemical forms, defined assimilable, i.e., according to the definition of the Soil Science Society of America, “in chemical forms accessible to the roots of the plants or in compounds easily converted into these forms during the growing season of the plants”.

In nature the organic matter in the soil is therefore mineralized, i.e. decomposed into organic elements that may be absorbed by the vascular plants. The inevitable losses of materials from one ecosystem to another are compensated by the solubilisation of the minerals in the soil, through the combined action of air, water and living things (microorganisms and vascular plants). However, this solubilisation is always rather slow and, in some cases, the opposite process may occur, i.e. the insolubilization of nutritional elements and, consequently, the natural ecosystems are only able to tolerate small losses. Serious disturbance factors, such as a flood or a plague of locusts, which remove materials and energy from the ecosystem and transport them elsewhere, require a very long time for the soil to recover the capacity to support plant life, a capacity that is commonly defined as fertility.

Agriculture interrupts the natural cycles, subtracting large quantities of plants (and the elements they contain) from the soils that produced them. Agriculture, by definition, involves the removal of organic matter to the detriment of the soil. Consequently, in any type of agriculture the soil fertility tends inevitably to diminish if steps are not taken to replenish it.

1.3 Present and Future

For the ecological reasons given above, it is not possible abandon fertilization without seriously compromising the yields and/or soils fertility. The loss of the latter would constitute an enormous ecological damage, as it would destroy the "core of environmental equilibria" and eliminate not only the bases of agricultural production, but the very survival of life on our planet. Thanks to its peculiar characteristics, the soil is the only environmental sector that, except in very few cases, does not need to be decontaminated: soil is self-cleaning. However, this capacity does not authorize us to automatically consider agricultural soil as the natural destination for all the wastes from urban and industrial activities or to be exploited at will. The use of highly polluting materials and excessive exploitation of the soil can lead to its death, i.e. to the loss of the capacity to conserve energy and materials and support plant life. If it is necessary to avoid the secondary effects of potentially damaging agricultural practices from one side, on the other it is indispensable to prevent any damage to the soil by human agricultural or extra agricultural activities.

2 Mineral Fertilizers

Mineral fertilizers are certainly the most widely used system in recent decades to supply different nutrients useful to the plant growth and crop production. The solutions given by the market for these products are extremely wide and heterogeneous with commercial formulations more or less simple and specific for different vegetables. In this context do not exist then the conditions to report the multiple options in detail, for this reason, reference will be made to the simple fertilizers most used by growers.

2.1 Simple Nitrogen Fertilizers

2.1.1 Calcium Nitrate

Calcium nitrate, which may contain traces of ammonium nitrate, must have a minimum nitrogen content of 15%, of which not more than 1.5% is ammonia nitrogen. The nitrogen percentage in the pure salt varies between 11.86% (for hydrate salt) and 17.07% (for anhydrous), while the commercial product generally has 15–15.5%. The fertilizer is in irregular greyish or almost white granules. It is highly soluble in water, 121 g/100 mL at 20 °C. The aqueous pH of the pure salt is practically neutral and the commercial product containing excess calcium has an alkaline pH.

Calcium nitrate is the typical nitrogen fertilizer with rapid effect. Due to its solubility and the consequent leachability of nitrogen (the nitric ion is not retained by the absorbent capacity of the soil), to avoid losses, it is advisable to split its distributions over the course of the crop season.

It is normally distributed at pre-emergence and the fertilizing action is particularly useful on clay soils. Being a low-content fertilizer with a generally high cost, its use is justified for high-value crops, such as horticultural crops, in which an immediate effect is desired. Unlike sodium nitrate, prolonged use of this fertilizer does not lead to a worsening of the structural properties of the soils.

2.1.2 Ammonium Nitrate

Ammonium nitrate must have a minimum nitrogen content of 20%, half nitric and half ammonia. The nitrogen percentage in the pure salt is 35%, while in the commercial product it varies between 26 and 33.5%. The product containing more than 28% is subject to special composition, labelling, transport and storage regulations due to its hazardous nature, even if not for human health and the environment. Ammonium nitrate is in fact an "explosive" or more correctly a strong oxidant that may produce very hazardous exothermic reactions when it comes into contact with some materials, especially where there are sources of heat. Ammonium nitrate is highly soluble in water: 214.2 g 100 mL^{-1} at 25 °C. The dissolving takes place with a strong absorption of heat: adding six parts of salt to ten of water at 13 °C, the temperature lowers to around −14 °C. It is an extremely hygroscopic compound and for this reason has a strong tendency to solidify during storage. The pH of the aqueous solution is acid, as a consequence of the hydrolysis of the salt coming from strong acid and weak alkali: the pH of the solution at 1% is 5.4.

The two nitrogen forms present in ammonium nitrate produce a fertilizer that combines a prompt crop response (nitric fraction) to a quite prolonged effect (ammonia fraction) so it can be used on all crop types. In calcareous soils, to avoid ammonia losses, the fertilizer must always be lightly buried.

2.1.3 Urea

The nitrogen content in urea must not be lower than 44%, with no more than 1.2% of biuret, a by-product of the synthesis of urea that, at high doses, can be toxic for plants. The nitrogen content in the pure product is 46.65%, while the commercial product generally contains 46%. It is highly soluble in water: 66.7 g 100 mL^{-1} at 0 °C and 145 g at 70 °C.

The high solubility of urea favors its dispersal in the soil. Once introduced, it is rapidly transformed into ammonia in times that vary from a few hours to 3–4 days depending on the temperature and organic matter content in the soil. It has the highest nitrogen content and lowest cost per fertilizer unit of all the solid ammonia fertilizers. It can consequently be considered the best nitrogen fertilizer except for very specific needs. In fact, the use of urea is unadvisable when low nitrogen doses are to be distributed, less than 70–80 kg ha^{-1}, especially with centrifugal fertilizer spreaders that do not guarantee distribution uniformity with small quantities. In conditions of high temperature, low moisture content and abundant urease, there may be gas losses of ammonia, especially in calcareous soils following distributions without burial. The use of urease inhibitors may help to limit this.

2.1.4 Nitrogen Fertilizers and Vegetables

Nitrogen is one of the most important nutrient for plants that heavily affects growth and development of plant. For this reason is important to optimize its management during the cultivation of many vegetable species both from an agronomic and environmental point of view. The nitrogen form could influence differently the yield and the nutritional quality of vegetables. In spinach, for example, fertilizers containing N under forms not readily available to the crop increased nitrate and oxalate accumulations less than fast N-release fertilizers, but their effect on yield was limited (Stagnari et al. 2007). Highest yield with nitrate and oxalate contents lower than the limit imposed to avoid health problems, were achieved with $\mathrm{Ca(NO_3)_2}$ at rates of 130 kg N ha^{-1} and at 150 kg N ha^{-1} with $\mathrm{NH_4NO_3}$. Also the accumulation of important macronutrients for human diet is influenced by nitrogen fertilization. The same authors found an increase of Ca, K, and P with the $\mathrm{Ca(NO_3)_2}$ application. The glucose, fructose, sucrose as well Mg accumulations are not alterable in spinach with nitrogen fertilization. As reported before, nitrates content is a really important aspect strictly controlled by big retailers and by European regulation (UE N. 1258/2011). For this reason the fertilization management should consider this aspect and should limit nitrates accumulation especially for leafy vegetables (Santamaria 2006). Several studies were carried out on this topic reporting different solutions. Different fertilization strategies for lowering nitrate content were studied for chicory and rocket salad (Santamaria et al. 1998). For other leafy vegetables such as red chicory the increase of N application did not affect the amount of nitrates in the plant (Filippini et al. 2011). Moreover for other species such as *Brassica campestris*, *Brassica chinensis* and *Spinacia oleracea*, Chen et al. (2004) studied the effect of nitrate supply on plant growth. Another experiment (Wang and Li 2004) showed that the application of ammonium chloride, ammonium nitrate, sodium nitrate, and urea significantly increased the yields and nitrate concentrations of Peking cabbage and spinach. Although N forms had no significantly different effect on yields, input of nitrate N fertilizer increased nitrate accumulation in vegetables much more than did ammonium N. Vegetable yields were not increased continuously with N rate, and an excess input of N fertilizer more or less reduced plant growth, leading to yield decline for the earlier harvests. This trend was also true for nitrate concentrations in some vegetables and at some sampling times. However, as a whole, nitrate concentrations in vegetables were positively correlated with N rates. As a result, addition of N fertilizer to soil was the major cause for vegetables increasing their nitrate contents (Wang and Li 2004). In tomato (Heeb et al. 2005a) no significant differences in shoot biomass and yields of red tomatoes were observed between NO_3^- or NH_4^+ fed plants. The NH_4^+-N-dominated treatments (which also had high Cl^- concentrations) showed increasing incidence of blossom-end-rot (BER)-infected fruits. In the organic-N treatments, shoot-biomass production and yields were lower than in the inorganic-N treatments, but fruit quality was good with few BER-infected fruits. Also fruit taste can be affected by the nitrogen form (Heeb et al. 2005b). Significantly higher scores were achieved for sweetness, acidity, flavor and acceptance for the tomatoes grown with the organic or the ammonium-dominated treatments compared with the tomatoes grown with the nitrate dominated nutrient solution. It is suggested that ammonium is an equivalent nitrogen source for tomato plants compared with nitrate and that, when tomato plants are supplied with reduced nitrogen forms such as ammonium or organic nitrogen, an improved tomato fruit taste can be observed.

Other authors demonstrated that vegetables quality is influenced by nitrogen form (Mozafar 1993). Nitrogen fertilizers, especially at high rates, seem to decrease the concentration of vitamin C in many different fruits and vegetables, among them potatoes, tomatoes and citrus fruits, the major sources of this vitamin in human nutrition in many societies. Nitrogen fertilizers are also shown to increase the concentrations of carotenes and vitamin B_1 in plants. Since excess use of nitrogen fertilizers increases the concentration of NO_3 in plant foods and simultaneously decreases that of ascorbic acid, a known inhibitor for the formation of carcinogenic N-nitrous compounds from nitrite, it appears that the use of these fertilizers may have a double negative effect on the quality of food plants. Vitamin C and several carotenoids have antioxidant properties and reportedly reduce the risk of cardiovascular diseases and some forms of cancer.

2.2 *Simple Phosphate Fertilizers*

Human intervention in the global phosphorus cycle has mobilized nearly half a billion tonnes of the element from phosphate rock into the hydrosphere over the past half century. The resultant water pollution concerns have been the main driver for sustainable phosphorus use (including phosphorus recovery). However, the emerging global challenge of phosphorus scarcity with serious implications for future food security, means phosphorus will also need to be recovered for productive reuse as a fertilizer in food production to replace increasingly scarce and more expensive phosphate rock (Cordell et al. 2011).

2.2.1 Solubility of Phosphorus

In phosphate fertilizers the solubility of the phosphorus is of particular importance. In fact, the availability for the plants is conditioned by the solubilization of the phosphate compounds in the soil water. Consequently, the phosphorites can only provide nutriment to plants if the phosphorus is made soluble with an industrial process. In field conditions solubilization only occurs when there is sub acid soils (pH 5.5–6.5), but it is anyway very slow. Much more frequently, there is the opposite reaction, i.e. the insolubilization of the soluble forms of phosphorus.

2.2.2 Simple Superphosphate

Simple superphosphate must be composed essentially of monocalcium phosphate and calcium sulphate (gypsum) and have a minimum content of 16% P_2O_5 soluble in neutral ammonium citrate, of which at least 93% soluble in water. Simple superphosphate has variable solubility according to the principal phosphate constituents. The solubility in neutral ammonium citrate is total for mono and dicalcium phosphates, practically nil for tricalcium. Superperphosphate is not hygroscopic when it has been correctly prepared and well matured. The cost of the fertilizer units is quite reasonable and the market could potentially absorb more, but the availability is limited. This fertilizer is also of great interest for its high solubility and acidifying capacity, but especially for the supply of considerable amounts of sulphur to the soil and therefore to the crops, as well as trace microelements. It is therefore of particular interest for crops that need sulphur (onion, garlic, rape, cabbages, etc.).

2.2.3 Phosphoric Acid

The only liquid phosphate fertilizer allowed by law is phosphoric acid, which must contain 28% of phosphorus pentoxide from phosphoric acid (H_3PO_4). Phosphoric acid is an almost colourless liquid, with a density of 1573 (pure product) and pH of 2 in a water solution at 1%. It is completely soluble in water. Phosphoric acid is corrosive and so must be transported, stored and handled with care, obeying the laws on hazardous products.

2.2.4 Triple Superphosphate

Triple superphosphate with a minimum content of 38% of P_2O_5 soluble in neutral ammonium citrate, is widely used thanks also to the cost per fertilizer unit, generally less than that of phosphorus from other sources. It is a product obtained by reaction of the phosphorites with rather concentrated solutions (50–55% of P_2O_5) of phosphoric acid, composed almost exclusively of monocalcium phosphate with minimal contents of sulphur and microelements. Also triple superphosphate must have at least 85 or 90% of the content soluble in water.

2.2.5 Phosphate Fertilizers and Vegetables

Food and vegetables production requires application of fertilizers containing phosphorus, nitrogen and potassium on agricultural fields in order to sustain crop yields. Phosphorus application with different way and forms it was widely studied in the last years. It is known that the high phosphorous fertilizers content use in agriculture is extremely important (Cordell et al. 2009) and also for this nutrient there are some experiments both on leafy and fruit vegetables. In the first case Wang and Li (2004) showed that the effects of P fertilization on vegetable growth and nitrate accumulation were species and sampling-time dependent. By addition of P fertilizer, yields of green cabbage and rape were increased, while those of spinach and cabbage had no significant changes. Peck et al. (1980) studied how pea (*Pisum sativum* L.), snap bean [*Phaseolus vulgaris* (L.) *var. humilis*], cabbage (*Brassica oleracea* var. *capitata*), and table beet (*Beta vulgaris* L.) were influenced by concentrated superphosphate fertilization. Concentrated superphosphate increased phytic acid concentrations in immature and mature pea seeds and in mature snap bean seeds. Oxalic acid concentrations in table beet plants decreased with increasing rates of CSP fertilizer. More recently Shaheen et al. (2007) showed for onions that the addition of phosphorus as chemical source increased the plant growth if compared with the natural phosphate. With increasing the rates of P_2O_5 up to 114 units per ha, the values of plant growth parameters recorded their highest peaks. The obtained data showed that the application of P fertilizer in the form of super-phosphate (chemical) gained the heaviest tonnage of bulbs yield, and the highest values of bulb dimension as well as average bulb weight. The highest tonnage of bulbs yield (25.52 and 37.42 tonnes ha^{-1}) respectively for 1 and 2 season were associated with that of plants which supplied the highest P rate i.e. 114 units of P_2O_5 ha^{-1}. Total protein as well as N and P content of onion bulb tissues recorded their peaks with that plants which received phosphorus in the form of superphosphate.

Phosphorous application does not always affect crop quality as reported for tomato by Oke et al. (2005). In general, soil and foliar phosphorus supplementation did not provide a statistically significant increase in yield. Tomato juice was evaluated for various quality characteristics including pH, titratable acidity, precipitate weight ratio, total solids, serum viscosity, Brookfield viscosity, color, lycopene levels, vitamin C, and flavor volatiles. Changes observed in several quality parameters were marginal, statistically insignificant and influenced by the season. Therefore, it appears that phosphorus supplementation may not significantly affect the processing quality parameters in tomato fruits.

2.3 Simple Potassium Fertilizers

2.3.1 Potassium Chloride

Potassium chloride must have a minimum content of 37% of K_2O, but the product on the market generally has 60%. The fertilizer is in whitish-grey crystals or, if ferrous oxide is present, red. The pH is practically neutral and the solubility is 34.4 g 100 mL^{-1}.

Potassium chloride is the most economical source of potassium and most widely used in the world. Its use is limited only by the presence of chlorine, which may cause damage to sensitive crops (tobacco, fruits, grapevines and many horticultural species), even if the problem may, in many cases, be overcome with distribution some months prior to sowing, transplanting or, for perennial crops, the start of root activity. Chlorine is in fact highly soluble and is not kept by the soil, but is easily removed with the percolation of excess rainwater.

2.3.2 Potassium Sulphate

Potassium sulphate must have a minimum content of 47% of K_2O and a maximum chlorine content of 3%. The pure salt is in white crystals, while the fertilizer is a white, grey or yellowish crystalline powder. The sulphur content, expressed as anhydride sulphur trioxide (SO_3) in the pure salt is 45.9%. Sulphate is around three times less soluble than potassium chloride: 12 g 100 mL^{-1} of water at 25 °C. The hygroscopicity is minimal in the pure salt, but may increase due to the salts that accompany the commercial product. The pH in aqueous solution is neutral or acid, depending on the production method.

Potassium sulphate is the potassium fertilizer of greatest value due to the presence of sulphur, almost complete absence of chlorine and low salinity. The main obstacle to its use is the quite high cost per fertilizer unit. Potassium sulphate, although it is an important source of potassium for crops, is less used than chloride. Potassium sulphate is the best source of potassium for crops of tobacco, potatoes, lemons and grapevines. Due to the low salinity index its use is preferable on crops that need high potassium fertilization and where the absence of chlorine is imperative, as well as in soils where salinity is a problem. Sulphate is also appreciated for the availability of sulphur. In fact, 0.4 kg of sulphur is supplied to the soil for every kg of potassium sulphate distributed.

2.3.3 Potassium Fertilizers and Vegetables

About potassium fertilizers use and vegetables response some experiments were conducted. Although the responsiveness of many of the crops was similar there were marked differences and the optimum levels of K (defined as the level at which a further 10 kg ha^{-1} increased yield by 1%) varied from 0 to 360 kg ha^{-1}, depending on the crop (Greenwood et al. 1980). Responsiveness was largely independent of the plant family to which the crop belonged, but was related to the mean plant weight at harvest; the larger the weight the less responsive the crop. No general relation existed between responsiveness and duration of growth. The K percentage in leaves dry matter (including stems) of crops receiving the optimum levels of K fertilizer was mainly determined by the family. It was generally between 0.9 and 1.1 for the *Amaryllidaceae*, between 1.1 and 1.2 for the *Leguminosae* and between 1.9 and 2.5% for the *Cruciferae*. The difference between the K percentage in the dry matter with the optimum level of K fertilizer and that with no fertilizer was proportional to responsiveness. K percentage at harvest was a good indicator of the extent to which crop growth was restricted by lack of potassium. At harvest crops receiving the optimum levels of K fertilizer contained between 29 and 220 kg ha^{-1} of K, but the uptake increased asymptotically to a maximum as K applications raised to higher levels. Maximum uptake for nearly all crops was almost double the uptake with the optimum fertilizer application. Percentage recovery of 100 kg ha^{-1} of added K fertilizer varied between 8 and 70%, roughly in proportion to the total crop dry weight, which varied between 1 and 15 t ha^{-1}. Different K fertilizer effects on crop quality were also measured and over the practical range of applications the effects were generally small. Other data about *Leguminosae* family and potassium application were obtained by Zhao-Hui et al. (2008). Their experiment showed that the application of K fertilizer increased the yield and the application of K fertilizer was often associated with increased sugar concentrations in kidney beans. The same authors demonstrated that vitamin C content in kidney beans was not affected by K fertilization, whereas vitamin C was increased in rape with K application as reported by Yang et al. (1999).

2.4 Microelements-Based Fertilizers

Numerous microelements are indispensable for plant life. The following methods can avoid the appearance of deficiencies in these elements:

- use of organic or mineral fertilizers that naturally contain them;
- enrichment of fertilizers with microelements;
- direct administration of microelements with appropriate fertilizers.

The first method is the most used in traditional agriculture, but the lack of organic fertilizers availability and the greater "purity" of modern fertilizers make difficult the applicability. The addition of microelements to mineral and organo-mineral fertilizers can be a good solution as long as this does not involve an excessive increase in the selling price. The use of specific fertilizers is a generally simpler way to make up for specific deficiencies. Microelements-based fertilizers may in fact be obtained from many chemical compounds present in nature or obtained industrially. Both inorganic salts (sulphates) and organic compounds are usually used, generally defined as chelated.

Some of the most widely-used microelements-based fertilizers are summarized below.

Different fertilizers contain boron that, being an anion, cannot be in chelate form; there are organic compounds with the element as boron ethanolamine. Boric acid, obtained by the action of an acid on a borate is not often used alone as a fertilizer, but is in many mixtures. Sodium borate, containing borax, sodium pentaborate or tetraborate at different hydration levels, is the most widely-used fertilizer due to its solubility and low cost. In light soils this fertilizer may rapidly be leached. Calcium borate is less soluble and the minimum content is determined as total boron (and not soluble). Boron ethanolamine, obtained by the reaction of boric acid with ethanolamine, is the only boron-based fertilizer linked to an organic compound. The product is liquid at ambient temperature. Lastly, there are liquid fertilizers such as borate fertilizer in solution and borate fertilizer in suspension.

Molybdenum is also an anion and therefore, like boron, cannot be chelated. There are four molybdenum-based inorganic fertilizers: sodium molybdate, ammonium molybdate, molybdenum-based fertilizer and molybdenum-based fertilizer solution.

For the different metallic, or cationic, microelements (cobalt, copper, iron, manganese and zinc) analogous categories of fertilizers exist. The simplest products are salts obtained chemically that contain a salt of the element as essential component (cobalt salt, copper salt, iron salt, manganese salt and zinc salt).

The microelements that can be chelated include the metallic chelates, represented by organo-mineral compounds in which the metallic cation is surrounded by a chelating agent (binder) forming a ring. The chelates are used as fertilizers to prevent soil fixation as hydroxides or insoluble salts of the metals essential for the plants, or to facilitate absorption through the leaves. An ideal chelate on the one hand is stable enough to not react in the soil and, on the other, should break down easily in the plant that has absorbed it as an intact molecule. Indeed, plants can assimilate the entire molecule of the chelates, then utilizing the metal. When used as leaf fertilizer or in fertirrigation, a secondary advantage, but not insignificant, is that chelates are less corrosive than salts. Plants in nutrient solution grow in a similar way independently of the isomer utilized, even if more iron is usually absorbed from the ortho-ortho than from the ortho-para isomer. On the contrary, in calcareous soil, crops grow better showing less chlorosis with the ortho-ortho, even if in some cases analogous results are obtained with a 50% mixture of the two isomers. In general, the ortho-para has less capacity to maintain the iron available in the soil solution. Actually, in both soil and nutrient solution, the ortho-para isomer behaves in the same way as the more economical iron chelated with EDTA and it has been confirmed that the results obtained in nutrient solution cannot be extrapolated to field situations. In conclusion, it has been ascertained that the ortho-ortho isomer of EDDHA has a greater capacity to transport iron to the plants than the ortho-para isomer. The difference is greatly accentuated when the plants are cultivated in calcareous soil, where the ortho-para isomer is not efficacious. This means that the agronomic value of iron chelated with EDHHA in a calcareous soil depends almost exclusively on the content in the ortho-ortho isomer.

In order to choose the best product for the local conditions it is indispensable to know the stability of the chelate, especially according to the pH. Too often chelates are suggested for use on alkaline soils that are unstable at those pH values. The stability of the different pairs of chelates-microelement also depends on other factors and, in particular, the presence of other metals in the fertilizer or soil, but the following general indications can be given:

- cobalt: in neutral or alkaline soils DTPA provides the most stable chelates, while HEDTA is best in soils with pH lower than 7; EDTA gives good results in neutral soils.
- copper: in neutral or alkaline soils the best stability is with DTPA, while EDDHA is preferable in acid soils and HEDTA can be used in all conditions of pH.
- iron: EDDHA is stable at all levels of pH, but DTPA and HEDTA have better stability in neutral or alkaline soils and EDTA in acid soils.
- manganese: DTPA, EDTA and HEDTA have good stability, but only in soils with sub-acid to alkaline pH, chelates are lacking that give satisfactory results in acid soils.
- zinc: in calcareous soils the best stability is with DTPA, followed by HEDTA and EDTA; HEDTA is instead the best chelate in acid soils where EDTA is also efficacious.

3 Organic Fertilizers

Organic products can only be defined as a fertilizer if they contain the principal nutritional elements (particularly nitrogen and phosphorus), disregarding the other functions of organic matter.

3.1 Fertilizers from By-Products

All types of processing of natural organic materials produce a series of by-products that can be reutilized as fertilizers. Many of these have high organic matter content, therefore their nutritional contribution is not particularly high, but they can be used as optimal soil amendants, usually after a composting process. To be used as fertilizers, by-products must have the following characteristics:

- good content of nutrients effectively utilizable by plants;
- have physical characteristics that guarantee usability;
- no hazardous for humans, animals and the environment;
- low cost;
- no further onerous processing;
- available in cultivation areas, constantly and in high amounts;
- no economically more advantageous utilizations;
- classifiable as fertilizers in accordance with the laws in force.

The first requirement for a by-product to be considered as a fertilizer is that it contains nutrients in a form that is directly or indirectly available for plants. Materials with a concentration of macroelements lower than 2–3% are not usually classifiable as fertilizers, but only as amendants and, often, only after composting and to be used just in the area around the place of production. Indeed, only a significant nutrient content can justify the cost of transport from the place of production to the field where the material will be used. Industrial organic by-products usually contain mainly nitrogen and, in some cases, also phosphorus and potassium. The materials that contain the highest nutrient concentrations and are therefore the most interesting by-products for the production of fertilizers are animal wastes.

A high nutrient content is not enough to transform a material into a good fertilizer. It also has to have physical characteristics that allow ease of distribution on the field. Materials should be liquid or in suspension, or with very small dimensions or pelleted.

Being by-products and therefore potentially “wastes”, it has to be clear that they are safe for man, animals and the environment.

The cost is certainly the key parameter for deciding if a by-product can be used as fertilizer. It must be as low as possible to make the end product competitive with other fertilizers. The organic matter and organic nitrogen content are considered as an added value. Indeed, the slow release and very limited leaching of this nitrogen form can be considered a strong point on the market. However, the relatively low content of nutrients involves a general increase in the production and marketing costs. The cost for purchasing a by-product is instead very often “negative”: in fact almost all the materials available can be classified as “by-products” and not “wastes” only if they are used to produce fertilizers. There are two possible cases:

1. materials obtained directly from the producer: the only alternative is almost always the treatment as wastes with the relative high costs;
2. materials produced by a third party (animal wastes) and/or that need their characteristics improved (animal hides): the producer of the “waste” must pay for the work to be done and this payment must totally or partially cover the cost of the treatment.

3.2 Advantages and Limitations

There is a basic difference between fertilizers and organic amendants: the former supply nutrients, in particular nitrogen and phosphorus, and therefore do little to create and maintain organic matter in the soil. These are instead the typical functions of amendants. When it is stated that fertilizers have a "fertilizing capacity 5 (or 10 or 20) times that of manure" this only means that they supply nutrients in doses 5 (or 10 or 20) times higher. The supply of energy, i.e. of organic matter that can form structural humus, is instead minimal. For example: 100 kg of mature cattle manure contains on average 75 kg of water, 20 kg of organic matter and 0.5 kg of nitrogen, as well as other elements, while 100 kg of torrefied leather may contain 70 kg of organic matter and 10 kg of nitrogen. Consequently, 2000 kg of manure are necessary to supply 10 kg of nitrogen and only 100 kg of torrefied leather that, under this aspect, is worth 20 times manure. However, given that 20 kg of urea is sufficient to supply the same amount of nitrogen, urea would therefore be worth 100 times the manure. Instead, if the amounts of organic matter supplied with these fertilizers are considered, for urea they are zero, for torrefied leather around 70 kg, while manure reaches 400 kg and is thus worth six times the leather and much more than the urea. Similar considerations can be made for the majority of organic or organo-mineral fertilizers. Obviously, this gradual release of nutrients makes the use of organic and organo-mineral fertilizers inadvisable when a rapid response of the crop is required and where there may be negative effects from the release of elements, in particular nitrogen, at certain crop stages. This is the case for the winter cereals, many varieties of tobacco and in tree nurseries, in which a late availability of nitrogen can delay ripening and/or compromise the quality of the product. However, the main limitation to the use of organic and organo-mineral fertilizers is economic: the cost of the nutrients deriving from these fertilizers is always higher than from mineral fertilizers and is not always justified by the advantages of lower losses that, also because of the heterogeneity of the organic products, are anyway difficult to evaluate.

3.3 New Resources

3.3.1 Compost

The composting process can be defined as the production of fertilizers from organic wastes that are biologically decomposed. The composting process is split into an active phase, also called bio-oxidation, characterized by processes of breaking down the organic components and a maturation phase, characterized by processes of transformation of the organic matter that culminate in the formation of humic substances. Many raw materials can be used for composting and it is generally preferred to process materials with different characteristics together, in order to obtain mixtures in which the oxidation develops well. This is obviously linked to microbial activity, which must be given the ideal conditions to multiply and accelerate the process.

Traditional field agriculture is without any doubt the quantitatively most important sector for the use of organic fertilizers and the one that can best exploit compost produced from clean matrices, i.e. free of macroscopic polluters (glass, plastic and metals) and with heavy metals contents comparable to traditional amendants.

For agronomic use the compost must have:

- good organic matter content;
- appreciable, but not excessive presence of nutrients in order to avoid limiting conditions in distribution and therefore the amendant effect;
- sufficient maturation, but not necessarily complete, given that the fermentation processes continue in the soil;
- level of refinement not high: screening between 10 and 20 mm ensures good homogeneity and, at the same time, allows the product to be distributed with a manure spreader.

In strictly agronomic terms there are some quality differences between the available composts. The green composted amendant has suitable physical-chemical characteristics for plant growing and a limited salinity compared to other composts, making its use less problematic in some situations such as on perennial crops. Compost from green wastes, especially if produced from matrices with a high woody component, has low nutrient values.

The mixed composted amendant, as well as guaranteeing humified organic matter (amendant function), also provides a conspicuous fertilizing supply. Crops that require lots of nutrients make use of this nutritional capacity, such as horticultural crops or crops that are incorporated into the soil.

Although their composition is highly variable, composts are sources of organic matter that guarantee the amendant effect and supply a discrete amount of nutrients that depend on the mineralization level. It is estimated that around 20% of the nutrients are released during the first year. Compost can be profitably used in gardening, both professional and amateur, especially in the compacted and nutrient-poor soils that are common in many urban areas. For the mixed composted amendant the rates to distribute are calculated on the basis of the nutrient contents, trying to supply especially the nitrogen needs of the crop. In this way the maximum amount of organic matter is distributed. Exceeding the calculated dose may be hazardous for the crop in relation to the excess nitrogen. By evidence of long term trials which evaluated the use of compost (Gobbi et al. 2016), in Table 1 the average main chemical traits of Municipal solid waste compost used for 8 years are reported.

Since compost has become available at little cost and with well-defined physical characteristics, it has become one of the materials used in the formation of loams for plant nurseries in percentages varying from 20 to 30%, and up to 70% for potting composts. The characteristics of the compost are often complementary to those of

Table 1 Average chemical characteristics of municipal solid waste (MSW) used in long-term trial

Feature	Unit measure	Values
pH		8.73
EC	mS cm^{-1}	3.03
Organic matter	%	45.5
Organic carbon	%	26.4
Dry matter	%	70.0
C:N ratio		15.6
N	% dry weight	1.78
P	% dry weight	0.48
K	% dry weight	1.22
Cr	mg kg^{-1} dry weight	15.9
Pb	mg kg^{-1} dry weight	16.3
Cd	mg kg^{-1} dry weight	0.05
Zn	mg kg^{-1} dry weight	148

Gobbi et al. (2016)

peat, for this reason it is suitable for addition in the mixes to obtain substrates with the desired quality.

Recently in Italy, there has been a strong reduction in the use of mineral fertilizers in favor of organic amendments and natural fertilizers (ISTAT 2013). In 2013 41.1 million tonnes of fertilizers were distributed in Italy, 13.4% less than the previous year. Referring to the last 10 years, the reduction of mineral fertilizers in Italy amounted to 23.4%. The increase in the use of organic manure and natural fertilizers such as compost is linked to experiments at the European, but also at national level. These trials, combined with the increasing costs of mineral fertilizers, allowed producers to verify how compost works in crop growth as a good source of organic matter and nutrients. Warman (2005) reported after a long-term application of compost (12 years) in comparison with mineral fertilizers that the long-term use of compost can produce similar yields and elemental analysis for most crops in compost-amended and conventionally-fertilized soils. More in detail the fresh weight yields from the six plots, in a sandy loam soil and temperate climate, showed that the compost treatment resulted in numerically, but not significantly, higher yields for the carrots, peppers, onions and tomatoes, and significantly higher yields for green and yellow beans. Cauliflower and Brussels sprouts yields, however, were higher in the fertilizer-amended plot. Soils with compost had higher pH, CEC, C, N and Mehlich-3 extractable levels of P, Ca, Mg, Mn, Zn and B compared with the fertilized plots. However, the increased nutrients in the compost-amended soil did not increase the nutrients in the leaf tissue or the edible portion of the plant. Of the 16 elements tested, only P and K were higher in the fertilizer-amended plant leaf tissue, while levels of P were significantly higher in the edible portion of the plant. Soil incorporation of composted municipal solid waste (MSW) usually results in a positive effect on the growth and yield of a wide variety of crops and the restoration of ecologic and economic functions of land. Agricultural uses of MSW have shown positive results in terms of yield for a variety of field crops (e.g., maize, sorghum, forage grasses) and vegetables for human consumption (e.g., lettuce, cabbage, beans, potatoes, cucumbers) (Shiralipour et al. 1992). Specific responses are crop and site dependent as are reported also by Montemurro et al. (2005) in tomato. In some cases, elevated trace metal uptake was noted with lead and boron of greatest concern (Gallardo-Lara and Nogales 1987; Islam et al. 2007; Smith 2009). Where long-term monitoring has been possible, benefits persist and actually accrue when suitable soil/crop management practices are followed. Levels of toxic elements in plants for human consumption are either not well known or thresholds were not reached (Nicoletto et al. 2013b).

3.3.2 Sewage Sludges

Sewage sludges can be an interesting source of nutrients and organic matter for soils. Being waste materials, it is necessary that their characteristics guarantee the absence of polluting elements (in particular heavy metals) and pathogens for plants, animals and humans. The sludges can be distributed on the soil or used in composting, together with other materials. In agriculture, the sludges are directly usable deriving from the depuration of wastewaters coming exclusively from civilian and/or producing establishments with the condition that their characteristics are not substantially different from those of civilian sludges. The utilization in agriculture is allowed only if the sludges have been treated, are suitable for producing a fertilizing and/or amendant and corrective effect of the soil and do not contain harmful or toxic substances over established limits.

Use of the sludges must take into account the environmental situation, the different crops and the constraints on spreading, in particular in terms of maximum quantity distributable. From the agronomic and environmental conservation viewpoint it is not appropriate to distribute an average rate on all the land every year, but rather to supply the different crops with rates of sludge suitable to their nutritional requirements. Summer crops, maize in particular, are those that can best utilize the characteristics of the sludges. In order to calculate the amounts of sludge to distribute the nitrogen supply is considered first and then that of phosphorus and potassium within the maximum application limits of sludge. Any surplus supplies of phosphorus and/or potassium are, within limits, tolerable if they are taken into account in the fertilization of the crops grown in the years following the sludge application. Given their scarce mobility, the two elements persist in the soil, therefore the supplies may be concentrated on just one crop in the rotation, leaving those that follow to benefit from the residual fertility. It should also be considered that only a part of the nutrients will be effectively available for the nutrition of the plants. Indeed, numerous experiments (Cheung and Wong 1983; Tandi et al. 2004; Singh and Agrawal 2008) have demonstrated that the crops can utilize less than 50% of the nitrogen and phosphorus and around 80% of the potassium distributed with the sludges. The organic matter evolves slowly, influenced by pedoclimatic conditions and only part of the nutrients become available in the year of application.

This also explains the multi-year effect of organic fertilizations and justifies the decision to distribute sludges at three year intervals.

3.3.3 Anaerobic Digestion Residues

Digestate, a by-product of the anaerobic digestion process, is a stabilized material with good fertilizing characteristics, with a "ready effect" due to mineralization of the organic nitrogen to ammonia. Trials have demonstrated the strong and weak points of the digestate: the former include the fertilizing efficacy and thus the possibility of substituting chemical fertilizers, and the low odour emissions; the latter the possible increments of ammonia in the atmosphere and losses of nitrates if the distributions do not coincide with the uptake cycle of the crops (Barbanti et al. 2010).

A series of trials were conducted in Emilia Romagna and abroad that compared the digestate and mineral nitrogen on different energy crops.

The results demonstrate an overall correspondence of nitrogen use efficiency between digestate and mineral fertilizers. Nitrogen use efficiency is obtained by multiplying the total nitrogen by a coefficient varying between 30 and 65%, depending on a series of factors: the coefficients of efficiency matched to every combination between product, time and method of distribution, and crop (Barbanti et al. 2010).

The environmental effects from the use of digestate have also been studied. Attention was focused on the emissions in the atmosphere of ammonia (NH_3), one of the substances responsible for the phenomena of acidification and eutrophication, and on the release of nitrous oxide (N_2O) and methane (CH_4): these are two powerful greenhouse gasses with a Global warming potential (Gwp) at 100 years equal to 296 and 23 times that of CO_2 (Directive EC 28/09). As already mentioned, the digestate has a high percentage of nitrogen in ammonia form ($N\text{-}NH_4$), which can more easily volatilize in the form of NH_3. Emissions of N_2O and CH_4 from the soil are, instead, more frequent in conditions of water saturation or anyway high soil moisture content. The distribution of digestate has therefore, in general, increased the losses of ammonia by volatilization compared to the pre-digestion material, while it has limited the emission of N_2O from the soil. Instead, little information is available regarding methane losses in the atmosphere, which anyway seem to be more linked to the storage phase than agronomic use (Moitzi et al. 2007). For example Petersen (1999) demonstrated that the emissions of N_2O reduced distributing the digestate on the soil rather than animal sewage. The losses in this form were modest, not even 1% of the total nitrogen distributed, but still serious given the nature of the problem. A more recent study (Möller and Stinner 2009) confirmed a 38% reduction in the fluxes of N_2O, thanks to the co-digestion of crop and vegetation pruning residues, with respect to the direct ploughing in of these biomasses. In the same study a digestate from cattle slurry had slightly higher losses of ammonia by volatilization than the slurry, but not more than 15% of the nitrogen supplied with surface distribution. The effect of the digestion of crop residues rather than their burial also led to a reduction of the nitric nitrogen content in the soil between autumn and spring; this gives a lower risk of leaching that is a not minor extra benefit.

The need to dispose of the sludge from bio-digesters and wastes of various types encourages the agronomic use of digestate. This by-product has the same nutritional capacity as the original matrices and is suitable for ameliorative actions such as solid/liquid separation and composting of the former.

The digestate has little organic matter and contains nutrients in easily assimilated form, even if diluted to a level of a few g/kg. It thus requires an application rate in the order of many tonnes per hectare to be able to carry out an appreciable nutritional action, like that of livestock slurries.

As in livestock wastes, the nitrogen in digestates is present in ammonia form but also, in less quantity, in organic form. In pig slurries ammonium is the prevalent form (approx. 75%), while in those from cattle it is the organic form (60%) (Bechini et al. 2009). Evaluation of the agronomic and environmental fate of the two nitrogen forms (organic and ammonia) involves the following considerations. If the temperature is adequate and sufficient oxygen is available, the ammonia nitrogen of the wastes incorporated in the soil is rapidly transformed into nitrate by the nitrifying bacteria. The ammonia is therefore available for the plants either directly, when they can utilize the ammonium, or indirectly, when they preferably utilize the nitrate. The latter, because of its high mobility, may easily be lost by leaching, in particular if the sludge is applied to the soil at a time far removed from the peaks of crop uptake, for instance when it is spread in autumn or well before sowing. Instead, before it can be used by the crops, the organic nitrogen needs to be transformed into inorganic form (first ammonia and then nitric) through mineralization of the organic matter. Consequently, the organic nitrogen is available to the crops later than the ammonia form. Furthermore, the decomposition of the organic matter in the wastes (in particular of those stored in anaerobic conditions, like the slurries) may involve a partial and temporary immobilization of the inorganic nitrogen (nitric or ammonia), thus reducing its availability for the plants. This immobilization consists of the assimilation of mineral nitrogen taken from the soil solution, which the microbial population does when its growth is fed by relatively nitrogen-poor organic matter. The assimilated nitrogen may return again to mineral form following the death of the microbial biomass and mineralization of its remains. Part of the organic nitrogen is resistant to microbial degradation and its transformation into ammonium and nitrate is very slow and may even happen a long time after the sludge is distributed on the soil. Depending on when the sludge is spread, the sowing date of the crop and length of its cycle, as well as the cropping sequence, the nitric nitrogen may be released when there is no strong crop uptake or even when there is no crop in the field, with possible risks of dispersion of the nitrates in the waters or their denitrification. From the agronomic point of view the result of these complex dynamics can be summarized as follows:

- the fertilizing effect of the nitrogen in the first growing season after distribution of the wastes in the field depends substantially on their ammonium content;

- the ammonium is not completely available if there are losses after the sludge distribution (volatilization of ammonia, leaching or denitrification of nitrate, immobilization of inorganic nitrogen in the microbial biomass);
- the organic component is mineralized much more slowly and becomes quantitatively important only if the effects of repeated distributions on the same soil are summed up (Bechini et al. 2009).

Relatively few studies are available on this, a sign of the still scarce knowledge on the subject. The majority relate to the digestion of pig slurries without the addition of other biomasses. The studies were done on different soils, comparing the yield response of the crops: maize, wheat and meadows to fertilizations with digested and non-digested slurries.

The digestates normally used had a higher N-NH_4/N-total ratio (approx. 10–20%) than that of the non-digested slurries; when available, the C/N ratio of the digestates was 40–75% lower. The pH of the digestates (usually above 8) was 0.3–0.9 higher than the non-digested slurries. In the field trials the yield responses were not significantly different except in two cases:

1. in Germany, an experiment conducted on spring-sown bread wheat with 80% of the slurries applied in pre-ploughing and 20% at pre-emergence: the digestate was better able to show its fertilizing value with respect to the non-digested slurry.
2. in Canada, a trial conducted on a meadow with application at pre-emergence led to a higher crop yield with the digestate compared to the non-digested slurry.

In a greenhouse trial conducted in Holland without the effect of rainfall and a temperature of around 20 °C, a digestate obtained from the co-digestion of pig slurry with food industry wastes was used. Three fertilizers (digestate, non-digested slurry and mineral fertilizer) were compared on a sandy soil with ryegrass (*Lolium perenne* L.) cut three times in 105 days. The digested slurry and mineral fertilizer gave substantially equal nitrogen use efficiencies and on average 27% higher than the non-digested slurry (Bechini et al. 2009).

The high ammonium content frequently found in digestates makes them similar to inorganic fertilizers, suggesting the same utilization methods (including distribution times). At the same time it should be remembered that the presence of nitrogen in organic form complicates the dynamics in the soil. This, if in the short term, can be a cause of immobilization reducing the availability of the ammonia nitrogen in the digestate; in the long term, following repeated applications, it will presumably accumulate in the soil and may constitute a reserve of nitrogen. Burial of the digestate is advisable to avoid dispersion of ammonia in the air.

Given the variability of the concentration of nutrients in the digestate due to the raw products used and the extraction system, an analysis of the wastes is advised prior to distribution in the field (Bechini et al. 2009).

Early studies about the effect of anaerobic digestates on manure characteristics compared the composition of digestates and solid farmyard manures. Recently, characterizations have been made mainly for liquid undigested and digested animal

Table 2 Chemical properties of digestate from manure

	Absolute values	Change[a]
DM (%)	1.5–13.2	−1.5 to −5.5
Organic DM (% DM)	63.8–75.0	−5 to −15
Total N (% DM)	3.1–14.0%	[b]
Total N (kg Mg^{-1} FM)	1.20–9.10	≈0
Total NH_4^+ (kg Mg^{-1} FM)	1.5–6.8	?
NH_4^+ share on total N (%)	44–81%	+10 to +33
Total C content (% DM)	36.0–45.0	–2 to –3
C:N ratio	3.0–8.5	–3 to –5
Total P content (% DM)	0.6–1.7	[b]
Total P (kg Mg^{-1} FM)	0.4–2.6	≈0
Water soluble P (% of total P)	25–45	–20 to –47
Total K (% DM)	1.9–4.3	[b]
Total K (kg Mg^{-1} FM)	1.2–11.5	≈0
Total Mg (kg Mg^{-1} FM)	0.3–0.7	≈0
Total Ca (kg Mg^{-1} FM)	1.0–2.3	≈0
Total S (kg Mg^{-1} FM)	0.2–0.4	?
pH	7.3–9.0	+0.5 to +2 units

Möller and Müller (2012)

[a] In comparison to undigested liquid animal manures, absolute values

[b] Increases with degree of DM degradation

DM dry matter, *FM* fresh matter, ? = No data found/no data available

slurries as well as for digestates derived from dedicated energy crops; available data indicate a wide range of nutrient contents (Table 2) as reported by Möller and Müller (2012).

Few publications address the use of digestates as fertilizers for vegetables demonstrating that digestates are an effective nutrient source (Möller and Müller 2012). Digestates may be most beneficial in organic vegetable cultivation, where quick release fertilizers are lacking (Furukawa and Hasegawa 2006). Incubation studies carried out under different soil temperatures (8 and 16 °C) demonstrate that the short-term N-release of digestate N is similar (e.g. blood meal, vinasse, etc.) or even higher (e.g. castor cake, poultry solid manure, feather meal, meat and bone meal, etc.) than the N-release of many commercial organic fertilizers often used as manures in organic vegetable crops, especially under low soil temperatures. This indicates the high suitability of digestates as a fertilizer even in the cool season (e.g. early spring), especially for high N demanding vegetables with a short growing period. Other studies have reported that supplementation by addition of P and micronutrients (particularly Fe) increases the shoot biomass of lettuce (Liu et al. 2011). Such a supplementation balances the relative P deficiency compared to N and improves Fe availability. Most investigations have shown that the vegetable nitrate content decreased significantly, when applying digestates as an alternative to mineral fertilizers under soilless (Liu et al. 2009) and sand culture, as well as in pot experiments (Lošák et al. 2011). The reduction in nitrate content has been related to differences in N composition. In contrast to nutrient solutions supplying nitrate, biogas digestates supply NH_4^+-N and as organic components mainly amino- and amide-N (Liu et al. 2009). Results on the effect of application of digestates derived from animal wastes on vitamin C content of vegetables are inconsistent (Liu et al. 2011). The use of concentrated digestates (fertilizer obtained after solid–liquid separation, filtration, etc.) from animal manures had significant effects on tomato fruits, including decreases in water content, and increases in electrical conductivity, contents of total N, total P, amino acids, proteins, soluble sugars, β-carotene, tannins, and vitamin C (Yu et al. 2010).

Some experiments considered also anaerobic digestates residues (ADRs) coming from vegetal matrices (Table 3) such as anaerobic digestate of fruit and wine distillery wastes applied in cauliflower and lettuce cultivation (Nicoletto et al. 2013a, 2014). Authors showed that cauliflower could be grown with ADRs without differing from mineral control yield. The marketable yield of lettuce was significantly lower than mineral control in the first cycle after ADRs application. This result could be due to the really short growing cycle of lettuce and the slow mineralization of ADRs. This is confirmed by the second following lettuce cycle where the production was statistically similar to the mineral control. Moreover some qualitative traits like antioxidant activity, total phenols content and vitamin C were not significantly affected.

3.3.4 Spent Mushroom Compost (SMC)

Another alternative organic matrix is the spent mushroom compost. This matrix consists of the by-products of the mushrooms cultivation on litter, once the latter is no longer able to support the production. Many species of mushrooms are cultivated world-wide and the global production is greater than six million tonnes and has an approximate value of at least $US14 billion. According to the Food and Agriculture Organization (FAO 2012) the most important producer of “mushrooms and truffles” is China with almost 65% of world production (Figs. 1 and 2).

A quarter of the world’s production of mushroom, 2104×10^3 tonnes per year, is generated in the European countries where Italy is the greatest producer with 785×10^3 tonnes per year (FAO 2012). One of the major environmental problems in the mushroom producing countries remains the treatment and disposal of the spent mushroom compost (SMC). About 5 kg of SMS is produced for each kilogram of mushrooms (Williams et al. 2001), so the amount of SMC in Europe and in the world is considerably high. The mushroom industry generates two main types of spent mushroom substrate, one for *Agaricus bisporus* (SMC-AB) and another for *Pleurotus ostreatus* (SMC-PO). SMS-AB (Fig. 3) is composed of a composted mixture of cereal straw and manure (poultry and/or horse manure and/or pig slurry), calcium sulphate, soil and residues of inorganic nutrients, whereas SMC-PO contains fermented cereal straw and residues of inorganic nutrients.

SMC could be used for energy production as reported by Williams et al. (2001) but many beneficial uses for spent mushroom substrate are currently being

Table 3 Chemical properties of anaerobic digestion residues (ADRs) from vegetal matrices on dry matter basis

Parameters		ADRs	
		Water extract	Ash content
pH		7.68	
EC	μS cm^{-1}	1.462	
Total organic matter	%	49.94	
Organic carbon	%	28.97	
Total N	%	1.18	
C/N		24.55	
Ash	%	50.06	
Dry matter	%	30.21	
P	mg kg^{-1}	42.6	5824
K		1942	3044
Ca		134	19,189
Mg		14.7	941
Mn		0.038	63.7
Al		0.363	3125
Fe		0.238	1659
Na		126	2039
Co		0.006	0.42
Cd		0	0
Cr		0.006	6.72
Cu		0.371	488
Pb		0	1.81
Ni		0.054	3.96
Zn		0.904	56.8
As		0.038	0.75
B		4.11	64.6
Li		0.665	6.79
Mo		0.018	0.60
S		72.3	1509
Sb		0.031	0.25
Se		0.031	0.25
Sn		0.018	1.73
Sr		0.542	56.4
Ti		0.006	23.3
V		0.012	3.97

Nicoletto et al. (2014)

implemented or evaluated internationally at agronomic level (Rinker 2002; Wever et al. 2005). This topic was studied since 80's with some trials aimed at the determination of the effects of spent mushroom compost on vegetable seedling emergence, growth, and elemental uptake and on plant growth and development

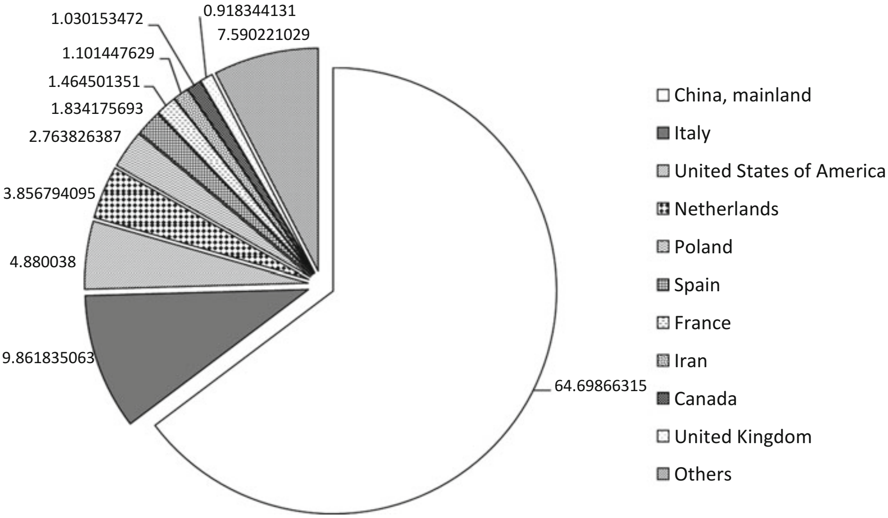

Fig. 1 World mushrooms and truffles production (%) according to Food and Agriculture Organization (2012)

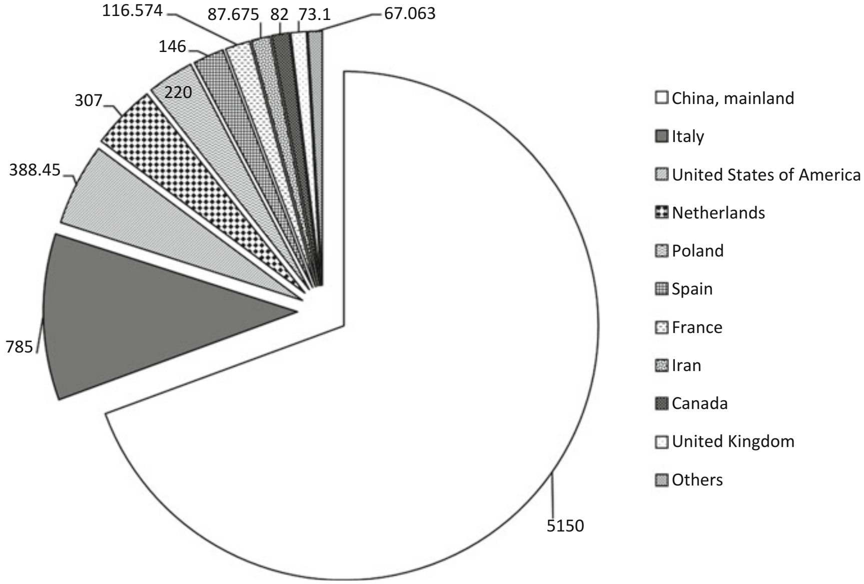

Fig. 2 World mushrooms and truffles production (tonnes 10^3) according to Food and Agriculture Organization (2012)

Fig. 3 *Agaricus bisporus* growing beds. The growing substrate can be used as spent mushroom compost at the end of growing cycle in open field

(Wang et al. 1984). SMC was also used for growing containerized woody ornamentals (Chong and Rinker 1994; Chong et al. 1991).

Although the SMC composition is obviously variable as reported by Jordan et al. (2008) and Fidanza et al. (2010), the average most important chemical aspects of SMC are reported in Table 4. These data were recorded from SMC collected in 15 different mushroom producers in north Italy (Gobbi et al. 2016).

In most of the cases, the addition of SMC to the growing media produced an increase in the pH values, salt contents, macro and micronutrient concentrations and a decrease in the water holding capacity contents in comparison to peat, whereas great differences were found in the air capacity values between SMS-based substrates and peat. Up to 75% SMC can be used in mixtures with peat for seed germination of the plant species studied. Regarding the most suitable SMC-based substrates for plant growth, any substrate could be used for tomato seedling production. However, all SMC-AB-based substrates and the media containing low dose of SMC-PO were adequate for growth of zucchini and pepper (Medina et al. 2009).

The SMC has been used in greenhouse for vegetable transplants (Lohr and Coffey 1987), cucumbers (Celikel and Buyukalaca 1999c), tomatoes (Celikel and Tuncay 1999a; Zhang et al. 2012) and eggplant (Celikel and Tuncay 1999b); impact on post-harvest quality on tomato (Polat et al. 2009). Other trials on vegetables were conducted in open field as reported by Rinker (2002) and Maynard (1993).

Table 4 The average most important chemical aspects of SMC

Feature	Unit measure	Values
pH		5.93
Organic matter	%	57.1
Dry matter	%	35.6
Organic carbon	%	33.1
N	% on dry weight	2.06
P_2O_5	% on dry weight	1.15
K_2O	% on dry weight	2.18
EC	mS cm^{-1}	6.58
C/N ratio		16.3

Gobbi et al. (2016)

4 Conclusions

In this brief overview about the fertilizers choice are reported some of the main opportunities offered by the fertilizers world in horticulture. It is also clear that the merely and exclusive use of mineral fertilizers is no longer applicable and free from any principle relating to good agricultural practices. In the present productive conditions, environmental issues and the sustainability of agricultural activities must be accompanied by appropriate expertise in fertilizer management. The continuous use of mineral fertilizers in intensive horticultural systems resulted in well-known soil problems, among which emerges the reduced presence of organic matter. Currently, despite the lack of traditional sources of organic matter such as manure, the choices can range among many opportunities offered by other agricultural sectors and agro-industrial world. The growing presence of biogas production systems producing together with innovative processing techniques of agricultural products provides continuous ideas to experiment and test new matrices able to supply nutrients to the soil in parallel with good organic matter content. This, in the long period, could actually allow a sustainable fertilization in horticulture.

Glossary

BER	Blossom-end-rot
MSW	Municipal solid waste
CEC	Cation-exchange capacity
GWP	Global warming potential
ADRs	Anaerobic digestates residues
SMC	Spent mushroom compost
SMC-AB	Spent mushroom compost for *Agaricus bisporus*
SMC-PO	Spent mushroom compost for *Pleurotus ostreatus*
DTPA	Diethylenetriaminepentaacetic acid

EDTA Diethylene triamine pentaacetic acid
EDDHA Ethyplene diaminebis (2-hydroxyphenylacetic acid)
EDTA Ethylene diamine tetraacetic acid
HEDTA Hydroxyethyl ethylene diamino triacetic acid

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Crop Rotation as a System Approach for Soil Fertility Management in Vegetables

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Abstract This paper reviews the recent literature on crop rotation as a tool to manage soil fertility specifically for vegetable production. All of the aspects dealing with soil fertility management, i.e. mineral and organic fertilisation, crop residues management, cover cropping and green manuring, and intercropping, are examined in the frame of crop rotations in conventional and organic systems for both specialised and non-specialised vegetable production. A focus is given on conservation tillage practices to manage green manures and vegetable crop residues. The design and modelling of vegetable rotations are described under the viewpoint of increasing the nutrient use efficiency and the self-sufficiency of the system. Some long-term experiments including vegetables are described which evaluate cumulated effects of rotations on soil fertility and vegetable production. It is concluded that only integrating all the available techniques of soil fertility management at a whole rotation scale it is possible to contribute to the productive, economic and environmental sustainability of the system. For example, little supplementation of mineral or fast-release organic fertilisers delivered with rational fertilisation techniques (e.g. starter, split, and localised fertilisation; fertigation) may help compensate the temporal and spatial lack of matching between nitrogen release from slow-release organic sources and crop nitrogen demand. This would help modulate nutrient supply in a more flexible way and improve crop nutrient uptake, so allowing more constant yields across years and limited risks of nutrient loss to the environment.

Keywords Cover crop • Green manure • Residue • Fertiliser • Fertigation • Nitrogen • Phosphorus • Organic • Conventional • Model • Pollution • Use efficiency • Self-sufficiency • Sustainability

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1 Introduction

Crop rotation is widely recognized as one of the key-strategies of conservative agriculture, aimed at guaranteeing the long term productivity and sustainability of agricultural systems (Colomb et al. 2013; Drinkwater and Snapp 2007; Gomiero et al. 2011; Hobbs et al. 2008), vegetable systems included (Nair et al. 2014; Raviv 2010).

Rotating crops gives direct benefits on soil fertility. Species differ in root architecture and ability to take nutrients from the soil (Gardner and Sarrantonio 2012; Pedersen et al. 2009) and some species may establish symbiosis with arbuscular mycorrhizal fungi having high nutrient extraction ability (Elfstrand et al. 2007) or with nitrogen (N) fixing bacteria, which provide the plant with N derived from the atmosphere (Ndfa) (Ledgard and Giller 1995). This latter aspect, typical of legumes, makes of N a renewable resource for the system and can be exploited by growing legumes purposely for green manuring, to supply new nitrogen to the soil for the following cash crop (Fageria 2007; Thorup-Kristensen et al. 2003). Crops also differ for growing season and cycle length, so that they may be differently able to intercept soil N. As an example, in temperate regions, cover crops having continuous growth in fall-winter may be used as a tool to prevent N loss from the system caused by leaching (Gabriel et al. 2012; Macdonald et al. 2005; Tonitto et al. 2006; Tosti et al. 2014; Vos and van der Putten 2004). Moreover cash crops differ in the amount and composition of crop residues returned to the soil (Agneessens et al. 2014; Fink et al. 1998). This, together with the type of fertilisers and the tillage options may affect soil organic matter content for a given environment (Carter 2001; Lal 2005), with effects on soil properties in the short-term (Alluvione et al. 2013) and especially in the long-term: i.e. soil structure, prevention of erosion, water holding capacity, nutrient stock, microbial activity, etc. (Alliaume et al. 2013; Diacono and Montemurro 2011; Fließbach et al. 2007; Hobbs et al. 2008; Mazzoncini et al. 2011; Nair and Ngouajio 2012).

Further agronomical benefits of crop rotations related to increased biodiversity will not be discussed here (Hooper et al. 2005; Moonen and Barberi 2008), as for example: the indirect management of crop protection, due to allelopathic effects towards soil-borne diseases (Bryant et al. 2014; Hooks et al. 2010; Ntalli and Carboni 2012; Snapp et al. 2005) and to temporal and spatial barrier to pest and disease diffusion (Kirkegaard et al. 2008; Meyling et al. 2011; Patkowska and Konopinski 2014); the improved weed control, due to competitive suppression or allelopathic effects towards volunteer species (Caamal-Maldonato et al. 2001; Haramoto and Gallandt 2004; Hill et al. 2007; Moonen and Bàrberi 2006; Pullaro et al. 2006) or because alternating crops may allow selective weeding by varying herbicides and mechanical operations (Chauhan et al. 2012; McErlich and Boydston 2014; Moonen and Bàrberi 2004).

Also economic and social aspects to be considered in the choice of the vegetable rotation (Dogliotti et al. 2004; Navarrete 2009; Nendel et al. 2013; Rahn et al. 2010; Raviv 2010) will be sometimes mentioned but not discussed here.

Despite these well-known benefits, crop rotation is often limited to few crops in the farm, especially in vegetable production, since each crop requires specific equipment and farmer's competence. In fact, although crop rotation is always recommended also in vegetable systems, the need of adopting this practice and the way it can be implemented depends on the context. Crop rotation might need to and can be sometimes derogated in conventional and/or specialized vegetable farms, while it results mandatory and actually more feasible in organic and/or non-specialised vegetable farms. Depending on the context, nutrients may be directly supplied to a vegetable crop by mineral or organic fertilisers, by resorting cover/green manure crops or intercrops, and by valorising previous cash crop residues. Whatever the source of nutrients, appropriate rotations may help optimal management of soil fertility to increase the nutrient use efficiency and the self-sufficiency of the system, so guaranteeing crop productivity while limiting negative side-effects on the environment.

2 Use of Fertilisers in Vegetable Crops

Nutrients for vegetables are mainly supplied by chemical or organic fertilisers. These are examined in another chapter of this book. It is useful to remind here that fertilisers represent external inputs needed to restore in the system nutrients removed with marketable yield. Except in the case of N, which can be derived from the atmosphere, fertilisers are indispensable to supply all the other nutrients in stockless systems. Moreover, fertilisers are also very useful in the practice to supply N, which is required in very high amounts to support high yields.

Chemical Fertilisers Generally chemical fertilisers are immediately available to crops, thus they are intended to be directly recovered by the crop they are supplied to. For this reason, strategies aimed at increasing the uptake efficiency of the single crop have been developed more than strategies aimed at increasing the efficiency of the system as a whole (Agostini et al. 2010). For example, localised and split fertilisation, as well as drip fertigation, are nowadays widely adopted by vegetable growers to achieve high nutrient uptake efficiencies (Battilani et al. 2003; Battilani and Solimando 2006; Farneselli et al. 2015b). Moreover, fertigation represents the most flexible tool to adjust the fertiliser rate during the growing season according to the crop nutritional status as revealed by quick tests (Farneselli et al. 2010, 2015b; Ulissi et al. 2011a, b). This allows keeping a critical (i.e. optimal) nutrient concentration in plant tissues in order to maximize growth and yield while avoiding superfluous costs and environmental pollution (Tei et al. 2002, 2003).

Organic Fertilisers On the other hand, the availability of nutrients from organic fertilisers and amendments, such as animal manure and compost, is lower than the total in the short-term and cannot be known precisely (Gaskell and Smith 2007; Hargreaves et al. 2008), because it varies with soil and weather conditions and organic matter composition. Nutrient release from organic fertilisers may not meet crop requirements at any growth stage and often occurs out of the crop growing cycle (Crews and Peoples 2005; Katroschan et al. 2014; Ren et al. 2014; Rosen and Allan 2007). The effect of a given organic fertiliser also depends on N demand, root architecture and growth habit of the vegetable crop. Morra et al. (2013) observed different uptake and use efficiency of N from compost in cauliflower, potato and onion. Anyway, if organic fertilisers are provided to crops with a substitute approach, just to replace mineral fertilisers, they actually delude expectations: in spite of the high cost of the nutrient unit (including transport and application costs), they result in low short-term availability and crop uptake efficiency of nutrients, and, in stockless farms, they do not alleviate the lack of self-sufficiency of the system. Compost and other amendments are known to increase soil organic matter content and related long-term soil fertility (Buyer et al. 2010; Morra et al. 2010; Nair and Ngouajio 2012; Treonis et al. 2010), but this is generally felt a minor issue by vegetable growers. Moreover, long-term effects of organic fertilisers on soil fertility and crop performances are seldom considered in the literature concerning vegetables, in lack of tailored long-term experiments where crops can be evaluated over many years. When long-term effects are evaluated, nutrient availability and crop yields come out similar for organic and mineral fertilisation (Moccia et al. 2006).

In the following sections it will be discussed how an appropriate sequence of crops in the rotation may help valorise and recover the nutrients supplied by organic and mineral fertilisers and limit environmental pollution. On the other hand, the use of fertilisers, even at low rates, may help valorise crop residues incorporated into the soil and guarantee available nutrients at due time and rates according to the following cash crop need (Araya et al. 2010; Farneselli et al. 2013b; Moreno-Cornejo et al. 2013).

3 Role of Cover and Green Manure Crops

The terms "cover crop", "catch crop" and "green manure" are often used as synonymous, although each term refers to a major agro-ecosystem service provided by the crop (Hajjar et al. 2008; Ramirez-Garcia et al. 2015). Kollas et al. (2015) made an attempt to straighten the glossary of terms used and proposed "intermediate crops" as a comprehensive term for all crops grown as non-cash crops in the rotation. Intermediate would reflect how these crops are termed in other European languages ("Zwischenfrucht", "Intercalare", "Culture intermédiaire", "Międzyplon") in contrast to English (UK), where "cover crop" is often used as the top category, regardless the fact that coverage is often not the aim pursued with the use of such crop.

More appropriately, a cover crop is grown principally to avoid negative consequences of fallow during the rainy season (soil erosion and compaction, water stagnation, N leaching). The term catch crop attains to the function of absorbing nutrients from deeper soil layers, especially mineral N, thus preventing the risk of N loss. A green manure/fertility building crop is grown to be then killed and provide organic matter and nutrients to the soil; this is expected to promote the growth of the following cash crops and the recoupling of C and N cycles, so contributing to increase or maintain soil organic carbon. Of course, when a cover/catch crop is killed with its biomass left in the field (incorporated into the soil or laying on the surface) it actually works as a green manure crop. For this reason, all these terms will be used indifferently here.

3.1 Effects of Cover Crops on Soil Nutrient Management

The use of different cover crop species increases the mobilisation and/or recovery of nutrients otherwise unavailable to cash crops. Each species has its own skill in exploring the soil at different depths and in extracting nutrients, which will be returned to the soil with cover crop residues. Effects are reported for nutrients other than N via acidification (Mohanty et al. 2006; Takeda et al. 2009; Varela et al. 2014) or through the improvement of soil biological activity, e.g. the enhanced soil exploration and phosphorus uptake due to arbuscular mycorrhizal fungi (Njeru et al. 2014). Some legumes are reported to increase phosphorus bioavailability thanks to the solubilisation of native phosphorus and its transfer to plant organic matter (Cavigelli and Thien 2003; Maiksteniene and Arlauskiene 2004). This could be exploited by supplying phosphorus fertilisation to green manures to increase its availability for the cash crop through mineralisation of the incorporated biomass (Horst et al. 2001; McLenaghen et al. 2004).

As far as N is concerned, cover crops may provide the soil with mineral N prevented from leaching and/or Ndfa accumulated by legume species. In organic stockless systems, where N is generally limiting, these sources of N become of primary importance (Berry et al. 2003; Mazzoncini et al. 2010; Migliorini et al. 2014).

The amount of N actually available to a cash crop after growing the cover crop and returning its biomass to the soil (N effect) is expressed by the following equation (Thorup-Kristensen et al. 2003)

$$\mathrm{Neff} = \mathrm{Nupt} \times \mathrm{m} - \mathrm{Nupt} \times \mathrm{r}$$

Where *Nupt* is the cover crop N uptake, *m* is the fraction of *Nupt* that will be available for the succeeding crop after the residue mineralisation, *r* is the fraction of *Nupt* that would have remained in the rooting zone anyway if no cover crop had been grown (Thorup-Kristensen et al. 2003).

The term *r* tends to 0 in light soils and rainy climates, where the soil mineral N would be leached below the cash crop rooting zone, while it tends to 1 in clay soils and dry climates, where the mineral N would remain in the soil explored by roots anyway (Willumsen and Thorup-Kristensen 2001). The space and time conditions in which N is absorbed are effective: the N taken up from deeper layers or absorbed at early stage of the cover crop cycle will produce lower value of *r* compared to that taken up from shallow soil layers and/or near the catch crop termination date (Alonso-Ayuso et al. 2014; Thorup-Kristensen and Dresbøll 2010).

The factors affecting *m* are numerous: for a given environment the residue composition represents a fundamental parameter for mineralisation: this include the C/N ratio, the lignin, cellulose and hemicellulose contents and the polyphenol content (Bending et al. 1998; Brennan et al. 2013; Reddy et al. 2008; Thorup-Kristensen and Dresbøll 2010). The C/N ratio is easy to calculate and it is a reliable index of the N mineralisation from an organic compound (Mancinelli et al. 2013). Pedo-climatic conditions as temperature, soil humidity and soil texture (which affects O_2 availability in the soil) also play a major role, by affecting biota activity (Nair and Ngouajio 2012). For example, most of incorporated crop biomass is mineralised in 1–2 months in Mediterranean spring-summers (Brennan et al. 2013; Mancinelli et al. 2013; Quemada 2004; Tosti et al. 2012).

The quality of biomass incorporated into the soil also affects the dynamics of Green House Gas (GHG) emissions (Chirinda et al. 2010; Huang et al. 2004; Pappa et al. 2011; Rizhiya et al. 2011) such as ammonia (NH_3), NO_x and nitrous oxide (N_2O) that are considered a threat to the environment (IPCC 2014). Generally, residues with high C/N ratios reduce N_2O emission, but cause temporary N immobilisation which reduces early N availability for the following crop (Huang et al. 2004; Sanz-Cobena et al. 2014).

Cover crops depleting soil mineral N and characterised by a slow N release after biomass incorporation result in a pre-emptive competition towards the subsequent crop (Thorup-Kristensen 1993), i.e. they temporarily immobilise soil N, so that it is not immediately available to the cash crop (Campiglia et al. 2014a, b). The consequent increase in the soil N stock would result in improved long-term fertility but this is hard to be quantified and perceived by farmers. For this reason, green manuring is often considered only for its potential use in alternative to fertiliser N and the green manure efficacy is evaluated in terms of actual N availability to the subsequent cash crop.

Both the total N supply and the N effect from green manures may vary much depending on species, soil and climate conditions, and the cultivation technique.

3.2 Choice of Cover Crop Species

An efficient cover crop should guarantee rapid establishment (Hashemi et al. 2013) and fall-winter growth, should develop a wide and deep root system (Thorup-Kristensen 2001; Vos and Van der Putten 1997), should be frost resistant and, if used for green manuring, should have N fixing ability (Brandsaeter et al. 2008; Möller et al. 2008; Thorup-Kristensen et al. 2003) and biomass mineralisation rates adequate to meet the subsequent cash crop requirements (Brennan et al. 2013; Justes et al. 2009).

These features depend primarily on the species (Brandsaeter et al., 2008; Brennan and Boyd, 2012a, b; Cherr et al. 2006a; Justes et al. 2009; Ramirez-Garcia et al. 2015).

Legumes Legume species have N fixing ability thus their N accumulation is not limited by the soil N availability as happens to the non-fixing species (Caporali et al. 2004; Cazzato et al. 2003a; Ledgard and Giller 1995; Peoples et al. 1995). Thus, crops specifically grown for green manuring generally include legume species, which can supply relevant amounts of N, a major portion of which is Ndfa. Considering the wide literature on this topic, green manure legumes accumulate in the above-ground biomass from less than 100 to over 300 kg N ha^{-1}, with Ndfa accounting for between 50 and 80%, depending on species and growing conditions (Benincasa et al. 2008; Brandsaeter et al. 2008; Thorup-Kristensen et al. 2003). A further 10-20% of N is contained in roots (Cazzato et al. 2003b; Choi et al. 2008; Khan et al. 2002). Moreover legume species provide biomass with low C/N ratio, leading to fast N release after incorporation and positive N effect already in early growth stages of the subsequent cash crop. For this reason, the N supplied by green manure legumes is released quickly and may even approximate the availability of mineral fertilisers, at least in mild spring environments (Seo and Lee 2008). In an experiment in Central Italy, Benincasa et al. (2010) found an N effect from incorporated pure vetch biomass at maize shooting similar to that observed with urea at the rate of 300 kg N ha^{-1}. On the other hand, there may be the case that the release of green manure N occurs to quickly (i.e. 3–6 weeks after incorporation), so that long season vegetables may experiment N deficiency at later growth stages (Gaskell and Smith 2007). Legumes are less efficient than non-legumes in preventing N leaching and generally more cold sensitive, thus they are characterised by slow winter growth and possible frost damages.

Grasses Most of gramineous species, like cereals, guarantee good establishment and continuous growth in winter (Thorup-Kristensen 2001). Their roots have good soil exploration and thus may absorb most of the N present in the soil. However, the high C/N ratio of the biomass causes very low mineralisation rates and may also cause immobilisation of soil N. Therefore these species generally cause high pre-emptive competition and low or even negative N effect to the following cash crop in particular during early growth stages (Campiglia et al. 2014a, b). Nonetheless, their ability to concentrate N in the topsoil after incorporation, maybe important for shallow-rooted low-N-demanding vegetables like onion, leek and lettuce (Thorup-Kristensen 2006b).

Crucifers Except for N fixing abilities, many crucifers cope with desired features of cover crops, provided frost resistant varieties are used and sown at due time (late summer-early autumn in many temperate climates) to grow enough to tolerate winter frost (Pace and Benincasa 2010). They have fast and deep root penetration (Dean and Weil 2009; Kristensen and Thorup-Kristensen 2007) and fast mineralisation after incorporation. The daily uptake rate of these species can reach 3–4 kg N ha^{-1} (Benincasa et al. 2010; Vos and Van der Putten 1997), so an active growth of few weeks may lead to substantial reduction of soil mineral N. The catching of N from deep layers is of great importance as it represents the easier leachable portion of the N pool in the system (Gabriel et al. 2012; Kramberger et al. 2009) and can be exploited to recover N not intercepted by shallow rooted crops (Thorup-Kristensen 2006a). The mineralisation rate of crucifer biomass is generally high, in agreement with its low C/N ratio (Ramirez-Garcia et al. 2015).

Mixtures Based on differences between species, increasing interest has been delivered to cover crops mixtures, proven by the increasing number of scientific papers and research projects produced on this subject in the latest years (Malezieux et al. 2009; Miao et al. 2011). The basic principle of intercrops is that companion species should have complementary ecological niches so that they can better exploit available resources (Vandermeer 1989). In particular, adopting mixtures between legumes and non-legumes can be an efficient tool to merge the advantages of the single species in the cover crop practice (Boldrini et al. 2006; Rannels and Wagger 1996). The mixtures are as efficient in absorbing soil inorganic N as non-legumes cover crop (Hauggaard-Nielsen et al. 2003; Kramberger et al. 2013; Thorup-Kristensen 2001; Tosti et al. 2014), but, at the same time, they add substantial quantity of N to the system (Brennan et al. 2010; Rannels and Wagger 1996), because of facilitative interactions (Benincasa et al. 2012; Hauggaard-Nielsen and Jensen 2005; Jensen 1996; Ofori and Stern 1987; Tosti et al. 2010). In intercrops, the legume is not N-limited and, in addition, the N fixation is enhanced by the soil N depletion caused by the non-legume companion, while the non-legume species can take advantage from the N releases by legume roots as root exudates (Fan et al. 2006; Paynel et al. 2001; Wichern et al. 2008). Moreover, in intercrops, species that do not overcome winter when grown by themselves can benefit by being planted with a nurse species (Creamer et al. 1997) and, as a result, total biomass accumulation, and in some cases also N accumulation, may be higher than in monocultures. Biomass composition is also affected by intercrops, with values of C/N ratio between those of companion species (Rannels and Wagger 1996). This may represent a tool to modulate N mineralisation rate and thus N availability for the subsequent crop (Boldrini et al. 2006; Tosti et al. 2012). In few words, cover crop mixtures between legume and non-legume species represent a “buffered system” in itself, able to guarantee stable N accumulation and adequate N availability for the subsequent crop, and a “buffering system” for the agro-ecosystem, able to prevent N leaching in the fall-winter (Tosti et al. 2014).

3.3 Cultivation Technique of Cover Crops

Besides the species, the cultivation technique may greatly affect the cover crop service.

Sowing Date Each species/cultivar has its own optimal sowing date for a certain climate and if this cannot be respected, an alternative species should be chosen.

Moreover, in intercrop, companion species should be chosen having similar sowing dates or a compromise should be adopted to avoid that one species prevails on the other. The crop should be established as soon as possible after the harvest of the previous cash crop in order to guarantee a timely interception of soil residual N. Undersowing the cover crop before the harvest of a previous cash crop may give some technical advantages (Bath 2001; Kolota and Adamezewska-Sowinska 2013), but can hamper the cash crop harvest and depress its yield due to competition (Chase and Mbuya 2008).

Sowing Density The sowing density may affect biomass accumulation and weed suppression, but the higher it is, the higher is the cost of the seed. Benincasa et al. (2010) found that halving the usual seed rate of hairy vetch in pure stand did not reduce biomass and N accumulation. The proportion of seed rates of companion species in intercrops can affect their biomass proportions at killing date, although soil and weather conditions may greatly alter this proportion by promoting or hampering the growth of one species with respect to the other (Tosti et al. 2012).

Termination Date The termination date represents a powerful tool to modulate total biomass and N accumulation and the C/N ratio of incorporated biomass (Alonso-Ayuso et al. 2014). The earlier the killing date, the lower the N leaching prevention and the total biomass and N accumulations. The risk of N leaching with early incorporation in winter is further increased by the fact that N can be released also at low temperatures (Magid et al. 2001). On the other hand, a late killing date increases the C/N ratio, thus causes low and shallow N availability in the soil (Bath 2000), and shorten the time interval before the cash crop establishment (Cherr et al. 2006b) with consequent risks of a non-timely seedbed preparation for the subsequent cash crop, especially in clay soils and rainy climates. Thus a compromise is generally necessary especially in vegetable systems where it may be crucial to avoid disrupting the planting schedule.

Late termination could also inhibit the vegetable root growth due to different causes: inhibitory substances contained in the cover crop biomass, lack of oxygen consumed for biomass demolition, development of diseases (Bath 2000; Skinner et al. 2012).

The choice of winter hardy or winter killed cover crop species has been hypothesised as a means to regulate the cover crop termination date. For example, when the cash crop requires an early sowing the use of a non-overwintering cover crop could be considered a natural way of terminating cover crops, saving herbicide application or ploughing (Brandsaeter et al. 2008; Thorup-Kristensen et al. 2003). However this strategy is risky when considering that winter frost might occur very early so minimising both the N catching effect and the N supply to the following crop. In practice, its adoption can be hypothesised only when the following vegetable crop is a deep-rooted one (Thorup-Kristensen 2006a, b).

Termination Modality Concerning the modality of cover crop termination, plough or disk biomass incorporation is more and more replaced by shallower incorporation or mulching, in agreement with one of the major principles of conservative agriculture (Hobbs et al. 2008; Hoyt 1999).

In case of no-tillage, several systems have been investigated in alternative to the incorporation into the soil of the cover crop biomass (Canali et al. 2013; Luna et al. 2012; Montemurro et al. 2013). Except for frost killing, the crop may be terminated by using herbicides (only in conventional systems) or by mowing and/or chopping plants, or roller-crimping plants, and the residues can be left on the soil surface as organic dead mulches (Campiglia et al. 2014a; Montemurro et al. 2013; Teasdale et al. 2008). The placement of cover crop residues on the soil surface in no-tillage systems contributes to the accumulation of organic matter in shallower soil layers, so increasing soil organic carbon, biota mass and activity, and biodiversity (Mäder et al. 2002; Nair and Ngouajio 2012) in the layer where these factors are more effective for ameliorating soil properties (Alvear et al. 2005; Boulal et al. 2008; Hobbs et al. 2008; Madari et al. 2005; Sturz and Christie 2003; Verhulst et al. 2011). The soil under the mulch is cooler and wetter than without mulch (Hoyt 1999; Leavitt et al. 2011) and this, together with the lack of biomass incorporation affects the mineralisation process, which results in a slower N release (Campiglia et al. 2010a, 2014a, b; Sainju et al. 2002). The effect of this depends on the environment and the crop. In tropical and sub-tropical climates it may be beneficial (Branco et al. 2013; Thönnissen et al. 2000; Wang et al. 2009), while in temperate climates, this causes delays in soil warming in spring and delays in vegetable establishment (Alliaume et al. 2014; Boulal et al. 2012; Leavitt et al. 2011), especially for species with transplant roots requiring high soil temperatures, like melon (Tittarelli et al. 2014). This also may have effects on vegetable nutrition depending on the cycle length and the cultivation period. The expected N recovery should be low in short season vegetable crops grown in spring, high in full-season vegetable crops grown in summer. The rooting depth of the vegetable may also play a role on this (Thorup-Kristensen 2006b), but this might result combined with the effect of increased root exploration in shallower soil layers. Finally, mulching mitigates greenhouse gas emission and N volatilisation (Abdalla et al. 2014; Fontanelli et al. 2013), and has smothering effect on weeds (Campiglia et al. 2010b; Canali et al. 2013; Leavitt et al. 2011; Steinmaus et al. 2008).

In recent studies, the above-ground biomass of different winter cover crops placed in strips as organic dead mulches in no-tillage systems has been proposed as a means for N supply and yield improvement of summer crops like processing tomato, sweet pepper and melon (Campiglia et al. 2010a, 2014b; Canali et al. 2013; Stagnari and Pisante 2010).

The no-tillage termination may imply regrowth of the cover crop which compete with the cash crop. For this reason, this modality of termination should be adopted only with cover crop species showing negligible regrowth after mowing, as it is for hairy vetch (Campiglia et al. 2010a).

Compared to the mulching/no-tillage strategy, shallow incorporation with minimum tillage practices is a less conservative technique, but gives advantages for the subsequent crop establishment and enhances biomass break-down and N availability (Hoyt 1999).

Strip tillage, which is widespread in the USA and has been more recently proposed also in Europe (Morris et al. 2007; Trevini et al. 2013) is a good compromise between no-tillage and minimum tillage. Different results have been reported depending on the green manure crop, the killing date, the use of fertiliser supplementation and herbicides to manage the strips throughout the growing season, and the subsequent vegetable crop (Brainard and Noyes 2012; Delate et al. 2008).

The spatial arrangement of green manure biomass after killing may be crucial for the N recovery of wide spaced vegetables and should be evaluated in the frame of conservative tillage practices. Broadcast incorporation of green manure biomass is expected to be not adequate in wide spaced crops especially in case of shallow rooted species because in early growth stages roots are not able to intercept N far from the row and later on they are not able to recover the N leached in deep layers. Strategies to increase N recovery in this cases could be the use of cover crops with higher C/N ratio (e.g. by using mixtures of legumes and non-legumes) or the use of mulching instead of incorporation, both for slowing the N release (Thorup-Kristensen 2006b). However this can be proposed for low-N-demanding vegetables like onion and lettuce, while it would limit the initial growth of high N demanding crops (Thorup-Kristensen 2006b). Another strategy could be represented by a first strip incorporation along the future vegetable crop row followed by a between-strip incorporation some weeks later (Bath 2000). This author found that delaying red clover incorporation between leek rows by 2–4 weeks after leek plantation caused lower N availability in early leek stages because of prolonged red clover N uptake that counteracted the effect on better synchronisation of N supply.

Interaction with Localised Irrigation and Fertigation Drip irrigation in wide spaced vegetables may enhance the problem of the inefficient uptake of green manure N incorporated broadcast, because localised soil wetting may promote limited soil exploration by roots, especially under high irrigation frequencies and low water volumes (Segal et al. 2006; Silber et al. 2003). On the other hand, fertigation with drip systems can represent a tool to mitigate the effects of either the temporal or spatial lack of matching between nutrient release from incorporated green manure biomass and the nutrient demand of the wide spaced vegetable (Farneselli et al. 2013b; Tei et al. 2015). In early growth stages fertigation can deliver nutrients close to vegetable rows and integrate nutrient release from green manure biomass according to green manure biomass composition and season weather.

Economic Aspects Overall, the use of cover crops for green manuring implies some complication in the vegetable cropping schedule, but may allow an efficient and reliable management of soil fertility especially in organic stockless systems, where it results more economically sustainable than the use of most organic fertilisers (Gabriel et al. 2013). Some evidences from Central Italy (Boldrini et al. 2006; Guiducci et al. 2004) demonstrated that, taking into account the seed and the sowing and killing operations, the cost of the kilogram of N from good green manures (those accumulating more than 200 kg N ha^{-1}) may be 2–3 times higher than that of urea, but is much lower than that of pelleted poultry manure allowed for organic farming.

4 Intercropping Vegetables

Intercropping vegetables is another strategy that may contribute to their nutrient availability. Intercrops may be instantiated for either spring-summer or fall-winter vegetables. In temperate regions, the latter seem to be more justified for a fertility management purpose (Yildirim and Guvenc 2005), while nutrient availability for spring-summer vegetables can be efficiently managed by fall-winter green manures, as discussed previously. Intercrops may be grown between two cash vegetables (Unlu et al. 2010) or between a vegetable and a non-vegetable species working as living mulch (Chase and Mbuya 2008; Kolota and Adamezewska-Sowinska 2013). The intercropping period may last for the whole growing cycle or may be temporary, limited to a part of it (Chase and Mbuya 2008; Kolota and Adamezewska-Sowinska 2013). It may be the case of temporary intercrops between a vegetable cash species and a legume that works as gregarious, for green manuring purpose, i.e. grown to be terminated at an intermediate stage of the vegetable cycle to relay the accumulated N. This strategy may be also efficient for weed control between vegetable rows especially if the living mulch is mowed and left as soil cover, unless the living mulch competition towards the main vegetable is greater than that of weeds (Chase and Mbuya 2008; Lotz et al. 1997).

The interaction between companion species implies facilitation and competition effects which can be quantified by dedicated parameters (e.g. land equivalent ration, LER; relative yield total, RYT; etc.) (Malezieux et al. 2009; Weigelt and Jolliffe 2003). In particular, the total yield of the intercrop is expected to be higher than that achievable in the unit area by each of the species grown in pure stand, but on the other hand, each species is more widely spaced than normal so it will yield less than it would if it was cultivated on the whole unit area. This is undesirable if only one of the companion species is the vegetable cash species (Thorup-Kristensen et al. 2012). As already discussed for green manures, also in intercrops the fertility building component represents an unproductive phase and thus should be limited to a minor portion of the whole system (Watson et al. 2002). Moreover, intercropping implies complications in cultivation operations (plantation, fertilisation, protection, harvest), especially if the coexistence of species lasts for the whole growing cycle and companion species are both cash ones, while this can be a minor problem in case of temporary intercropping with an understorey species used as living mulch (Chase and Mbuya 2008; Kolota and Adamezewska-Sowinska 2013). The implications of this last case are similar to those discussed for strip green manure termination.

5 Crop Residue Management

Vegetable crop residues are often abundant and rich on nutrients (Fink et al. 1998; Moreno-Cornejo et al. 2014) and thus represent a key-tool to manage soil fertility in the frame of a rotation. One of the main features of most vegetable residues is the high amount of N, which is due to high fertilisation rates and the low C/N ratio and content of cell wall compounds, and to harvest carried out before the end of the biological cycle. This, together with the high residual mineral N left in the soil (Benincasa et al. 2011; De Neve and Hofman 1998; Tei et al. 1999) leads to high risk of N loss by leaching and volatilisation in humid environments (Agostini et al. 2010; Rizhiya et al. 2011). A rapid sequence of cash crops mitigates this risk, but there may be the case that residual N so far exceeds early and or total needs of the newly implanted crop.

The management of vegetable residues has been exhaustively reviewed by Agneessens et al. (2014) and is briefly reported here. In alternative to broadcast incorporation of crop residues into the soil, several alternatives can be adopted. Crop residues can be mown and left on the soil surface while the below ground plant portion remains undisturbed and able to resprout, so working as a cover crop. This results in a slowed N release from above ground residues and in an efficient N catching by the resprouted crop, because no time is lost to implant a new catch crop. Strip tillage may allow combining this practice with the need to establish a new cash crop (Trevini et al. 2013). This would represent a way to establish a temporary intercrop, a sort of relay between the old and the new cash crop (Delate et al. 2008), with the advantage (compared to normal intercrops between two cash crops) that only the new crop is cared, regardless of the old one. The resprouted crop and its residues could be then incorporated into the soil later on, depending on weather conditions and N management options.

Mixing the N-rich residues with N-immobilising materials such as cereal straws, composts and saw dust may help to immobilise soil N in view of a rainy season, but this practice has to be further explored and fine-tuned, because then mineralisation should restart at due time and rate not to hamper the growth of the subsequent cash crop (Agneessens et al. 2014).

Another way to intercept and recycle nutrients released from vegetable residues is growing catch crops (Agneessens et al. 2014). Among the aspects of cover crops previously examined, in the case of vegetable residues the seedbed preparation and the sowing date represent the major factors affecting the catch crop efficiency, because any delay will result in a relevant N loss. Conservative tillage techniques, like minimum tillage and no-tillage may help (Stagnari et al. 2009).

Finally, residues can be removed from the soil to prevent temporary N surplus and in the meanwhile they can be used in feeding animals, composting, or bio-digesting for bioenergy production (Agneessens et al. 2014). In all these cases, the by-products of these processes can be returned to the soil at due time as manures. However, the economics of manipulation and transport of such a bulky material has to be considered in the evaluation of the actual feasibility of this strategy.

6 Crop Rotation in Non-specialised Organic and Conventional Farming Systems

Organic systems differ from conventional ones because the formers cannot rely on chemicals for fertilisation and crop protection (Gomiero et al. 2011). Thus the improvement of self-sufficiency, which is recommendable in any system, is crucial for organic systems, and crop rotation may represent a main tool to achieve this goal. This implies that organic systems should be developed according to an *ad hoc* design (Altieri and Rosset 1996), avoiding the simplistic approach of the so-called conventionalisation of organic agriculture (Darnhofer et al. 2010), where, for example, organic fertilisers and green manures are used as surrogates of mineral fertilisers. Concerning nutrients, however, the self-sufficiency in stockless farms can be achieved only for N, which can be derived from the atmosphere, while all the other nutrients need to be restored by external inputs. Moreover, both organic and conventional systems need to improve the use efficiency of all nutrients, either to reduce external inputs or to limit environmental impact (Tuomisto et al. 2012). Therefore, crop rotations should be examined under both N self-sufficiency and nutrient use efficiency.

An example of organic vegetable crop rotation specifically conceived to pursue self-sufficiency in N was designed by Thorup-Kristensen (1999, 2002) for the northern Europe environment. This rotation alternates green manure crops (grass clover, fodder radish, cabbage residue left in the field after harvest), several vegetable crops differing for N requirements and root depth (cabbage, leek, onion, carrot), a grain legume (green pea) and a cereal (barley), in a sequence that is expected to build up N, take it up efficiently, and minimise losses. The timing of green manure establishment and incorporation and some other expedients may help increase N management in the rotation: thus, for example, undersowing the grass clover in a barley crop guarantees continuous ground cover and enhance green manure crop growth; leaving the cabbage residue grow after cabbage harvest allows continuous ground cover and catching of residual N; incorporating the grass clover in autumn may be adequate for a deep-rooted crop like cabbage to be transplanted in spring, because the vegetable can recover the N from deep soil layers, while in case of a shallow-rooted crop like leek, the green manure has to be incorporated at the end of winter, closer to the time of transplanting in order to allow the vegetable absorb N before it is leached towards deeper layers (Bath 2000, 2001; Thorup-Kristensen 2006b); after green manure incorporation, high N demanding vegetables should come first, while low N demanding vegetables may be grown later, using the residual N availability; grain legumes may be used to restore a certain N availability (Poltronieri et al. 2013) while avoiding to use great part of land for green manures.

In the long-term, such a system would become deficient for other nutrients such as phosphorus (P). Rotating crops with different root depths may allow to recover and recycle P and other nutrients (Sylvain and Thomas 2013) as well as incorporating biomass with different composition may affect microbial community composition (Nair and Ngouajio 2012) and enhance the activity of enzymes involved in the release of nutrients like P (Boldrini et al. 2008; Elfstrand et al. 2007), although Keller et al. (2012) obtained no indication that the greater microbial activity of the organic systems resulted in a mobilisation of stable P forms.

In any case, in the long term, macronutrients like P must be necessarily supplied from external sources to avoid progressive soil depletion (Berry et al. 2003; Oehl et al. 2002; Oelofse et al. 2010). For this reason external inputs are necessary at least to reintegrate the contents of P and other nutrients not derivable from the atmosphere (Biswas and Narayanasamy 2006; Morra et al. 2010; Nelson and Janke 2007; Ozores-Hampton 2012). The use of external inputs can be minimised by adopting strategies that can increase the use efficiencies of nutrients other than N (Schröder et al. 2010; Sylvain and Thomas 2013; Veneklaas et al. 2012). In fact, the overuse of amendments and fertilisers can cause losses to the environment also for nutrients other than N. This is important for P, both for the high impact of P losses to the environment (Ozores-Hampton 2012; Sylvain and Thomas 2013) and because P rocks represent a limited and non-renewable resource (Biswas and Narayanasamy 2006; Jordan-Meille et al. 2012; Van Vuuren et al. 2010). For example the P use efficiency may be increased by using cultivars with high uptake efficiency (Walker et al. 2006). Moreover, P bioavailability can be increased by amendments (Walker et al. 2006) or green manures (Rick et al. 2011) or by adding phosphorites to composting materials (Nishanth and Biswas 2008).

Strategies to increase self-sufficiency for nutrients cope with those needed to increase nutrient use efficiency. As far as the N is concerned, there are two main tools that allow to increase the nitrogen use efficiency (NUE) of the rotation as such: the use of catch crops in fall winter and the use of deep-rooted vegetable crops (Thorup-Kristensen 2002) to be alternated to shallow-rooted vegetables, which are not able to take up N from deep soil layers.

The use of catch crops is very effective for vegetable crops leaving very high amounts of N after harvest. Rye and fodder radish were used by Nett et al. (2010) to recover the high amount of N left by a cauliflower crop. However only a small part of the recovered N was available to the following beetroot crop, because the mineralisation rate of incorporated biomass was very low, especially for rye. As an overall conclusion, authors found that in ¾ of cases, these cover crops resulted in a decreased N availability for the following cash crop as compared to fallow. However crop rotation represents a major strategy to compensate for possible low efficiencies in the use of nutrients supplied by green manures (Crews and Peoples 2005). So for example the N supplied by green manures can be exploited by the second or third vegetable crop of the sequence (Campiglia et al. 2014a). Nett et al. (2011), in a more comprehensive study based on data from several locations and experiments, found that the application of cover crops in a vegetable system compared to fallow reduced the N balances surplus, but this reduction was moderate, accounting for only 13 kg N ha^{-1} on an overall average.

As far as the cultivation of cereals is concerned, Nendel (2009) demonstrated that vegetable rotations that include cereals are the most efficient N users. Thorup-Kristensen (2010) proposed to use minimally fertilised cereals to "clean up" N left by vegetable crops. This is particularly important when the cereals follow shallow-rooted, short-season crops like lettuce.

It is worth to remind here that, to improve the N use efficiency of the system and limit N losses, all the best management practices, besides rotations, should be adopted (Nendel 2009) starting from avoiding overabundant N inputs either in conventional or in organic systems (Agostini et al. 2010; Benincasa et al. 2011; Schmutz et al. 2008; Tei et al. 2015). It should be considered that in many cases, the comparably high N rates used for vegetables are not compensated for by any yield increase. Buckland et al. (2013) did not observed any decrease of onion yield when reducing the usual N rate by 2/3. The effect of an overuse of fertilisers varies with local soil and climate characteristics, because for example the risk of N leaching is higher with sandy soils and rainy climates (Nendel 2009). For some vegetables, excessive N supply can even result in marketable parts becoming unmarketable by developing disorders, such as hollow stems, fuzzy curds or black midribs (Nendel et al. 2009).

Since it is practically impossible to test all management options and crop rotations at the farm level, models are needed to design and evaluate rotations and estimate inputs and outputs of the system (Dogliotti et al. 2004). As reported by Nendel et al. (2013), most of the models applied to vegetables in rotations were not designed for specific conditions and peculiarities of vegetable production. On the contrary, the EU-Rotate_N model was developed (Rahn et al. 2007, 2010) to help customizing the most rational crop rotation to effectively manage soil N fertility in vegetable production. The model considers crops differing for growing period and cycle length, and takes into account plant root system (extension, length, depth and distance from the crop row), above ground growth and N uptake (biomass and N accumulation and partitioning between marketable yield and residues), weather factors (rainfall, temperature, radiation), soil properties (hydrological parameters, pH, organic matter content) and thus water and N flows in the soil-plant-atmosphere system. Moreover, Rahn et al. (2010) pointed out that, differently from other models applied to vegetable systems, the EU-Rotate_N model considers also economic aspects of rotated crops (crop yields and farmer income, and related and non-related costs), and thus it represents a useful support system for both farmers and policymakers. The EU-Rotate_N model has been demonstrated to work well for non-specialised rotations in the Northern Europe environment (Schmutz et al. 2008; Rahn et al. 2010).

Several studies have investigated the effect of crop rotations on soil fertility for vegetables in organic and conventional systems, but few of them are long-term comprehensive studies with crops repeated over many years to account for inter-annual variation of effects.

Thorup-Kristensen et al. (2012) used a mixed rotation with cereals (oat, rye) and vegetables (onion, carrot, lettuce, fodder radish, white cabbage), to evaluate one conventional system (C) and three organic systems, one based on livestock manure (O1), the other two based on cover/green manure crops for the management of N fertility: of these latter two, one was based on complete green manure killing and broadcast biomass incorporation (O2), the other on cover crops strip incorporation in correspondence with vegetable rows while leaving cover crop growing between the vegetable rows as intercrop (O3). The authors reported that main differences were not recorded between conventional and organic systems but between systems relying on fertilisers (i.e. both the conventional and the organic based on livestock manure) and those based on cover/green manure crops. In the latter, the authors observed greater soil exploration by roots, especially in deep layers, and thus higher uptake of soil mineral N and lower N leaching. Growing cereals as part of the vegetable rotation allowed improving N husbandry. However, based on nutrient balances, it comes out clear that O2 and O3 will be limited in the long term period by P and K depletion.

Farneselli et al. (2013a, 2015a) reported results concerning a long term comparison between an organic and a low-input conventional system, where vegetables (processing tomato and melon) have been rotating with other crops (winter and summer cereals, winter and summer grain legumes) since 1998. In the low-input conventional system authors use chemical fertilisers in agreement with the EU regulation 2078/92 and updates, in the organic system they use green manures in case supplemented with allowed organic fertilisers (poultry manure, leather by-products). In this comparison, average organic vegetable yields were not much lower but more variable across years than conventional ones, because the amount of N supplied by green manures and the timing of N release from incorporated biomass not always met cash crop N requirement. In terms of N use efficiency, tomato resulted more efficient in the organic than in the conventional system, while the opposite was for melon. The authors explained this evidence with the spatial lack of matching between N release from green manure biomass and early N demand of melon. Unlike tomato, melon is a very wide spaced crop (0.5 plants m^{-2} in rows 2 m apart, vs. 3 plants m^{-2} in rows 1 m apart for processing tomato) and its roots have slow and shallow growth. Therefore, the crop in early stages is less able than tomato in intercepting the N released by green manure biomass incorporated broadcast and later on is not able to recover N probably transported in deep layers by rainfall and irrigation. The authors also underlined that green manures in some years supplied even more nitrogen that needed and this also caused lower crop NUE compared to the conventionally grown crop were the N rate was decided year by year according to the need. In fact, despite the higher apparent N surplus of the organic system, the total soil N content at the end of the first six-year rotation did not differ in the two systems (Boldrini et al. 2007). Thus, growing cereals in fall-winter after vegetables was considered a key strategy to keep the residual N in the soil in both systems (Farneselli et al. 2013a, 2015a).

7 Crop Rotation in Specialised Vegetable Cropping System

Crop rotations described in the previous section are all conceived for non-specialised vegetable farms. In specialised vegetable farms, no room is generally available for winter cereals and also cover/green manure crops are often neglected to minimise the unproductive fertility building phases. Thus, specialised vegetable systems necessarily rely on fertilisers (Caturano et al. 2008), and indeed, more than self-sufficiency they should pursue high nutrient use efficiency and low environmental pollution.

Nendel (2009) demonstrated that pure vegetable rotations, with up to three crops per season result as the highest emitters of N losses. The N loss is particularly high in case of organic fertilisers and amendments (Morra et al. 2010, 2013; Song et al. 2009). Thus, strategies need to be developed to improve nutrient management in specialised vegetable farms (Ren et al. 2010). As for non-specialised farms, the nutrient use efficiency of the system can be achieved by both increasing the use efficiency of each crop and the use efficiency of the rotation as such.

Strategies to increase the nutrient use efficiency of single crops have been already mentioned (see Sect. 2) and consist of appropriate combinations of rate, type, method and timing of fertiliser (and water) application, based on accurate evaluation of crop nutrient availability compared to the requirement at any growth stage (Agostini et al. 2010; Nendel 2009; Tei et al. 2015). In most cases, nitrogen use efficiency can be appropriately increased by combining organic amendments and mineral fertilisers. In fact, the formers increase soil organic matter which enhances soil N retention capacity, while mineral fertilisers may help supply available N in the short term (Evanylo et al. 2008; Morra et al. 2013). Moreover, water management is also crucial to increase N use efficiency and reduce N loss (Mao et al. 2003). Models have been used to simulate water and N dynamics and growth of single vegetables under different water and fertiliser management (Gallardo et al. 2009; Rinaldi et al. 2007; Zhang et al. 2009; Hu et al. 2010).

The nutrient use efficiency at the rotation scale can be increased by appropriate sequence of vegetable crops. The EU-Rotate_N model has been applied to different specialised vegetable rotations in the Mediterranean environment (Nendel et al. 2013) and has been found to work well, except for some crops like fennel that need a more appropriate parameterization. Authors observed that if a same crop may be implanted in autumn or spring it may result in a different use of N depending on the growing season (Nendel et al. 2013). This should be considered in intensive vegetable farms, where the crop sequence may vary to allow for off-season production.

A long-term comparison between an organic and a conventional specialised vegetable rotation including 6 cash crops (tomato, melon, fennel, lettuce, cauliflower and bean) was reported by Campanelli and Canali (2012). In both systems, most of the nutrient input was supplied by fertilisers, but the organic system included also three fall-winter green manures: hairy vetch to support growth and yield of a high N demanding crop like tomato; barley to intercept the high residual

N left by tomato and because winter cereals are recommended to forerun melon; radish to recover N in deep soil layers left by fennel and because the low C/N ratio of its biomass allows a fast release that was expected to (but did not completely) meet the requirement of a short-cycle vegetable like lettuce. Despite overall off-farm nutrient inputs in the organic system were lower than in the conventional system, average crop yields were similar in the two systems except for lettuce and bean which yielded less in organic. On the other hand, in four years the soil organic C increased by 37% and total N by 22% compared to the conventional system. This should also guarantee long-term nutrient availability and crop yields in the organic system (Moccia et al. 2006).

Despite the mentioned advantages of rotating crops, in much specialised intensive vegetable farms there is also the case that only one species is grown across years. The following two strategies have been observed in practice.

The first is that the crop is grown in the same field. In this case, grafted plants are often used to limit soil-borne disease and external inputs are needed for either pest and disease control or fertilisation management. Mineral and organic fertilisers represent the main tool to guarantee both adequate nutrient availability in the short term and favourable soil properties in the long term (Ren et al. 2010, 2014). Nonetheless, if the cash crop is represented by a summer vegetable, fall-winter green manure crops may be used to increase N husbandry and bio-disinfect (“bio-fumigate”) the soil (Summers et al. 2014).

The second way adopted by very specialised intensive farms to cultivate only one species over hundreds of hectares every year is to rent different fields yearly to guarantee time intervals of at least three-four years before the crop is repeated, in order to avoid soil-borne diseases (Benincasa et al. 2014). In this case, crop rotation is generally committed by the vegetable grower for the year preceding the vegetable crop and is generally aimed at reducing the risk of pest and disease diffusion, more than at managing soil fertility. In the year following the vegetable crop, the vegetable grower does not care about the crop to be cultivated but the owner of the field might be interested in valorising vegetable residues to increase soil fertility for the following crop. Thus, although crop rotation is payed less attention, it can be still taken into consideration by either the vegetable grower or the field owner in order reduce the cost of fertilisation.

Finally, it has to be at least mentioned here that nowadays specialised vegetable production is often carried out in the greenhouse. This implies specific management options and would deserve a separate dissertation. In particular, soilless systems are often used which make crop rotation not necessary. Where greenhouse crops are grown on the soil, crop rotation is still recommendable, but of course any unproductive phase needs to be avoided to limit greenhouse amortization costs. Thus fertility building crops are generally not justified unless they give additional advantages, as for example the bio-fumigation against soil-borne diseases (Michel et al. 2013; Neubauer et al. 2014). Indeed, in greenhouse crops grown on the soil, off-farm fertilisers are the main sources of nutrients, and in particular organic fertilisers represent the main tool to counteract the decrease of soil organic matter promoted by the warm greenhouse environment (Voogt 2013). Due to high temperatures and air humidity typically maintained in greenhouses, organic matter (soil organic matter, crop residues and organic fertilisers) mineralises rapidly, which should be taken into account to guarantee an adequate supply and use of nutrients, with particular attention to N, the loss of which may be important in the greenhouse production (Tian et al. 2010, 2011). In greenhouse production systems where the latest technology is not at hand, fine-tuning of irrigation and N fertilisation in combination must be paid attention to. The use of flood or furrow irrigation in simple greenhouses causes intensive nutrient washing, which is often directly compensated for by applying another high fertiliser dose. This practice is reason to large environmental problems due to nitrate leaching in greenhouse production areas and irrigation management is often the key to optimise N use efficiency (Song et al. 2009). The EU-Rotate_N model has been used with this aim for greenhouse systems considering a whole rotation (Guo et al. 2010) or single species like cucumber (Sun et al. 2012) and tomato (Soto et al. 2014; Sun et al. 2013).

8 Conclusions

Rational rotations contribute to improve the nutrient use efficiency and pursue the self-sufficiency for nitrogen in vegetable production, which is a main research subject. The species to sequence should be chosen appropriately, considering their growing season and cycle length, root depth, nutrient extraction ability and N fixation, nutrient requirement and return to the soil with crop residues. Based on these aspects, the rotation should be designed allowing each crop to use most of the nutrient rate within its own growing cycle and to recover residual nutrients (in particular N) by a suitable subsequent crop. The adoption of cover crops/ green manures and the appropriate management of crop residues may be functional to these aims, although the amount and timing of nutrient release from these sources not always match the demand of the subsequent vegetable crop.

The convenience and the operational margins to follow these guidelines depend on the farm context, on whether the vegetable system is conventional or organic, specialized or not specialized, stockless or not. In stockless vegetable systems, which are common worldwide, the self-sufficiency for non-N nutrients cannot be achieved and thus mineral or organic off-farm fertilisers are necessary anyway in the long term, although well designed rotations may improve the nutrient use efficiency and thus reduce the need of nutrient inputs. Organic fertilisers supply all nutrients, nitrogen included, thus in the vegetable systems where they are used, in particular in the organic systems, part of the N necessary to vegetables is often supplied by these fertilisers. Based on this fact, perhaps it should be accepted that achieving the complete self-sufficiency for nitrogen might be not crucial and that a limited amount of N can be reasonably supplied with fertilisers. This little N supplementation from mineral or fast-release organic fertilisers delivered with rational fertilisation techniques (e.g. starter, split, and localised fertilisation;

fertigation), could help compensate the temporal and spatial lack of matching between N release from slow-release organic sources and crop N demand. In general, it would help modulate nutrient supply in a more flexible way and improve crop nutrient uptake, so allowing more constant yields across years and limited risks of nutrient loss to the environment. After all, it is by integrating all the available techniques of soil fertility management at a whole rotation scale that it is possible to contribute to the productive, economic and environmental sustainability of the system.

Glossary

N Nitrogen
C Carbon
P Phosphorus
K Potassium
NH_3 Ammonia
NOx Nitrogen oxides
N_2O Nitrous oxide
C/N C to N ratio
Ndfa Nitrogen derived from the atmosphere
Neff Nitrogen effect
Nupt Nitrogen uptake
NUE Nitrogen use efficiency
GHG Green house gas
LER Land equivalent ratio
RYT Relative yield total

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Localized Application of Fertilizers in Vegetable Crop Production

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Abstract Localized applications of fertilizers are alternatives to broadcast applications across the entire field surface for economic, environmental and technological reasons. These alternative methods are the modified broadcast method, the banding application method, and the fertigation method used with drip irrigation. Beginning with the scientifically established fact that root system architecture of plants responds to fertilizer placement, this chapter covers first environmental regulation in the United States, the nutrient losses through leaching, the methods used for measuring nutrient loads, nutrient load estimates, the main factors that affect nutrient loads in field production, and some common strategies used for reducing nutrient loss (nitrification inhibitors, grafting and irrigation management). Using the vegetables grown on Florida's sandy soil as an example, the second section outlines the principles and practices for localized fertilizer applications to vegetable crop production. In commercial vegetable production, soil testing is the foundation for all sound fertility programs. The implementation of the soil-test recommendation requires (1) the selection of the proper rate, source, timing and placement of fertilizer, (2) the correct conversion of nutrient rates provided by the soil test results (N, P_2O_5 or K_2O needed on a per hectare basis) to that of organic amendments, cover crop residues or fertilizers on a length-of-row basis, and (3) custom-built, well-calibrated equipment. In commercial production, localized fertilizer applications need to be adjusted to the production system capabilities and constraints (flat ground or raised beds; direct-seeded or transplanted crop; irrigation method; and/or mulching). A well-planned fertilization program requires

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an irrigation schedule to maximize nutrient-use efficiency and yield potential while reducing the risk of nutrient losses due to leaching.

Keywords Modified broadcast • Banded fertilizer • Starter fertilizer • Fertigation • Best management practice • Leaching • Controlled-release fertilizer • Nutrient load • Lysimeter • Cover crop • Nitrification inhibitors • Grafting • Crop nutritional requirement • Standard bed spacing

1 Introduction

For economic, environmental and technological reasons, localized applications of fertilizers have emerged as alternatives to broadcast applications across the entire field surface. Despite their negative effect on soil biological cycles and the generation of gases and particulates through burning, slash-and-burn methods used widely in early agriculture and still today in some parts of the word, were the first use of inorganic fertilizer for the production of cultivated plants (Brady 1996; Palm et al. 1996). Broadcast applications of fertilizers are still used today in vegetable production for the application of liming materials, soil amendments, composts and manures. The application of nutrients through overhead irrigation systems is another form of broadcast application.

In contrast to these methods, "localized applications of fertilizer" refers to application methods that place fertilizer only on a portion of the field, typically near the seeds, the transplants or the plants. Also, localized fertilizer application may reduce nutrient losses from the areas of the field where crop roots are not present. These alternative methods to the broadcast application method are (1) the modified broadcast method (fertilizer is applied in large swaths only where the raised beds will be formed), (2) the banding application method (material is applied near the seeds or plants as starter fertilizer or banded sidedress fertilizer), and (3) the fertigation method with drip irrigation (soluble nutrients are applied to the root zone through the drip irrigation; Table 1; Figs. 1, 2, 3 and 4). Localized applications of fertilizers are used to increase the uptake rate of applied nutrients, thereby reducing the application rates, the fertilization cost and reduce the environmental impact of vegetable production. The effectiveness of fertilizer applications is measured by the Nutrient Use Efficiency (NUE).

The NUE of crop plants can be expressed as the yield of nutrient [the most studied are with nitrogen (N) and phosphorous (P)] produced by each unit of available nutrient in the soil. This NUE is usually divided into two processes: uptake efficiency (the ability of the plant to remove nutrients from the soil normally present as nitrate (NO_3^-), ammonium (NH_4^+) or phosphate ions ($H_2PO_4^-$ or HPO_4^{2-}), and the utilization efficiency (the ability of the plant to transfer the N and P to the shoot and reproductive plant parts). Improvements in NUE by vegetable crops is accomplished mainly through changes in cultural practices in the field (including fertilizer placement, timing of application and source selection, and irrigation management)

Table 1 Selected attributes of fertilizer application methods used in vegetable crop production

	Application method				
Attribute	Broadcast	Modified broadcast	Starter	Banded	Injected
Timingof application	Preplant	Preplant	At planting	Preplant or sidedress	Sidedress
Fertilizer type	Granular	Granular	Liquid	Granular or liquid	Liquid
Common nutrient content	Lime, sulfur, organic materials, composts, N, P and K for direct-seeded crops	Compost, N, P, K, Ca, Mg, micronutrients	Mostly P, some N, some K	Organic materials, compost Mostly N, P, K	Mostly N, K
Unit of application[a]	kg·ha^{-1}	kg HA^{-1}	L HA^{-1}	L HA^{-1} or kg HA^{-1}	L HA^{-1}

[a] 1 HA = linear meters of bed (or row) in one hectare at standard bed (or row) spacing

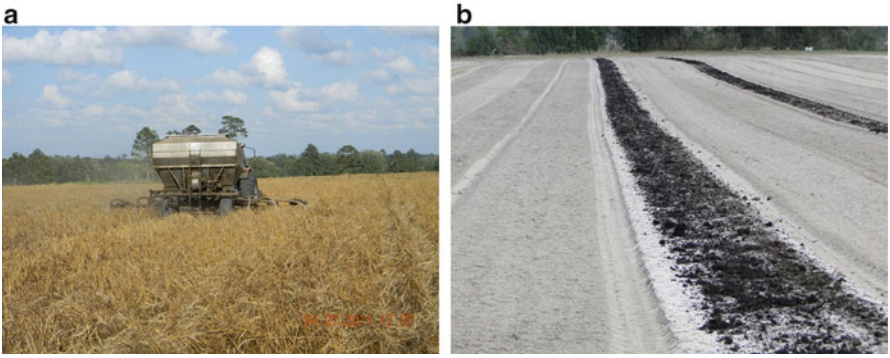

Fig. 1 Modified broadcast application of (**a**) granular fertilizer into the cover crop and (**b**) poultry litter onto bare soil. Note in (**a**) the three tubes on each side that apply fertilizer where the raised beds will be formed (Photo credits: (**a**) Joel Love, and (**b**) Robert Hochmuth)

and alterations of the architecture of the root system. Improvements in utilization efficiency may be achieved through breeding and molecular biology.

Since in this book fertilizer sources are already covered under *"Organic matter mineralizationas a source of nitrogen"*, "*Fertilizers: Criteria of choice for vegetable crops"*, and *"Crop rotation as a system approach for soil fertility management in vegetables"*, this chapter covers first general topics related to localized fertilizer applications (root response to fertilizer application, environmental regulation in the United States, nutrient losses through leaching, methods used for measuring nutrient loads, nutrient load estimates, field factors affecting nutrient loads, and strategies for reducing nutrient loss). Using the vegetables grown on Florida's sandy soil as an example, the second section outlines the principles and practices for localized fertilizer applications to vegetable crop production.

Fig. 2 Banded application of fertilizer on the bed shoulders and under the plastic mulch during the preparation of a seepage-irrigated tomato field in South Florida (Photo credit: Monica Ozores-Hampton)

Fig. 3 Banded sidedress applications of granular fertilizer to (**a**) potato (Solanum tuberosum) rows, (**b**) sweet corn (Zea mays) plants, and (**c**) sweetpotato (Ipomoea batatas) vines (Photo credits: Lincoln Zotarelli (**a**), and Robert Hochmuth (**b**, **c**))

Fig. 4 Liquid fertilizer tank mounted on a pallet, containing liquid 8-0-8 and used for the injection of N and K into the two drip irrigation systems using Mazzi injectors. Note on each system (from *right* to *left*), the back flow prevention device, the injection port, the pressure gage, the screen filters (in *red*), and the solenoid valve (in *black*; photo credit: Robert Hochmuth)

2 Root Response to Localized Fertilizer Application, the Environmental Impact of Vegetable Crop Production and Strategies for Reducing Nutrient Loss

2.1 Vegetable Crops Root Growth, Shoot Growth and Yield Response to Fertilizer Placement

Root architecture responds to fertilizer application and placement. Early work established that exposure of barley *(Hordeum vulgare)* plant roots to high concentrations of N, P or potassium (K) fertilizers caused a localized promotion of the initiation and subsequent extension of both first- and second-order lateral roots (Drew 1975; Fritsh and Nichols 1975). Since then, these results have been documented with many food crops that adjust their root architecture to low N and P conditions through inhibition of primary root growth, promotion of lateral root growth, enhancement of root hair development and cluster root formation (Garnetti et al. 2009; Muñoz-Arboleda et al. 2006; Niu et al. 2012; Zotarelli et al. 2009).

As reviewed by Lea and Azevedo (2006), some of the genes involved in NO_3 uptake include at least four different transport systems: (a) constitutive high-affinity (cHATS), (b) nitrate-inducible high-affinity (iHATS), (c) constitutive low-affinity (cLATS) and (d) nitrate-inducible low-affinity (iLATS). Two families of genes encoding NO_3^- transporters have been identified in plants: NO_3^- transporters *NRT1* and *NRT2*. In *Arabidopsis thaliana,* over 50 members of the larger *PTR* family to which the *NRT1* genes belong and seven members of the *NRT2* family have been identified. A family of five NH_4^+ transporter genes designated *AMT1;1* to *AMT 1;5* were originally identified in *A. thaliana*, which were related to cyanobacterial NH_4^+ transporters, while in tomato (*Solanum lycopersicum*), only three *AMT1* genes were isolated. Both plants had a second *AMT2* sequence more related to transporters isolated from *Saccharomyces cerevisiae* and *Escherichia coli*.

Progress in molecular biology in the last decade have identified many genes involved in root architecture response to nutrient presence in the soil, mostly with P (Beebe et al. 2006; Richardson et al. 2005). Although the response of a root system to locally available nutrients can be predicted in general terms, the precise degree and direction of growth cannot be anticipated (Robinson 1994). The mechanisms for activating alterations in root architecture in response to P deprivation depend on changes in the localized P concentration, and transport of or sensitivity to growth regulators such as sugars, auxins, ethylene, cytokinins, nitric oxide, reactive oxygen species and abscisic acid (Niu et al. 2012). In the process, many genes are activated, which in turn trigger changes in molecular, physiological and cellular processes. As a result, root architecture is modified, allowing plants to adapt effectively to the low-P environment (Niu et al. 2012; Smith and Smet 2012).

Genes that respond to P deficiency can be grouped into ‘early’ genes that respond rapidly and often non-specifically to P deficiency, and ‘late’ genes that impact the morphology, physiology or metabolism of plants upon prolonged P deficiency (Hammond et al. 2004). The use of micro-array technology has allowed researchers to catalogue the genetic responses of plants to P deficiency. Genes whose expression is altered by P deficiency include various transcription factors, which are thought to coordinate plant responses to P deficiency, and other genes involved in P acquisition and tissue P economy (Hammond et al. 2004).

Phosphorus availability and uptake by plants is enhanced by mycorrhizae. Under limiting-P conditions, plants may obtain adequate P through modifications to root architecture, carbon metabolism and membrane structure, exudation of low molecular weight organic acids, protons and enzymes, and enhanced expression of the numerous genes involved in low-P adaptation. These adaptations may be less pronounced in mycorrhizal-associated plants. The formation of cluster roots under P-stress by the non-mycorrhizal species white lupin (*Lupinus albus*), and the accompanying biochemical changes exemplify many of the plant adaptations that enhance P acquisition and use (Ramaekers et al. 2010; Vance et al. 2003).

Improvements in accessing scientific literature and computing capabilities in the last decade have made it possible to compile, analyze, and interpret many independent experiments together. This methodology is known as meta-analysis (Cochran 1954). In brief, a meta-analysis is performed on some measure of the effect of the treatment relative to the control from each trial. This so-called “effect size” standardizes the response and allows for comparisons between studies. The effect size is calculated as the ratio of experimental treatment mean divided by the control mean. Once a thorough literature search is performed, the main steps of a meta-analysis are (1) categorizing the literature (strategies and treatment definition), (2) characterization of main environment and management factors, (3) extracting variable values and building a database, and (4) performing the statistical analysis.

This methodology was used to determine mycorrhizal responses to N, P, and atmospheric CO_2 in field studies. A meta-analysis showed that mycorrhizal abundance decreased 15% under N fertilization and 32% under P fertilization, while elevated CO_2 elicited a 47% increase (Treseder 2004). Nitrogen effects varied significantly among studies, and P effects varied significantly among lead investigators. Most other factors did not affect mycorrhizal responses. These results suggest that mycorrhizal fungi levels may increase substantially under elevated CO_2, but decline moderately under P additions (Treseder 2004). Another meta-analysis concluded that mycorrhizal colonization was increased most by inoculation (29% increase), followed by shortened fallow (20%) and reduced soil disturbance (7%) (Lekberg and Koide 2005). The effect of crop rotation depended on whether the crop was mycorrhizal. Increased colonization resulted in a yield increase in the field of 23% across all management practices. Biomass at harvest and shoot P concentration in early season were increased by inoculation (57% and 33%, respectively) and shortened fallow (55% and 24%). Reduced disturbance increased shoot P concentration by 27%, but biomass was not significantly affected. Biomass was significantly reduced in 2% of all trials in which there was a significant increase in colonization. Irrespective of management practice, an increased mycorrhizal colonization was less likely to increase biomass if either soil P or indigenous inoculum potential was high (Lekberg and Koide 2005).

2.2 The Nutrient Gradient System

A practical application of Drew's findings (1975) that crops roots respond to the localized application of N, P and K is the nutrient gradient system used for vegetable crops grown with seepage irrigation (Geraldson 1970). Seepage irrigation consists of the management of a shallow water table perched on an impermeable soil layer found at the 1–2 m depth. Basic components of the gradient-mulch system include 70–90 cm-wide flat-topped soil beds raised to 25–30-cm above ground, covered by full polyethylene mulch. Based on soil test results, 0–30% of the N and K, and 100% of P and micronutrients are broadcast applied into the bed. The remaining N and K are applied as two bands (one near each bed shoulder) in 5-cm deep groves (Fig. 2). Seepage irrigation maintains a constant water table level at the 40–45 cm depth. Intermittent ditches are also provided for irrigation and drainage purposes from a precisely leveled field with a slope of about 10 cm every 100 m. With this fertilizer placement, a three-dimensional concentration gradient decreasing with distance from the surface-applied fertilizers is superimposed on the moisture-air gradient. Thus, the root from a germinating seed or transplanted seedling can develop in that portion of the bed where the most favorable levels of nutrients, moisture, and air occur. Once the root system becomes established in a favorable portion of the soil bed, nutrients and moisture must continue to be supplied as they are removed by the root; soluble nutrients move by gradient diffusion from the band to the root. The less soluble nutrients mixed in soil bed continue to become available by equilibrium action, also as removed by the root.

Unlike in other production systems where water and nutrient availability fluctuate, the nutrient gradient system allows for vegetable crops roots to have a constant access to water and nutrients (Sato and Morgan 2012).

In broad terms, nutrient pollution occurs when nutrients move outside of the target application area (typically the root zone) through leaching or erosion (caused by rainfall or irrigation), nutrient cycling (Cockx and Simonne 2014; Simonne and Morgant 2013) or accidental non-target application. Off-target movement of nutrients may occur during the production season or when the fields are left fallow after the last harvest. Hence, all BMP efforts are focused on keeping nutrients in the root zone and on managing fields year round (FDACS 2015; Hartz 2006; Simonne et al. 2010). Any loss of nutrient reduces the effectiveness of the fertility program.

2.3 Environmental Regulations in the United States

In response to the public awareness of environmental issues, section 303(d) of the US Clean Water Act (US Congress 1977) required that states identify impaired water bodies and establish Total Maximum Daily Loads (TMDLs) for pollutants entering these water bodies. Best Management Practices (BMPs) are defined as specific cultural and/or structural practices aimed at reducing the negative environmental impact of agricultural production while maintaining or increasing yield and productivity. Mounting evidence exists world-wide that these two constraints are compatible (Singh and Ryan 2015). The role of the states was to define how the Clean Water Act was to be implemented at the local level. In 1987, the Florida legislature passed the Surface Water Improvement Act requiring the five Florida water management districts to develop plans to clean up and preserve Florida lakes, bays, estuaries and rivers. In 1999, the Florida Watershed Restoration Act (Florida Senate 1999) defined a process for the development of TMDLs. A TMDL represents the quantity of a pollutant a water body can accept and still have its water quality parameters consistent with its intended use. Based on the water body, the pollutants may be a nutrient (typically N or P), an organic compound or a microorganism.

The Florida Department of Agriculture and Consumer Services (FDACS) released and adopted by rule 5M-8 the first version of the "*Water Quality and Quantity Best Management Practices for Florida Vegetable and Agronomic Crops*" manual in 2005 and released an updated version in 2015 (FDACS 2015). Jointly developed by professionals from FDACS, the University of Florida, the water management districts and commodity groups, this manual outlines all the possible BMPs that farmers may implement. Agronomic and vegetable crops growers officially join the BMP program by (1) developing a BMP plan for their land and (2) signing a notice of Intent (NOI) to implement BMPs. Growers with a signed NOI receive a presumption of compliance with water quality standards and are eligible for cost share programs (FDACS 2015).

The "first generation BMPs" outlined in the 2005 version of the BMP manual proposed a multitude of approaches including fertilization plans and irrigation schedules (FDACS 2015). Second generation BMPs intensely focus on water and nutrient management and include controller-based real-time irrigation scheduling (Cardenas-Laihacar and Dukes 2010; Zotarelli et al. 2008a, b), low-pressure drip-irrigation (Poh et al. 2011a, b), the use of the Soil Phosphorus Storage Capacity Index to predict the risk of P loss outside the root zone through leaching or erosion (Florida Statute 1994; Rice et al. 2013), controlled-release fertilizers (Guertal 2009; Morgan et al. 2009; Simonne and Hutchinson 2005), amendments that increase soil water holding capacity such as biochar (Biederman and Harpole 2013; Singh et al. 2010), polymers (Bavernik 1994), or zeolites (Ming and Allen 2001; Sepaskhah and Yousefi 2007)], and amendments that increase soil organic matter content such as manures (Ulén 1999), compost (Hepperly et al. 2009) or cover crops (Hartwig and Ammon 2002; Tonitto et al. 2006).

Since the late 2000s, the Florida Department of Environmental Protection (FDEP) has been developing and approving Basin Management Action Plans (BMAPs; http://www.dep.state.fl.us/water/watersheds/bmap.htm). BMAPs are the blueprint for restoring impaired water bodies by reducing pollutant loadings to meet the TMDLs. Each plan includes a comprehensive set of strategies such as permit limits on wastewater facilities, urban and agricultural BMPs, conservation programs, financial assistance, and revenue generating activities. These plans are developed with input from local stakeholders and are adopted by Secretarial Order to be enforceable. In watersheds with adopted BMAPs, agricultural producers must either implement FDACS-adopted BMPs or conduct water quality monitoring prescribed by FDEP or their water management district.

2.4 Nutrient Loss Through Leaching

Leaching is the vertical movement of soluble nutrients with the water front while erosion is the loss of soil particles through water surface movement. Hence, water is the driver of these two processes which ties nutrient management with water management. Early estimates of nutrient loss to the environment measured nutrient concentrations in shallow wells or in suction lysimeters. While these measures are relatively easy to collect and may be compared to established thresholds, they have the limitations that (1) they are affected by precipitation, (2) it is difficult to clearly define what area of the soil or water body the sample represents, and (3) because concentrations are intensive measures, they cannot be added. Yet, many studies have reported seasonal and temporal variations in nutrient concentrations in vegetable fields.

Nutrient in solutions tended to be low in undisturbed ecosystems (<1.00 mg L^{-1} of $NO_3{-}N$; Chinnasamy and Hubbart 2014) whereas in intense vegetable production systems, $NO_3{-}N$ concentrations of up to 20–33 mg L^{-1} were reported in Sri Lanka with potato (*Solanum tuberosum*) grown on bare ground (Rajakaruna et al. 2005) and 35–40 mg L^{-1} $NO_3{-}N$ in Florida with tomato (*Solanum lycopersicum*) and pumping (*Cucurbita pepo*) produced with plasticulture (Simonne et al. 2006). These levels exceed by several factors the acceptable $NO_3{-}N$ concentrations in potable water allowed by the World Health Organization (10 mg L^{-1} of $NO_3{-}N$). As an alternative, research has focused on the direct measure of nutrient loads lost under the root zone of vegetable crops. Nutrient loads are expressed in kg·ha^{-1} and have the advantage of being additive.

2.5 *Nutrient Loads*

2.5.1 Determination of Nutrient Loads

Nutrient load may be determined indirectly or directly. The indirect approaches of measuring load include nutrient flow models and nutrient balances. Nutrient flow models are important tools for evaluating the impact of nutrient leaching on water quality at the watershed level, and play an important role in designing agricultural and environmental policies. Direct methods for calculating load at the field level are resin traps, soil sampling, or drainage lysimeters (Farneselli et al. 2008; Pampolino et al. 2000; Zotarelli et al. 2007). While each of these methods has its own advantages and limits, small, in-row drainage lysimeters are emerging as a practical tool for direct load measurements (Gazula et al. 2006; Migliaccio et al. 2006; Zotarelli et al. 2008a,b). A partial vacuum may be added to drainage lysimeters to prevent water logging without compromising the accuracy of the results (Evett et al. 2006). The accuracy of drainage measurement (+/− 0.0013 mm) was nearly two orders of magnitude better than that of the lysimeter weight measurement (1 mm), ensuring that the continuous drainage measurement may be included in the weight balances determination of evapotranspiration (ET) without diminishing the accuracy of ET values (Evett et al. 2006). The limitations of these methods are (1) installation requires soil disturbance, (2) sample collection may be time consuming, and (3) the sampling tubes of some lysimeters that may be near the soil surface (for sample collection) may interfere with tillage.

2.5.2 Nutrient Load Estimates

Several compilations of published in-field load estimates for vegetables crops are available (Khai et al. 2007; Ramos et al. 2002; Simonne et al. 2010; Ulén 1999). These estimates ranged from 1 to 400 kg.ha^{-1} of N, and varied based on crops, cultural practices, rainfall pattern, slope, and irrigation/fertilizer management. The methodology used for extrapolating load calculations to a per-hectare basis also affected the final number. Hence, efforts should be made to standardize protocols and methodology for in-field load estimation. At least, research reports should clearly provide the actual load estimate together with the calculations (and assumptions) used to extrapolate the results at the field level. In calculating nutrient loads, equal importance should be given to the determination of the volume of soil affected by the nutrient movement as to the estimation of the nutrient concentration since the load is calculated by multiplying one with the other (Farneselli et al. 2008).

2.5.3 Field Factors That Affected Nutrient Loads

A meta-analysis reviewed those strategies that have proven effective in reducing NO_3-N leaching and aimed at quantifying the scale of reduction that can be achieved (Quemada et al. 2013). Forty-four scientific articles that investigated four main strategies (water and fertilizer management, use of cover crops and fertilizer technology) were used to create a database with 279 observations on NO_3-N leaching and 166 on crop yield. On average, management practices that adjust water application to crop needs reduced NO_3-N leaching by 80% without a reduction in crop yield. Improved fertilizer management reduced NO_3-N leaching by 40%, and the best relationship between yield and NO_3-N leaching was obtained when applying the recommended fertilizer rate (Quemada et al. 2013). Replacing a fallow with a non-legume cover crop reduced NO_3-N leaching by 50% while using a legume cover crop did not further reduce NO_3-N leaching (Quemada et al. 2013).

In another meta-analysis on experiments that compared crop yield, NO_3-N leaching, or soil NO_3-N levels between conventional (receiving inorganic fertilizer with a winter bare fallow) and diversified systems [using either (1) a non-legume over-wintering cover crop that was amended with inorganic fertilizer or (2) a legume over-wintering cover crop with no additional N fertilizer], vegetable yields under non-legume cover crop managements were not significantly different from those in the conventional, bare fallow systems, while average leaching was reduced by 70% (Tonitto et al. 2006). However, yields under green manure fertilization were not significantly different from those in the conventional systems when legume biomass provided $\geq$110 kg N ha^{-1} (Tonitto et al. 2006). On average, NO_3-N leaching was reduced by 40% in legume-based systems relative to conventional fertilizer-based systems. Post-harvest soil NO_3-N status, a measure of potential N loss, was similar in conventional and green manure systems suggesting that reductions in leaching losses were largely due to avoidance of bare fallow periods (Tonitto et al. 2006). Nevertheless, in-field estimates provide a practical basis for educating growers and improving their cultural practices especially when rainfall and irrigation amounts and distribution are provided. These results support the current BMP approach that grower education should focus on irrigation management, fertilizer management, and cover crop use.

2.5.4 Strategies for Reducing the Risk of Nutrient Leaching

The main strategies currently available to reduce nutrient loss discussed here include using nitrification and ureases inhibitors, grafting, and irrigation management.

Nitrification and urease inhibitors may reduce N losses, thereby increasing crop N-use efficiency. However, their effect on crop yield is variable. The use of the common nitrification inhibitors (dicyandiamide (DCD) and 3,4-dimethylepyrazole phosphate (DMPP)) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) may be recommended in order to increase both crop yields and N use efficiency (grand mean increase of 7.5% and 12.9%, respectively) as shown in a meta-analysis (Abalos et al. 2014). However, their effectiveness was dependent on the environmental and management factors of the studies evaluated. Larger responses were found in coarse-textured soils, irrigated systems and/or crops receiving high N rates. In alkaline soils ($\text{pH} \geq 8$), the urease inhibitor NBPT produced the largest effect size. Given that their use represents an additional cost for sweet corn (*Zea mays*) farmers, understanding the BMPs to maximize their effectiveness is paramount to allow effective comparison with other practices that increase crop productivity and N-use efficiency (Abalos et al. 2014).

Vegetable grafting is a cultural technique that consists of establishing in the field or in a greenhouse a plant that is made by the union (through hole insertion, tongue approach or cleft grafting) of two other plants –the rootstock and the scion. Grafting is commercially practiced worldwide in tomato, pepper (*Capsicum annuum*), eggplant (*Solanum melongena*), cucumber (*Cucumis sativus*), watermelon (*Citrullus lanatus*) and small melons (*C. melo*) production (Lee 1994). Grafted plants have expressed “grafting vigor”, a concept that reflects that the phenotype of the grafted plant is more than the addition of the two separate phenotypes of the root stock and scion. On one hand, grafting is viewed as a promising tool to increase resistance to soil-borne diseases (King et al. 2008), fruit quality (Rouphael et al. 2010), and tolerance to abiotic stresses (Schwarz et al. 2010), salinity (Choi et al. 2011) and heavy metals (Savvas et al. 2010). On the other hand, grafting increases production costs (two seeds are needed; survival rate during healing may be variable), requires skilled labor or expensive grafting equipment, and occasional results in external rooting of the scion (Lee 1994). Yet, although grafting increased the total cost of field-grown tomato production, the increase in marketable fruit yield may generate in some cases a significant gross economic return that may offset the cost of using grafted transplants (Djidonou et al. 2013a). However, these results were based on a small-plots research study and not in commercial fields.

The grafting vigor and the potential of grafted plants to show enhanced water and NUE has been actively investigated in recent years in the hope of making grafting a BMP (Simonne et al. 2010). Most studies of grafted vegetable responses to fertilization and irrigation have been made with specific scion-root stock combinations. Schwarz et al. (2010) noticed that limited information exists on the effect of grafting on nutrient uptake or on the choice of scion for the enhancement of NUE. Most studies of the potential benefits of using grafted plant for improved NUE were conducted with cucurbit or solanaceous crops. In greenhouse conditions, melon plants grafted onto ‘Dinero’, ‘Jador’, and ‘P360’ (*Cucurbita moschata* Duchesne × *C. maxima* D.) rootstocks needed 5.7, 5.2, and 6.1 mM of NO_3^-, respectively, to reach half-maximum shoot dry weight, whereas plants grafted onto ‘PS1313’ rootstock and the control treatment (non-grafted plants) needed 9.1 and 13.1 mM of NO_3^-, respectively (Rouphael 2010). Under field conditions, increasing the N fertilization rates from 0 to 120 $\text{kg}\cdot\text{ha}^{-1}$ increased the total and marketable melon yields, whereas the NUE decreased (Rouphael 2010). When averaged over all N rates, the marketable yield, NUE, and N uptake efficiency were higher by 9%, 11.8%, and 16.3%, respectively, in 'Proteo' grafted onto 'P360' than in non-grafted 'Proteo' plants (Rouphael 2010). Mini-watermelon plants 'Minirossa' either non-grafted or grafted onto 'Macis', 'Vita' (*Lagenaria siceraria* [Mol.] Standl.), 'PS1313', and 'RP15' (*C. maxima* D. × *C. moschata* D.) rootstocks grown in hydroponics were compared based on shoot dry biomass, leaf area, root-to-shoot ratio, SPAD index, shoot N uptake, and nitrate reductase activity 40 days after transplantation in response to NO_3 concentration in the nutrient solution (0.5, 2.5, 5, 10, 15, or 20 mM of NO_3^-). Mini-watermelon grafted onto 'Vita' rootstock needed the lowest NO_3- concentration (1.31 mM) in the nutrient solution to reach half maximum shoot dry weight (Colla et al. 2011).

In another experiment, the suitability of 'Vita' as a rootstock with high NUE to improve crop performance and NUE of grafted mini-watermelon plants was evaluated under field conditions (Colla et al. 2011). Increasing N rates from 0 to 100 kg ha^{-1} improved total and marketable mini-watermelon yields. When averaged over N rates, the marketable yield, NUE, N-uptake efficiency, and N-utilization efficiency were significantly higher by 39%, 38%, 21%, and 17%, respectively, in 'Minirossa' grafted onto 'Vita' compared to non-grafted 'Minirossa' plants (Colla et al. 2011). Increasing the N fertilization rate from 0 to 60 kg ha^{-1} to 'Proteo' melon grafted on 'P360' increased melon yield by 21%, whereas increasing the N rate from 60 to 120 kg ha^{-1} increased melon production by only 10% (Colla et al. 2012). Similarly, increasing N fertilization rate from 0 to 50 kg ha^{-1} to mini-watermelon 'Minirossa' grafted on 'Vita' increased mini-watermelon yield by 47%, whereas increasing N rate from 50 to 100 kg ha^{-1} increased mini-watermelon yield by only 5% (Colla et al. 2012). When averaged over N rates, the yield, and NUE were higher by 10%, and 12%, respectively in 'Proteo' grafted onto 'P360' than in non-grafted 'Proteo' plants and by 39%, and 38%, respectively in 'Minirossa' grafted onto 'Vita' than in non-grafted 'Minirossa' plants (Colla et al. 2012). Hence grafting melon and mini-watermelon plants onto selected rootstocks can be used as a quick and effective method to improve productivity and increase NUE in cucurbits (Colla et al. 2011, 2012).

Tomato plants were grown in a fumigated field with 12 combinations of two drip-irrigation regimes (50% and 100% of commonly used irrigation regime) and six N rates ranging between 56 and 336 $kg{\cdot}ha^{-1}$). In 2010, the 50% irrigation regime resulted in higher total and marketable yields than the 100% irrigation regime (Djidonou et al. 2013b). Plants grafted onto 'Beaufort' or 'Multifort' rootstocks showed an average increase of 27% and 30% in total and marketable fruit yields, respectively, relative to non-grafted plants. Grafting significantly increased tomato yields, whereas grafted plants showed greater potential for yield improvement with increasing N rates compared with non-grafted plants. Greater fruit set and higher average fruit weight as a result of grafting were observed in both years. Grafting with the two rootstocks significantly improved the irrigation water and N use efficiency (Djodonou et al. 2013b). These results support the use of grafting as a BMP. These results also emphasize the need to control and report irrigation regimes (amount and frequency) in all scientific studies presenting results on vegetable crops responses to fertilizer rates, NUE or nutrient losses below the root zone. Further research should seek to develop rootstocks with enhanced water and nutrient uptake capabilities.

Current fertilization recommendations for vegetable crops production were developed with non-grafted plants. Yet, grafted tomato yield was significantly influenced by N rates, but similar yields were achieved at 168 kg·ha^{-1} and above (Djodonou et al. 2013b). Since the current recommendation for tomato production is 224 kg·ha^{-1} (Vallad et al. 2014), these results suggest the need for developing irrigation and N fertilization recommendations specifically for grafted tomato production. Due to increased water and N use efficiency, current recommendations for non-grafted tomato plants may result in over-irrigation and/or over-fertilization.

While this approach has produced practical information about the benefits of grafting on water and NUEs, it is unrealistic to expect that irrigation and fertilization requirements will be specifically developed for all the possible scion/root stock combinations. Instead, an exhaustive scientific study of this topic may require a genetic approach and a molecular explanation of the grafting vigor (Ruiz et al. 1997). After observing that the ability of grafted melon to absorb N, K and Mg was greater than that of those grown on their own roots, Min et al. (2006) stated that grafting had changed the character of melon's nutrient absorbability. In addition, self-grafting (which involves a single genotype) did not increase tomato yield as compared to the standard method (Djidonou et al. 2013b). Since no DNA movement from root stock to scion (or vice versa) is expected, distance gene expression may occur through the transport of RNAs through the graft union in the phloem. Harada (2010) compiled the endogenous RNA having long-distance transportability through sieve elements. Recent molecular biology advancements open the way for the targeted development of vegetable varieties (grafted or not) with improved water and NUEs (Bindraban et al. 2015; Ruiz et al. 2006). One approach is to develop an understanding of the plant response to different N regimes, especially to N limitation, using various methods including transcription profiling, analyzing mutants defective in their normal response to N limitation, and studying plants that show improved growth under N-limiting conditions (Kant et al. 2010).

Irrigation management is another method available to control nutrient leaching. In the field, most vegetable crops are irrigated with furrow irrigation, seepage irrigation, overhead irrigation or drip irrigation (Allen et al. 1998; Fereres et al. 2003; Locascio 2005). Scheduling irrigation is to determine when to irrigate and how much to apply. For all irrigation methods, the components of an irrigation schedule are (1) determining a target irrigation volume based on reference evapotranspiration (ETo) and crop age; (2) adjusting this amount based on soil moisture measurement (Thompson et al. 2007a); (3) determining the contribution of rainfall; (4) developing a rule for splitting irrigation, and (5) keeping irrigation records (Dukes et al. 2010, 2012; Simonne et al. 2012) (Table 2). Excessive water (from irrigation or rainfall) may move soluble nutrients below the root zone, especially in coarse-textured soils (Simonne et al. 2014). Despite some common misconceptions, "pulsing" irrigation (splitting a longer irrigation into shorter ones) did not increase the lateral movement of water in mulched beds on sandy soil when drip irrigation was used (Poh et al. 2009).

Drip irrigation management should be adjusted to soil conditions. Using computer simulations, Cotte et al. (2003) established that (1) drip irrigation may improve plant water availability in medium and low permeability fine-textured

Table 2 Generic irrigation schedule and fertilizer plan for vegetable crop production

Generic irrigation schedule
1. Select a target irrigation volume based on weather demand [assessed through reference evapotranspiration (ETo) or Class A Pan evaporation (Ep)] and crop stage of growth
2. Fine tune schedule based on daily soil moisture measurements (soil water tension or volumetric water content)
3. Determine the contribution of rainfall to crop water needs
4. Follow a rule for splitting irrigation volume (highest volume for one event before leaching is expected)
5. Record date and amount of rainfall and irrigation events
Generic fertilizer plan
1. Soil test, understand the recommendation and make the correct calculations
2. Lime if necessary
3. Apply organic amendments (cover crop, compost, or manure)
4. Incorporate the preplant fertilizer; then sidedress or develop a weekly fertigation schedule, adjusting amount to crop growth stage
5. Use foliar fertilization (this practice is recommended for the application of micronutrients to high-pH soils when need)
6. Assess the efficacy of the fertilizer program through leaf sampling or petiole sap analysis
7. Trap residual nutrients at the end of the season with a cover crop
8. Record date of application, material, placement and source of all fertilizer used

soils, providing that design and management are adapted to account for their soil hydraulic properties, (2) in highly permeable coarse textured soils, water and nutrients move quickly downwards from the emitter, making it difficult to wet the near surface zone if emitters are buried too deep, and (3) changing the fertigation strategy for highly permeable coarse-textured soils to apply nutrients at the beginning of an irrigation cycle can maintain larger amounts of nutrient near to and above the emitter, thereby making them less susceptible to leaching losses.

The risk of nutrient leaching caused by the mismanagement of irrigation is not uniform throughout the growing season in greenhouse and field production. Typically, major leaching events occur when soil N concentrations are high and water is moving through the soil profile (Meisinger and Delgado 2002). Based on a greenhouse industry survey, total irrigation during the first 6 weeks after crop establishment was generally excessive, being >150% and >200% of modelled crop evapotranspiration (ETc) in 68% and 60% of greenhouses, respectively (Thompson et al. 2007b). During the subsequent period, applied irrigation was generally similar to modelled ETc, with only 12% of greenhouses applying >150% of modelled ETc (Thompson et al. 2007b). Similar observations were made with corn (Spalding et al. 2001), strawberry (*Fragaria annassa*) (Guimera et al. 1995), tomato (Vázquez et al. 2006) and watermelon (Simonne et al. 2014) when excessive irrigation was observed during the vegetative period. Hence, educational efforts should focus on irrigation and fertilizer management early in the season.

While all these concepts related to localized fertilization application are the focus of intense research from a wide array of scientific fields, progress in field productivity, resource management, and environmental impact depends on the degree of application of the research advances by vegetable producers. Using vegetable production in Florida as an example, the following section summarizes the practical application of these concepts to field production.

3 Principles and Practices for Localized Fertilizer Applications to Vegetable Crops

3.1 Vegetable Crops and Production Systems

Vegetable crops are produced using many different production systems. Large-seeded crops like sweet corn, snap bean (*Phaseolus vulgaris*), English pea (*Pisum sativum*), southernpea (*Vigna unguiculata*) or okra (*Abelmoschus esculentus*) are typically direct seeded, whereas transplants are usually used for the establishment of small-seeded crops such as tomato, bell pepper, eggplant, lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea* var. capitata), broccoli (*B. oleracea* var. italic) or onion (*Allium cepa*)]. Due to the cost of seeds and low germination rates in the field, large-seeded triploid (seedless) watermelon crops are also established using transplants. Large-seeded crops such as small melons, cucumber, summer or zucchini squash (*Cucurbita pepo*) may be direct seeded or transplanted. Other vegetable crops are vegetatively propagated: daughter plants (strawberry), vine cuttings or “slips” [sweetpotato (*Ipomoea batatas*)] or “seed pieces” (potato) are used for field establishment. Direct-seeded crops, sweetpotato and potato crops are usually grown on flat ground or small uncovered or open beds, whereas transplanted and strawberry crops are usually established on raised beds. Raised beds may be covered with a polyethylene mulch or remain uncovered. Polyethylene-mulched beds may be used to grow one, two (double cropping) or three (triple cropping) crops. Crops may also be direct-seeded or transplanted into a cover crop. Vegetable crops may be grown as dry-land crops in areas with fine-textured soils and/or during the rainy season. In other cases, vegetable crops may be irrigated with furrow, seepage, overhead (center pivots, linear moves, travelling guns, or sprinklers) or drip irrigation. All these combinations of establishment method, soil preparation and irrigation method affect the fertilizer programs used.

3.2 Overview of Crop Nutritional Requirements (CNR) and Soil Testing Methods

The amount of nutrients needed to produce economical yields is called the crop nutritional requirement (CNR) (Liu et al. 2015). The CNR may be provided by the soil, organic amendments, cover crops residues, or fertilizers. Soil-test methods exist to determine the potential nutrient contribution from the soil, and therefore by difference, the amount of nutrients needed to be supplied by amendments, cover crop residues and/or fertilizers. Soil testing consists of soil sampling and drying, and an extraction step followed by chemical analyses (Mylavarapu 2009). Routine analyses measure the amount of extracted nutrients, salinity, and pH of a soil. The selection of an extracting solution (also called "extractant") is based on soil pH, cation exchange capacity (CEC) and organic matter content. Many extractants are used worldwide and little standardization exists among regions or countries. Single-element extractants may be grouped as acid extractants, chelating agents, buffered salt solutions, or unbuffered salt solutions (Houba et al. 1996; Jordan-Meille et al. 2012; Rauret 1998). In contrast to single-element extractants, Universal extractants are extracting mixtures that have been calibrated for most essential nutrients (Jones 1990; Zhang et al. 2013). They are popular among soil testing laboratories because they allow for the diagnosis of most elements based on a single extraction step. Soil test ratings are associated with a probability of yield response to additions of the nutrient.

For all these production systems, the proper development and implementation of soil-test based fertilizer programs for vegetable crop production require the appropriate selection of the source, rate, timing and placement of the fertilizer. Fertilizer rates may be found in production recommendation publications (Hochmuth 2003; Kemble 2014; Vallad et al. 2014). Timing and placement are often linked based on the form (granular or liquid) and the equipment used. This section covers (1) the basic concepts of soil testing and (2) fertilizer recommendations for vegetables grown in Florida; the placement, timing and calculation of (3) starter fertilization rates, (4) modified broadcast fertilizer rates, (5) banded fertilization rates, and (6) liquid fertigation rates. Finally, examples of how to properly calibrate fertilizer application equipment, how to adjust fertilizer rates when non-standard bed spacings are used, and how to estimate the nutrient contribution of broadcast-applied composts and manures to the nutrition of vegetable crops established on raised beds are provided.

3.3 Principles and Practices for Localized Fertilizer Applications to Vegetable Crops

3.3.1 Principle 1

The four pillars of vegetable production are (1) a marketing plan, (2) a fertilization plan, (3) an irrigation schedule, and (4) a pest management plan. Nutrients and water management are linked. All efforts to correctly manage nutrients may be negated by an inadequate irrigation program.

3.3.2 Principle 2

Fertilizer placement and application method are affected by crop method of establishment, irrigation method, and mulching (Table 3).

Table 3 Summary of fertilizer application methods used for crops grown in Florida with the main production systems

Irrigation method	Typical crops in Florida	Fertilizer application method				
		Broadcast	Modified broadcast	Banded	Injected	Foliar fertilization
Bare ground						
Seepage	Potato, cabbage, celery, radish, green bean, sweet corn, broccoli. summer squash, cucumber	Lime or sulfur when needed. 30–50% of the N and K, and 100% of P and micro-nutrients for closed-row crops	Preplant “bottom” or “cold” mix with 30–50% of the N and K, and 100% of P and micro-nutrients	Sidedress	N/A[a]	Recommended for micronutrients for crops grown on calcareous soils
Overhead	Green bean, sweet corn, sweet potato, broccoli		Preplant application of 30–50% of the N and K, and 100% of P and micro-nutrients	Sidedress	N/A	Most of the N and K included in irrigation water are taken up by the roots
Drip	Pumpkin, watermelon, small melons	Lime or sulfur when needed	Preplant application of 0–50% of the N and K, and 100% of P and micro-nutrients	Possible, not practical	Daily or weekly liquid fertilization	Recommended for micronutrients for crops grown on calcareous soils

First crop grown with polyethylene mulch						
Seepage	Tomato, bell pepper, eggplant, watermelon, small melons	Lime or sulfur when needed	Preplant "bottom" or "cold" mix with 30–50% of the N and K, and 100% of P and micro-nutrients	Dual bands on shoulder ("hot" mix)	N/A	Recommended for micronutrients for crops grown on calcareous soils
Drip	Tomato, bell pepper, eggplant, strawberry watermelon, small melons		Preplant application of 30–50% of the N and K, and 100% of P and micro-nutrients	Possible, not practical	Daily or weekly liquid fertilization	
Second or third crop grown in sequence on the same polyethylene mulch (double or triple cropping)						
Seepage	Summer squash, cucumber, watermelon, small melons	Not possible	Not possible	N/A	Weekly injection of liquid or dry fertilizer on the bed shoulders using a fertilizer wheel	Recommended for micronutrients for crops grown on calcareous soils
Drip	Small melons, cabbage, cucumber, watermelon	Not possible	Not possible	Possible, not practical	Daily or weekly liquid fertilization	

[a] N/A = not applicable

3.3.3 Principle 3

Fertilizer recommendations for vegetables grown in Florida are based on soil testing, and include (1) a base recommendation and (2) supplemental fertilizer applications allowed after (a) a leaching rain event (defined as a cumulative rainfall amount of 7.62 cm in 3 days or 10.16 cm in 7 days), (b) a measured "low" plant nutrient content established after leaf analysis or petiole sap testing, or (c) an extended harvest season (Table 4).

3.3.4 Principle 4

The "RRRRight" way to apply fertilizer is to (1) use the *Right Source* (what material should be used?), (2) use the *Right Rate* (how much material should be used)?, (3) applied at the *Right Time* (when should it be applied)?, and (4) positioned at the *Right Place* (where in the field and in relation to the crop roots should the fertilizer be placed?) (Hochmuth et al. 2014; Liu et al. 2015). This concept provides a blueprint for record keeping: date, crop growth stage, fertilizer formula or grade, quantity, placement, tractor operator, tractor speed, and weather conditions.

3.3.5 Practice 1

Startup (or "pop up") fertilization: Phosphorus is an essential element for root growth and it may not be readily available to seeds and transplants when soils are cool (<12–15 °C) and/or damp. Starter solutions containing P, and some N and K (as mono-potassium phosphate, ammoniated and triple superphosphate together with ammonium nitrate or potassium nitrate) may promote early growth by supplying available P. Overall, starter solutions represent a small percentage of the total fertilizer program (10–20 $\text{kg}\cdot\text{ha}^{-1}$ of P_2O_5). For seeded crops, starter solutions may be applied in a band (as granular or liquid) 5 cm to the side of the seed and 5-cm deep. For transplanted crops, starter solutions are often dissolved in the transplant water and applied in the transplant hole. In this case, the solution is delivered by gravity from a tank located above the wheel that punches the holes in the polyethylene mulch. Holes in the wheel deliver the starter solution directly and only into the transplant hole.

3.3.6 Practice 2

Based of crop planting pattern and size of the root system, fertilization may be calculated and implemented based on field surface (broadcast application) or on length of planted rows (starter, modified broadcast, banded or injected fertilizer). Standard bed or row spacings have been determined for most vegetable crops

Table 4 Nitrogen and potassium recommendations for strawberry grown with plasticulture in Florida on sandy soils testing “low” in Mehlich-3 phosphorous and Mehlich-3 potassium[a]

Production system			Recommended-base fertilization					Recommended-supplemental fertilization	
				Injected					
				Growth period					
	Nutrient	Total	Preplant	First 2 weeks	Sept. to Jan.	Feb. and Mar.	April	“Low” plant nutrient content	Extended harvest season
		kg·HA^{-1}	kg·HA^{-1}	kg·HA^{-1} day^{-1}				kg·HA^{-1} day^{-1} for 7 days	
Drip irrigation, raised beds and polyethylene mulch	N	168	0–45	0.34	0.67	0.84	0.67	0.67–0.84	
	K_2O	168	0–45	0.34	0.67	0.84	0.67	0.67–0.84	
	P_2O_5	134	134	0	0	0	0	0	

[a] 1 HA = 8333 m of beds; Source: Vallad et al. 2014; Conversions from original units made using 1 lb/A = 1.12 kg/HA

Table 5 Standard bed spacings and corresponding length of row (or bed) in one surface unit for the main vegetable crops grown in Florida[a]

Row spacing	45 cm	60 cm	75 cm	90 cm
Crop	Bean	Cabbage	Sweet corn	Potato, sweetpotato
Linear meters of row/ha	22,222	16,667	13,333	11,111

Bed spacing	120 cm	150 cm	180 cm	240 cm
Crop	Strawberry	Small melons	Tomato, bell pepper, eggplant	Watermelon
Linear meters of bed/ha	8333	6667	5556	4167

[a] Conversions from original units made using 1 ft = 30 cm; 1 acre = 43,560 sq-ft; 1 ha = 10,000 m^2

(Table 5). The length of bed (LBF, linear feet of row) in one acre may be calculated by dividing 43,560 sq-ft in 1 acre by bed spacing (BS): LBF (ft/acre) = 43,560 (sq-ft/acre) /BS (ft). The length of bed (L, meters of row, m) in one hectare may be calculated by dividing 10,000 m^2 ha^{-1} by the bed spacing (BS): L (m HA^{-1}) = 10,000 (m^2 ha^{-1})/BS (m). Note that 1 ha refers to a 1-ha field; 1 HA represents the standard length of row or bed at standard bed spacing.

3.3.7 Practice 3

Vegetable crops may be planted at bed spacings other than the standard ones when (1) fields are double or triple cropped, (2) limited land is available, or (3) when varieties with compact-growth habits are used. In this case, the conversion is done by expressing the recommended rate at standard bed spacing in kg/100 m of bed (Table 6).

3.3.8 Practice 4

The benefits of soil testing and correct fertilizer calculations are lost when application equipment is incorrectly calibrated (Table 7).

3.3.9 Practice 5

The contribution of cover crops, composts or manures that are broadcast applied over the entire field surface may be determined by identifying (1) the amount of material accessible by the roots and (2) the material mineralization rate (Table 8). In this example, the total nutrient supply made by a 10 t/ha application of compost was 140 kg·ha^{-1} of N, 160 kg·ha^{-1} of P_2O_5, and 84 kg·ha^{-1} of K_2O. However, only 15% (21/140), 35% (56/160), and 41% (34/84) for the muskmelon and 13% (18/140), 46% (74/160) and 52% (44/84) for the snap bean, of the total nutrient content in the compost are available to the first crops for N, P_2O_5, and K_2O, respectively.

Table 6 Adjustment to nitrogen fertilizer rates when non-standard bed spacings are used for (1) mini-watermelons and (2) a strawberry-muskmelon double crop sequence[a]

Crop	Length of bed (m HA^{-1}) [at standard (S) or reduced (R) bed spacing (m)]	Fertilizer rate based on planted surface kg·HA^{-1}	Fertilizer rate based on unit row of bed kg/100 m	Fertilizer rate based on field surface kg·ha^{-1}
Preplant application				
Watermelon	4167 [8 S][b]	56[b]	56/41.62 = 1.34	56
Mini watermelon	5556 [6 R][c]	56[b]	1.34[d]	1.34 × 55.56 = 74
Mini watermelon	6667 [5 R][c]	56[b]	1.34[d]	1.34 × 66.67 = 89
Injected fertilizer				
Strawberry	8333 [4 S][b]	168[b]–0[b] = 168	168/ 83.33 = 2.02	168
Muskmelon	6667 [5 S][b]	168[b]–56[b] = 112	112/ 66.67 = 1.70[d]	112
Muskmelon following strawberry	8333 [4 R][e]	168[b]–0[f] = 168	1.70[d]	1.70 × 8333 = 140

[a] Non-standard bed spacings may be used (1) when land is limiting, (2) when compact-growth habit cultivars are used (mini watermelons, for example), or (3) two or three crops are grown consecutively on the same plastic-mulched beds (double or triple cropping)

[b] From the production recommendations

[c] Reduced bed spacing allowed by smaller vine growth of mini watermelons

[d] Fertilizer rate based on length of row remains constant for all the bed spacings for the same crop

[e] The bed spacing of muskmelon is that of the first strawberry crop

[f] Double cropping does not allow the placement of broadcast-incorporated preplant fertilizer; all the fertilizer needs to be injected

3.3.10 Practice 6

When plasticulture (raised bed culture, drip irrigation and polyethylene mulch) is used, preplant N and K_2O fertilizer is typically applied using the modified-broadcast method and incorporated into the raised bed; the remaining N and K_2O is applied through daily or weekly injections of liquid fertilizer (Table 9).

3.3.11 Practice 7

Though popular in the industry for N and K, foliar fertilization recommendations in Florida are usually limited to the application of micronutrients to crops grown on calcareous soils. Leaf anatomy (impermeable cuticle only interrupted by lenticels and stomata) is not conducive for using the leaf as a means of delivering large amounts of nutrients into the plant. High pH (>7.5) in these soils make soil applications of micronutrients inefficient as they rapidly react to become plant-unavailable hydroxides. Hence, foliar fertilization should be used for application of

Table 7 Calibration of fertilizer application equipment for (1) a banded application of pine bark and (2) a modified-broadcast application of chicken manure

Banded application of ammoniumnitrate and potassiumchloride
Situation: For soils testing "low" in Mehlich-3 K, N and K_2O fertilization recommendation for tomato grown with seepage irrigation consist of applying 56 kg·HA^{-1} of N and K_2O broadcast incorporated in the bed and 168 kg·HA^{-1} of N and K_2O applied equally in two bands placed approximately 30 cm off the bed center on each side. If a mixture of ammoniumnitrate and potassiumchloride is used, how much fertilizer needs to be applied to each band in 1 meter of row?
Ammonium Nitrate (NO_3NH_4; 34-0-0): $100 \times 168/34 = 494$ kg·HA^{-1} of NO_3NH_4 needed to supply 168 kg·HA^{-1} N rate
Potassium Chloride (KCl; 0-0-60): $100 \times 168/60 = 280$ kg HA^{-1} of KCl needed to supply 168 kg·HA^{-1} K_2O rate
The total amount of NO_3NH_4-KCl blend needed is $494 + 280 = 774$ kg·HA^{-1}.
1 ha of tomato contains $10{,}000/1.8 = 5556$ m of bed and $2 \times 5556 = 11{,}112$ m of band.
Hence, each band will contain $774/11{,}112 = 0.070$ kg·m^{-1}.
Spreader calibration for the banded fertilizer
Situation: We need to calibrate the fertilizer spreader on a 10-m long tarp. Each tube is calibrated individually. How much weight of N-NH_4-KCl blend should be collected on the tarp if the spreader is well calibrated?
The target application rate calculated above was 0.070 kg m^{-1} of band. If the tarp is 10-m long and a single spreader is used, we should collect $10 \times 0.070 = 0.7$ kg of blend/10 m
The tractor operator makes 3 passes and collects 0.53, 0.58, 0.55 kg each time. Is this spreader calibrated? What do we do?
Make sure the tractor speed is constant over the tarp; check for uniformity of material; check for holes in the soil (uneven discharge)
Run 1 : $(0.53 + 0.58 + 0.55)/3 = 0.553$ kg (target: 0.70 kg)
Error: $(0.553–0.70)/0.70 = –21\%$
The fertilizer is currently under-applied at a rate of 21%. Calibration must be improved!
So, the options are to (a) decrease tractor speed or (b) change settings to increase discharge rate based on the type of spreader used. Changes are made. The tractor operator makes 3 new passes and collects 0.68, 0.73 and 0.72 kg each time. Is this better?
Run 2 : $(0.68 + 0.73 + 0.72)/3 = 0.71$ kg (target: 0.70 kg)
Error: $(0.71–0.70)/0.70 = +1.4\%$
The fertilizer is over-applied at a rate of 1.4%. This means that 170 kg·HA^{-1} of N and K_2O are applied instead of 168 kg·HA^{-1} of each. This is acceptable. The equipment is considered calibrated.
Modified-broadcast application of chicken manure and spreader calibration
Situation: We want to apply 50 kg N HA^{-1} using chicken manure (25 kg N t^{-1} @ 50% N available to first crop) to bell pepper grownon 180-cm centers. How much chicken manure should we collect on a 10-m long tarp?
$10{,}000/1.8 = 5556$ m of bed HA^{-1} on 180-cm bed spacing
So, we need 2000 kg·ha^{-1} = 2000 kg /5556 m of bed = 36 kg/100 m of bed
If we make a 10-m long run, we should collect $2000 \times 10/5556 = 3.60$ kg of chicken litter.
Trial runs need to be made as described above for the compost example.

Table 8 Contribution of organic materials to a fertilization plan based on crop planting pattern and mineralization rate

<table>
<tr><th colspan="2">Broadcast application of compost</th></tr>
<tr><td colspan="2">Situation: We want to apply 10 t·ha^{-1} of compost costing \$ 67t^{-1} + \$15 t ha^{-1} for spreading and transportation; compost has a fertilizer analysis of N 2%, P 1% and K 1% (dry weight basis), moisture content is 30%.</td></tr>
<tr><td colspan="2">Question 1: What rate of compost is this?</td></tr>
<tr><td colspan="2">10 t ha^{-1} =10,000 kg/10,000 m^2 = 1 kg m^{-2}</td></tr>
<tr><td colspan="2">We will apply 1 kg m^{-2} of compost, uniformly over the entire field, then we will incorporate it.</td></tr>
<tr><td colspan="2">Question 2: How much does this application cost?</td></tr>
<tr><td colspan="2">10 t × (\$67t^{-1} + \$15t^{-1} for application and transport) = \$820ha^{-1}</td></tr>
<tr><td colspan="2">Question 3: How much N, P_2O_5 and K_2O does this compost application provide?[a]</td></tr>
<tr><td colspan="2">Fertilizer analysis N 2%, P 1% and K 1% (dry weight basis) and moisture content: 30%</td></tr>
<tr><td colspan="2">Dry weight applied: 10,000 × 0.70 = 7000 kg</td></tr>
<tr><td colspan="2">Nutrient contributions:</td></tr>
<tr><td colspan="2">N: 7000 × 0.02 = 140 kg N ha^{-1}</td></tr>
<tr><td colspan="2">P: 7000 × 0.01 = 70 kg of P = 70 × 2.2910 = 160 kg P_2O_5 ha^{-1}</td></tr>
<tr><td colspan="2">K: 7000 × 0.01 = 70 kg of K = 70 × 1.2047 = 84 kg K_2O ha^{-1}</td></tr>
<tr><td colspan="2">Situation (ctd). We made a uniform broadcast application of compost. Good! Are the crop roots having access to all the compost? What will happen to the nutrients from the compost that was applied between the rows? Are all the nutrients available to the first crop? The twoside-by-side cases below show examples of a crop grown with plasticulture (Case 1: muskmelon) and of another crop grown on bare grown (Case 2: snap bean).</td></tr>
<tr><td>Case 1. We grow muskmelons on 75-cm wide beds and rows spaced 150-cm apart, how much nutrients will be accessible (under the plastic)?</td><td>Case 2. We grow snap beans on 45 cm row spacing and the roots grow 15 cm on each side, how much nutrients will be accessible (under the rows)?</td></tr>
<tr><td>In this case, only 75/150 = 50% of the compost will be under the plastic. Nutrients accessible to the muskmelon plant (assuming the roots system is mostly under the polyethylene mulch):</td><td>In this case, (15 + 15)/45 = 30/45 = 66% of the compost will be accessible by the roots. Nutrients accessible to the snap bean plants:</td></tr>
<tr><td>N: 0.50 × 140 kg = 70 kg of N</td><td>N: 0.66 140 kg = 92 kg of N</td></tr>
<tr><td>P: 0.50 × 160 kg = 80 kg of P_2O_5</td><td>P: 0.66 × 160 kg = 106 kg of P_2O_5</td></tr>
<tr><td>K: 0.50 × 84 kg = 42 kg of K_2O</td><td>K: 0.66 × 84 kg = 55 kg of K_2O</td></tr>
<tr><td colspan="2">Typically, 10–30% of N (we will use 20%), 70–80% of P (we will use 70%), and 80–90% of K (will we use 80%) will be available to the crop established immediately after compost application. How much nutrients will be available (released during the first crop and accessible to the roots)?</td></tr>
<tr><td>Nutrients available to the muskmelons (HA^{-1}):</td><td>Nutrients available to the snap beans (HA^{-1}):</td></tr>
<tr><td>N: 0.20 × 70 = 14 kg of N</td><td>N: 0.20 × 92 = 18 kg of N</td></tr>
<tr><td>P: 0.70 × 80 = 56 kg of P_2O_5</td><td>P: 0.70 × 106 = 74 kg of P_2O_5</td></tr>
<tr><td>K: 0.80 × 42 = 34 kg of K_2O</td><td>K: 0.80 × 55 = 44 kg of K_2O</td></tr>
</table>

[a] P × 2.29 = P_2O_5; K × 1.2 = K_2O; 1 HA = linear meters of bed (or row) in one hectare at standard bed (or row) spacing

Table 9 Example of fertilization rates used in conventional strawberry production: Granular modified broadcast preplant application rate and liquid injected weekly rate

Fertilizer program for strawberries
Situation. We are growing strawberries at a standard bed spacing of 120 cm. The soil test recommendation is 168-0-168 N-P_2O_5-K_2O ("high" P, "very low" K). In Florida, recommended N rate is not based on soil test and is a blanket total seasonal amount of 150 kg HA^{-1} with 0–50 kg HA^{-1} preplant incorporated in the bed, and the remaining injected weekly through the growing season starting at plant establishment.
We need to apply 34-0-34 N-P_2O_5-K_2O (1:0:1) preplant using a 15-0-15 fertilizer (a 1:0:1 type fertilizer).
How much 15-0-15 needs to be applied?
100 kg of 15-0-15 fertilizer contain 15 kg of N. We will need 227 kg of fertilizer applied to 8333 m of bed (or $227/8333 = 0.03$ kg m^{-1}) to apply 34 kg N HA^{-1}.
What happens if 13-4-13 is used instead of 15-0-15?
Based on the label, 100 kg of fertilizer contains 13 kg of N. For 34 kg of N, we need $100 \times 34/13 = 262$ kg·ha^{-1} of 13-4-13. (or 262 kg of 13-4-13/8333 = 0.03 kg m^{-1} of row)
How much P_2O_5 was applied?
P: $4 \times 262/100 = 11$ kg·ha^{-1} of P_2O_5 We apply nutrients (here P) that are not needed. Hence, the choice of fertilizer matters!
We need to apply 0.84 kg HA^{-1} $day^{-1}$of N and K_2O (1:0:1) through the drip using liquid 8-0-8 (1:0:1 also) **How much liquid fertilizer is needed for a daily injection? For a weekly injection? How much needs to be ordered for the whole season?**
A daily rate of 0.84 kg N is also $0.84 \times 7 = 5.88$ kg N $week^{-1}$ (assuming that 1 L = 1 kg)
Volume needed for 1 day: $0.84/0.08 = 10.5$ L HA^{-1}
Volume needed for 1 week: $5.88/0.08 = 73.5$ L HA^{-1}
So, a 73.5-L weekly injection of 8-0-8 to a 1-HA field provides 5.88 kg of N, no P, and 5.88 kg of K_2O.
For a 23-week-long season, we will need $73.5 \times 23 = 1690$ L HA^{-1} $season^{-1}$.

micronutrients on these soils. Most of the N and K applied to crops like sweet corn and snap beans through over-head irrigation system reach the ground first, and are actually taken up by the roots.

3.3.12 Practice 8

Reality check: Units for all factors should be clearly known every time application rates are calculated. In the end, "the result must make sense".

4 Conclusion

Fertilizers may be lost through chemical transformations or movement below the root zone of vegetable cops. By placing fertilizer near the seeds, transplants or plants, localized applications of fertilizers are strategies that increase the uptake rate of applied nutrients, thereby reducing the application rates, the fertilization cost and reduce the environmental impact of vegetable production. They are most effective when used together with cover crop, reduced tillage, nitrification and ureases inhibitors, grafting, and irrigation management. Recommended field cultural practices that may increase NUE include soil testing, fertilization plans, irrigation schedules, controller-based real-time irrigation scheduling, low-pressure drip-irrigation, the use of the Soil Phosphorus Storage Capacity Index, controlled-release fertilizers, amendments that increase soil water holding capacity (such as biochar, polymers, or zeolites), or that increase soil organic matter content (such as manures, compost, or cover crops). Further progress in nutrient use efficiency may (and will) be achieved through breeding and molecular biology that target root architecture and transport sites inside the roots. Sap analyses and identification of the mechanisms that govern the gene expression in the scion under the control of compounds produced by the root stock, may help explain the molecular basis for grafting vigor. Further progress may also come from better management in the field (applying smaller quantities of fertilizer more often). Ultimately, the effectiveness of the practices adopted by growers depends on the level of awareness growers have about the risk of nutrient loss, the cost of those practices, and field variability.

Glossary

AMT Ammonium transporter
BMAP Basin management action plan
BMP Best management practices
BS Bed spacing
Ca Calcium
CEC Cation exchange capacity
cHATS Constitutive high-affinity transporting system
cLATS Constitutive low-affinity transporting system
CNR Crop nutritional requirement
CO_2 Carbon dioxide
DCD Dicyandiamide
DMPP 3,4-dimethylepyrazole phosphate
DNA Deoxyribonucleic acid
Ep Evaporation
ET Evapotranspiration
ETc Crop evapotranspiration
ETo Reference evapotranspiration
FDACS Florida Department of Agriculture and Consumer Services
FDEP Florida Department of Environmental Protection
ft Feet
$H_2PO_4^-$ Dihydrogen phosphate ion
HPO_4^{2-} Hydrogen phosphate ion
HA Standard length of row or bed in 1 hectare at standard bed spacing

iHATS Nitrate-inducible high-affinity transporting system
iLATS Nitrate-inducible low-affinity transporting system
K Potassium
K_2O Potassium oxide
lb Pounds
LBF Linear bed feet length
Mg Magnesium
N Nitrogen
NBPT N-(n-butyl) thiophosphoric triamide
NH_4^+ Ammonium ion
NO_3^- Nitrate ion
NOI Notice of intent
NRT Nitrate transporter bn
NUE Nutrient use efficiency
P Phosphorus
P_2O_5 Phosphorus pentoxide
PTR Peptide transporter
RNA Ribonucleic acid
SPAD Soil-plant analysis development
sq-ft Square feet
TMDLs Total maximum daily loads

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Water and Nutrient Supply in Horticultural Crops Grown in Soilless Culture: Resource Efficiency in Dynamic and Intensive Systems

Giuseppe Pignata, Manuela Casale, and Silvana Nicola

Abstract It is currently possible to exploit specialised and standardised growing techniques in a context in which both land and water are becoming scarce. Agronomic innovation and automation are being coupled to an increasing sensitivity towards environment protection and a reduction in input losses. Consequently, modern horticulture is shifting from traditional culture systems, in the open field, to protected cultivation and soilless culture systems (SCS). Protected cultivation and SCS allow the provision of water and nutrients to the plant root system to be controlled and regulated, thus favouring root oxygenation. The punctual and real crop needs are satisfied by the hydroponic nutrient solution (HNS). SCS introduce both resource optimisation and a reduction in losses, and thus increase food security and profitability in modern dynamic and intensive systems. Some SCS require the use of substrates or substrate mixes that must be chemically stable and should prevent the release of elements that can interfere with the HNS composition, thus inducing both phytotoxicity and microbial contamination. An HNS should be formulated using microbiologically safe water, and calibrating the macro-, meso- and micronutrients on the basis of the chemical composition of the water. However, it is also necessary to consider the interactions that occur in an HNS formulation between the individual elements that can affect plant growth, crop yield and injury susceptibility. Indicators, such as pH, electrical conductivity, oxygen content and temperature, should be checked periodically. The HNS supply period per day, volume per unit area or per plant, and the number of events during the day should be determined and tailored for a proper plant production in SCS. The HNS supply, whether continuous or discontinuous, can be supplied directly to the root using sub-irrigation or nebulisation systems, or from the aerial part using drip irrigation or sprinkling systems. The water and nutrient supply in SCS can be organized either through open-cycle hydroponic systems, in which the plants are fed with a specifically prepared HNS, without recovering the drainage, or through closed-cycle hydroponic systems, in which the drainage is collected, analysed, sanitised,

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integrated with the absorbed nutrients and re-inserted into the system. Each horticultural crop has its own specific water and nutrient supply needs that arise from specific physiological responses.

Keywords Protected cultivation • Macronutrients • Mesonutrients and micronutrients • Hydroponic nutrient solution • Loss reduction • Raw material standardisation • Food safety and food security • Indicators • Open-cycle hydroponic systems • Closed-cycle hydroponic systems • Substrates

1 Introduction

Agricultural activities, and the practices involved in horticultural productions, have a growing impact on and relevance in modern society. The main implications concern food security, food safety, the environment and economy. Particular emphasis has been paid to the provision of horticultural products, natural resources, input use, rural area development and sustainability (Galdeano-Gómez et al. 2013; Lundqvist et al. 2008; Nellemann et al. 2009). In order to reach these goals, process and product standardisation and competitiveness are crucial, through environmentally respecting innovative practices and technologies, to ensure the efficiency of agricultural activities.

Horticulture is the sector of agriculture that has undergone most changes in recent years. Modern horticulture activities have been focused on research and investments in technology, crop yield increases and resource use efficiency, and in this way a dynamic intensive system has been created (Aznar-Sánchez and Galdeano-Gómez 2011; Dehnen-Schmutz et al. 2010). The main factors and elements that have been investigated, structured and ameliorated are:

(a) the specialisation and professionalism of the growers;
(b) innovative and technological growing systems;
(c) the selection of species and cultivars according to the supply chain and the final food sector;
(d) increases in precision in the efficient use of water and nutrients;
(e) harvesting practices;
(f) postharvest management practices.

Increasing a grower's technical knowledge, as well as the development and setting up of accessible growing systems, helps to promote protected cultivation systems as an alternative to traditional culture systems (TCS) in the open field (Engindeniz 2004; Gruda 2005, 2009). Protected cultivation systems can ensure precise inputs and the control of the growing conditions by means of capital-intensive instrumentation. Confined environments allow a specific microclimate and controlled conditions to be created, in which the radiation and wind movements are lower and the relative air humidity is higher than in an open field. The possibility of regulating growing factors, such as the water and nutrient supply, favours both improvements in the usage efficiency of input and reductions in losses, which in turn implies productive advantages and high added-value horticultural crops (Abou Hadid 2013; Grewal et al. 2011; Hitchon et al. 1991; Schnitzler et al. 2004). Protected cultivation has continuously been expanding, and has recently been accompanied by that of soilless culture systems (SCS) (Gruda 2009; Hussain et al. 2014; Rouphael et al. 2005).

The effective advantages that can be derived from protected cultivation and SCS utilisation require specialisation and technical skills on the functioning of the SCS, substrate properties, water quality, macro-, meso- and micronutrients traits, plant nutrient requirements and on the supply systems.

2 Soilless Culture Systems and Input Control

SCS have been used since the 1930s to perform experiments on plant nutrition and physiology (Engindeniz 2004; Olympios 1999). In recent decades, SCS have increasingly been set up and used in modern horticulture as innovative instruments and techniques to produce standardised fresh produce (Carmassi et al. 2005; Savvas et al. 2007; Sengupta and Banerjee 2012). SCS are the most intensive and effective production systems in today's horticultural industries.

In SCS, plants develop their root system in solid or liquid media in a limited space, isolated from the soil. The water and nutrients that are necessary for plant growth are supplied by a hydroponic nutrient solution (HNS) (Abad and Noguera 1998; Incrocci et al. 2006; Jensen 1997). SCS, by disconnecting the cultivation from the soil, eliminate problems related to crop rotations, soil exhaustion, soil mineral integration, soil salinization, soil diseases, poor soil structure and groundwater pollution caused by the excessive use of fertilizers (Santamaria and Signore 2004; Sardare and Admane 2013; Siddiqi et al. 1998; Van Os 1999). The use of SCS in protected cultivations introduces a series of horticultural production advantages, such as high yields, improvements in product quality, water saving and reductions in losses (Ferrante et al. 2003; Nicola and Fontana 2007; Rouphael et al. 2004; Scuderi et al. 2011). SCS are suitable for producing horticultural products with both a short growing cycle and a high plant density, and they increase earliness and allow the growing season to be extended (Colla and Saccardo 2003; Fontana and Nicola 2008; Grewal et al. 2011; Rodríguez-Hidalgo et al. 2010). Less irrigation water is used in SCS than in TCS in open fields. In general, SCS use 10% of the water required for growing the same species in TCS in open fields (Somerville et al. 2014).

The recognised high efficiency of SCS is due to the possibility of directly supplying water and nutrients to the root system, and of controlling the environmental conditions, inputs, growing factors and crop nutritional supplies. The precise and punctual inputs supplied to the crop help to reduce nutrient uptake stress. This condition allows the inherent and external quality and the hygienic status of the product to be affected directly and rapidly (Hussain et al. 2014;

Sengupta and Banerjee 2012; Zanin et al. 2009). In general, SCS allow standardised and uniform raw material to be obtained at harvest, with low toxic molecules and anti-nutritional residues (Di Lorenzo et al. 2013; Gruda 2009; Nicola et al. 2007). Nevertheless, SCS utilisation does not automatically lead to a high qualitative horticultural production.

Conflicting evidence exists concerning the effects of SCS on the visual quality, tissue browning and the phytochemical compound content in horticultural products, such as in strawberries, melons, tomatoes, peppers, eggplants, cucumbers, beans, celery, parsley, dill, basil, radish, lettuce, rocket, cress and spinach (Degl'Innocenti et al. 2005; Fallovo et al. 2009a, b; Fontana and Nicola 2009; Gruda 2009; Nicola et al. 2002, 2010; Selma et al. 2012; Tomasi et al. 2015; Zhan et al. 2009). SCS allow raw material with reduced agronomic and chemical residues, undesirable compounds and microbiological contamination to be obtained at harvest (Olympios 1999; Tognoni et al. 2005; Zanin et al. 2009). This is the result of:

(a) the absence of soil and weeds;
(b) the utilisation of a sterile substrate;
(c) reduced or even absent direct contact between the edible parts of the plants and the potential sources of contamination;
(d) reduced utilisation of over-head irrigations.

Consequently, horticultural products grown in SCS may require softer postharvest washing treatments than those cultivated in TCS in open fields, thus resulting in less plant tissue stress and reduced industry equipment deterioration (Fontana and Nicola 2008; Scuderi et al. 2011; Sardare and Admane 2013).

The positive horticultural performances of SCS, in terms of food security, food safety, natural resources, input use and sustainability, can mainly be attributed to the possibility of regulating and controlling the water and nutrient supplies and root oxygenation according to the crop stage growth and punctual plant needs (Castilla 2013; Fontana et al. 2004; Tognoni et al. 2005). SCS can thus enhance horticultural profitability through the best use of resources, and can favour development in rural areas, increasing competitive and intensive sustainable productions.

2.1 Classification and Principles of the Main Soilless Culture Systems

SCS vary according to their water and nutrient supply systems, the tools and equipment used for their distribution and the technical and technological automation that is introduced, which depends on the horticultural crop that is grown. The most commonly used SCS are based either on a liquid medium (nutrient solution) or on a solid medium (substrate).

2.1.1 SCS in a Liquid Medium

The **Nutrient film technique** (NFT) is one of the most commonly used systems, and it is one from which many other soilless culture systems have developed. The system is scheduled with an HNS flow, which is pumped from tanks into channels that have a slight slope (Hussain et al. 2014). The channels house medium cubes, in which the plants are anchored. The drainage is recovered at the end of the channels and is returned to the tanks and then to the system. NFT ensures an adequate aeration of the HNS and of the roots (Lim 1985; Olympios 1999). This system is used for leafy vegetables and fruit (Jensen 1997). In the case of long-cycle crops, an excessive plant root development can obstruct the HNS flow and create imbalances in the water and nutrient uptake, and thus introduce non-standardised and non-uniform plant growth (Cooper 1979; Malorgio 2004). An NFT system should be monitored and checked regularly to adjust the HNS composition and to avoid pump stops, which can cause the roots to dry out (Hussain et al. 2014; Wolosin 2008). NFT generally requires low volumes of HNS for plant growth. Apart from economic advantages, this also involves both easier HNS heating and cooling during the cold or warm seasons, respectively (Jensen 1997).

Working in a similar way to NFT, the **super NFT** adds a drip irrigation system, which uniformly distributes the HNS in the proximity of each plant, and thus allows slighter slopes and longer lengths of the channels than NFT (Lazzarin et al. 2001; Savvas et al. 2013). The super NFT partially reduces the negative effect of the excessive growth of roots, thanks to the uniform and well-distributed HNS supply system.

The **Mobile gully system** (MGS) is a highly automated system, which is very similar to NFT, in which the cultivation modules are positioned on a waterbed or on an HNS-bed. The cultivation modules are mechanically moved and spaced during crop growth, according to the growing phase and size of the crops. The movement of the cultivation modules allows constant and efficient transplanting and harvesting in specific areas of the greenhouse (www.hortiplan.com/en/mgs/).

The **Gravel film technique** (GFT) is similar to NFT, as far as the structure and the organisation of the channels are concerned. The difference concerns the presence of a 3–5 cm substrate layer in the cultivation modules, which physically supports the plants and allows the HNS to be distributed (Savvas et al. 2013).

The **New growing system** (NGS) is a versatile system that is similar to NFT, in which the plant roots grow homogeneously in multilevel cultivation channels so as to avoid obstruction of the HNS and to favour root aeration (Urrestarazu et al. 2005; www.ngsystem.com/en). The HNS is discontinuously pumped into the system, according to the environmental conditions, thus allowing more oxygenation and fertilizer savings than the NFT system. The design of the multilevel cultivation channel differs according to the adopted horticultural species.

The **Deep flow technique** (DFT) is an NFT that can be used for short-cycle crops, such as leafy vegetables, in which the HNS is supplied continuously in a 2–3 cm deep volume (Hu et al. 2008; Hussain et al. 2014). Several developments of the DFT have been made, and this has led to the characterization of the floating systems.

Floating growing systems (FGS) are relatively cheap and easy-to-use sub-irrigation systems that are used for the cultivation of short-cycle species, such as leafy vegetables and aromatic plants. FGS can be implemented with either a static or a dynamic HNS bed (Degl'Innocenti et al. 2005; Fontana and Nicola 2009; Hussain et al. 2014; Tognoni et al. 2005). FGS can be set either with continuous flotation (FL) or with ebb-and-flow flotation (EF) (Fontana et al. 2003, 2004, 2006; Nicola et al. 2005, 2007, 2016). FL consists of trays floating continuously on a waterbed or HNS, whose volume ensures a buffer effect on the system. FL requires relatively low labour costs and limited maintenance, and the result is an efficient use of water and a protected cultivation space (Fontana and Nicola 2008; Galloway et al. 2000; Gonnella et al. 2003). EF can be scheduled to have drying (ebb) periods with discontinuous flotation to reduce the risk of crop root hypoxia and anoxia. Oxygen sensitive species may suffer from stress, due to the consumption of oxygen dissolved in the HNS, if grown in FL (Goto et al. 1996; Fontana and Nicola 2009; Nicola et al. 2007; Son et al. 2006). In order to favour HNS aeration, FGS can be implemented with compressors or pumps to add air or oxygen to the solution itself (Nicola et al. 2016). Like FL, flood floor is a sub-irrigation system that is suitable for ornamental crops with long growing cycles that do not require frequent cultural operations or maintenance. The HNS is placed directly onto the greenhouse floor, which has a slight slope that conveys the drainage to the drainage tanks (Montesano et al. 2007).

The **Capillary mat system** can be implemented on a greenhouse floor or on benches on which a high capillarity absorbent pad, which allows a quick and homogeneous HNS distribution to the root system, has been placed. The HNS is usually supplied through drip irrigation (Rouphael et al. 2006).

Aeroponics involves plants being suspended in inert structures within which the HNS is nebulised directly onto the roots at a variable frequency and intensity during the day (Castilla 2013; Jensen 1997). The HNS that percolates from the roots and the structures is collected at the bottom of the cultivation structures, and is then conveyed to drainage tanks (Malorgio 2004). Aeroponics is a high innovative and technological SCS that is used for growing lettuce, strawberries and some flower species, such as roses, gerberas and chrysanthemums (Lazzarin et al. 2001; Tognoni et al. 2005).

2.1.2 SCS in a Solid Medium

A solid medium culture involves plants being grown in substrates of different materials and properties hosted in different types of cultivation modules, such as slabs, channels, gutters, bags, pots or containers of various shapes and materials. The width and length of the cultivation modules are variable in function of the SCS that is implemented, the size of the containers and the space that is available. The substrate holds the water and nutrient reserves for the plant, and is used by the root system as anchorage (Gruda et al. 2013; Sardare and Admane 2013).

The use of cultivation systems with a substrate is generally adopted during the nursery stage and for growing species that bear fruit and flowers. The HNS supply is usually scheduled with an intermittent flow by means of sub-irrigation, drip irrigation or sprinkler (Malorgio 2004; Pardossi et al. 2009).

2.2 The Perspectives of Soilless Culture Systems

SCS represent an advanced approach to sustainable agriculture that leads to a better input utilisation, plant growth efficiency and space rationalization enhancement. Given the high innovation and technology of some SCS, their extensive application and intensive utilisation require a significant initial investment, technical knowledge and management costs (Gruda 2009; Hussain et al. 2014; Montesano et al. 2007; Rouphael et al. 2005). SCS are characterized by a reduced available volume for the expansion of the plant roots, and by a defined and limited water and nutrient availability. These conditions imply continuous monitoring and checking of the functioning of the system, and a strict conduction of agronomic and cultural practices (Menzies et al. 1991; Savvas 2001; Silber and Bar-Tal 2008). Moreover, in order to satisfy the water and nutrient needs of the canopy, the root density must be high. This, in turn, results in restricted root growth and high root-to-root competition, thus leading to a rapid consumption of the oxygen and nutrients (Boland et al. 2000; Raviv et al. 2008). SCS have to be well scheduled and regulated to compensate for water loss, nutrient concentration depletion and re-integration, HNS aeration and flow, in order to avoid water and nutrient shortages and crop stress, and to favour suitable growing conditions for specific crops (Silberbush and Ben-Asher 2001).

3 Substrate Properties for Plant Nutrient Uptake

Various different types of media are currently used as substrates for SCS, and they each have different characteristics, properties and costs. The choice of which substrate to use in the SCS is a direct consequence of the SCS that is chosen, the HNS supply system that is adopted and the species that is cultivated. SCS substrates physically support the root systems and partially regulate the water and nutrient supply to the plants (Boodley and Sheldrake 1977; Engindeniz 2004). The water and nutrient supply, temperature variations and root expansion induce chemical and physical property changes in the substrates used in the SCS. The main variations concern substrate compaction and particle size alteration, porosity and a reduction in the water holding capacity (Di Lorenzo et al. 2013; Pardossi et al. 2009).

The chemical properties of the substrate, such as the macro-, meso- and micronutrient contents and the ion exchange capacity, affect the irrigation scheduling. The pH and electrical conductivity (EC) values in the substrate are both determined by the composition of the medium itself and by the solubilisation of the mineral elements supplied by the HNS. The solubilisation is in turn influenced by humidity, temperature and substrate composition (Zaccheo et al. 2009). A substrate should be chemically stable so as to prevent the contained nutrient elements from being released into the HNS. Any interaction between the substrate and HNS could cause changes in the calibrated HNS composition, thus unbalancing the nutrient supply planned and scheduled for the crop. Changes in the substrate composition could induce undesired salt precipitation and phytotoxicity. A physical loss and dragging of substrate particles, due to the HNS flow, could create problems for the filtering and sanitizing systems (Castilla 2013; Gallardo et al. 2013).

Inert substrates are able to significantly reduce the evapotranspiration area (Rouphael et al. 2005). Consequently, the most suitable substrates and mixes are those with the lowest nutrient composition. These substrates and mixes are preferable to highly concentrated substrates and mixes, because they allow the nutrient regulation to be targeted to the plants through the HNS utilisation (Gianquinto and Pimpini 2001; Gruda et al. 2013). Nevertheless, substrates with low nutrient contents are in some cases integrated to supply the macro-, meso- and micronutrients necessary to safely ensure continuous plant growth. Even certain physical properties, such as the density, porosity, water holding capacity and air content, could change unpredictably during plant growth and thus affect the irrigation volume and frequency efficiencies (Castilla 2013; Gianquinto and Pimpini 2001; Sequi et al. 2009).

3.1 *Soilless Culture System Substrates*

The media used in substrates can be classified as natural or synthetic and as organic or inorganic (Evans and Gachukia 2004; Malorgio 2004). Some examples of natural organic substrates are peat and plant waste materials, such as coconut fibre, wood fibre and bark; examples of natural inorganic substrates are vermiculite, sand, pumice, clay, volcanic material, tuff and zeolite; an example of a synthetic organic substrate is polystyrene; examples of synthetic inorganic substrates are perlite and rockwool (Sequi et al. 2009).

Regardless of the type and the classification, a good substrate for nursery and SCS should have the following characteristics:

(a) porosity above 75–80%, macro- and microporosity balanced to ensure an adequate water holding capacity, ventilation and excess HNS drainage;
(b) volume reduction and compaction resistance to dehydration;
(c) low nutrient supply;
(d) high pH buffer capacity;

(e) low cation exchange capacity;
(f) homogeneous composition;
(g) stability during the crop cycle;
(h) absence of pathogens, parasites and toxic substances;
(i) low microbiological contamination and heavy metal content;
(j) sanificable and reusable;
(k) easy availability and disposal;
(l) low cost (Castilla 2013; Di Lorenzo et al. 2013; Gruda et al. 2013; Raviv et al. 2002).

Peat is the medium that is most frequently used as a substrate in SCS, because it is light in weight, porous, homogeneous, relatively stable and microbiologically safe, with a high cation exchange capacity and a sub-acidic pH. Peat usually contains a higher organic matter content than 30% (Hussain et al. 2014; Pardossi et al. 2009; Zaccheo et al. 2009). The extensive use of peat at both the nursery stage and in SCS for horticultural production is provoking a gradual depletion of peat bogs, whose renewability is slow. This condition has caused the price of peat to rise, and consequently has encouraged input suppliers, producers, and also professionals to find alternative substrates that are compatible with the SCS used and the crop needs (Cattivello 2009; Rea et al. 2009; Sequi et al. 2009).

Coconut fibre obtained from coconut industries needs a series of treatments prior to being suitable as a growing substrate. The fibres, which are separated from other parts of the coconut, undergo 2–3-years of processing, during which they are composted, dehydrated, compressed and rehydrated. The coconut fibre preparation process affects the fibre quality and consequently the duration of the use of the substrate (Gianquinto and Pimpini 2001). Coconut fibre has a high water holding capacity and air retention capacity (Hussain et al. 2014).

Bark is used as a substrate at both the nursery stage and in SCS after 6 weeks of composting the wood processing waste. Bark is particularly used as a substrate for root expansion, because of its satisfactory permeability, water holding capacity, buffer capacity and cation exchange capacity (Bunt 1988; Evans and Gachukia 2004).

Vermiculite has a similar buffer capacity and a cation exchange capacity to peat. This makes vermiculite an interesting alternative substrate for SCS, despite its high nutrient content (Gianquinto and Pimpini 2001; Gruda et al. 2013). Moreover, vermiculite has a high water holding capacity (Hussain et al. 2014).

Sand is used for horticultural production in different cycle phases, according to the particle granulometry and size. Sand particles of 0.05–0.50 mm can be used for sowing and root expansion, while larger particles than 0.50 mm are used to increase the substrate drainage capacity during the growing cycle (Gianquinto and Pimpini 2001; Gruda et al. 2013). Sand is used in particular for horticultural crops that need a dry growing environment (Hussain et al. 2014).

Pumice is a lightweight and porous volcanic material that contains certain amounts of essential plant growing elements (e.g. sodium, potassium, calcium, magnesium, iron). These elements are gradually released during cultivation, and thus become available to the roots (Bunt 1988).

Expanded clay is a granular product produced by the dry heating of heavy clay. It is light in weight, with a low volume weight and a pH of about 7.0 (Dobričević et al. 2008).

Volcanic tuffs are used in SCS to exploit the physical properties of porosity and the cation exchange capacity, which vary according to the size of the particles (Raviv et al. 2002).

Zeolites are used for the sowing phase, during root expansion and during the growing cycle. Like pumice, zeolites contain essential plant growing elements (e.g. nitrogen, potassium), depending on their origin, and they are gradually released during cultivation, thus becoming available to the roots (Handreck and Black 2005).

Polystyrene is used during the nursery phase and the growing cycle, because of its high porosity, which reduces the risk of root asphyxia and prevents water stagnation for sensitive species (Bunt 1988).

Perlite is an inert and has a reduced buffer capacity and cation exchange capacity, as well as a low nutrient content. At the end of the crop cycle, perlite can undergo sterilization treatments that make it reusable for new crops (Boodley and Sheldrake 1977; Gianquinto and Pimpini 2001).

Rockwool is one of the most widely used substrates in SCS, because it is sterile and inert. It allows a good root anchorage, and its highly porous structure promotes root aeration and HNS drainage. Rockwool can be classified into three types, according to the thickness and arrangement of the fibres and to its water-repellency capacity (Castilla 2013; Jensen 1997).

Other synthetic inorganic substrates, which are only used rarely in the nursery and soilless culture industry, are **urea-formaldehyde foam**, **polyurethane foam** and **ion exchange resins**. Urea-formaldehyde foam is a lightweight material that has a high water holding capacity. Polyurethane foam is sometimes used in SCS because of its high water holding capacity, the absence of nutrients and its physical resistance. Ion exchange resins are capable of retaining cations (e.g. K^+, NH_4^+, Ca^{2+}, Mg^{2+}) and anions (e.g. NO_3^-, SO_4^{2-}, PO_4^{3-}) and of exchanging them with the ions present in the irrigation water or in the HNS (Gianquinto and Pimpini 2001).

3.2 *Substrate Mixes in Soilless Culture Systems*

Apart from the previously mentioned monotype substrates, mixes of two or more substrates are also used both during transplant production in the nursery and during soilless cultivation, with the aim of improving the physical and chemical properties of the plants by combining substrates with different characteristics. Substrate mixes vary according to the cultivated horticultural crop, the phenological growth stage, the size of the plant container and, more in general, according to the SCS that is adopted (Di Lorenzo et al. 2013; Pardossi et al. 2009).

Peat is usually used in mixes to increase the acidity of the growing media, thus creating favourable conditions for the plants, or in combination with porous matrices, such as pumice, to increase substrate aeration and softness (Joosten and Clarke 2002; Penningsfeld and Kurzmann 1983). Coconut fibre, bark, sawdust and wood chips are seldom used alone, but are frequently used in substrate mixes in a percentage of up to 50% of volume. Coconut fibre, bark, sawdust and wood chips are usually combined with peat and polystyrene, or even with other substrates that have a high drainage capacity (Castilla 2013; Hussain et al. 2014). Bark is used in substrate mixes to increase the structural stability, substrate porosity and the drainage capacity. Composted substrates, such as sawdust and wood chips, oenology and oil industry by-products, tanneries and leather processing waste, seaweed and rice hulls, can all be used in the formulation of substrate mixes to increase the buffer capacity and the cation exchange capacity (Bunt 1988; Evans and Gachukia 2004). Vermiculite is used in substrate mixes at crop sowing to promote root expansion, and during cultivation, because of its buffer and the cation exchange capacity. Mixes of sand and peat or other substrates can be used for the sowing and root expansion of seedlings, or later in the crop cultivation phase, because they increase both substrate porosity and drainage capacity. Pumice is used in combination with peat to increase the drainage and aeration of the substrate. Volcanic tuffs and clay are mainly used in substrate mix formulations at 10–35% of volume with peat to increase substrate porosity and the drainage capacity (Gruda et al. 2013). Clay is appreciated in particular in substrate mixes, because it increases both the buffer capacity and the cation exchange capacity. Polystyrene is added to other substrates, in amounts of 15–30% of volume, in order to improve the porosity of the medium, and consequently to reduce the risk of root asphyxia due to water stagnation. Perlite is used in substrate mixes to increase substrate softness, permeance and aeration. However, in the case of an excessive dosage in substrate mixes, perlite can cause a reduction in pH to values below 5.0, and this can result in phytotoxic effects (Jensen 1997). Rockwool can be mixed with other substrates to improve aeration and drainage capability, thus allowing a good root anchorage (Castilla 2013). Urea-formaldehyde foam is used in substrate mixes, at 20–30% of volume, to enhance the water holding capacity. Polyurethane foam can be used in substrate mixes to improve the water holding capacity, and to reduce the nutrient supply to the growing media. Ion exchange resins are added to substrate mixes, in amounts of 2–10% of volume, to increase the water holding capacity and regulate nutrient absorption, thus avoiding an excess of salts (Gianquinto and Pimpini 2001).

3.3 Management of the Substrates and Substrate Mixes

Substrates or substrate mixes are usually supplemented with different compounds that have specific physical and chemical properties. Nursery and SCS substrates can be integrated using:

(a) corrective compounds, to modify the pH;
(b) buffer substances, to reduce nutrient leaching due to the ion exchange capacity;
(c) binding compounds, to improve substrate compactness and transplant efficiency;
(d) wetting agents, to reduce substrate water tension, thus favouring water absorption;
(e) hydrogel, to increase the water holding capacity, thereby reducing the frequency of the HNS supply (Frangi 2009; Gruda et al. 2013).

Substrates and mixes can be reused a certain number of times according to their nature, the chemical imbalance that derives from the adopted water and nutrient management practices, physical alterations, safety level threshold and crop specificity. Before being re-used for a new crop, the substrates should be treated using physical sanitation systems (e.g. steam, sunburning) or using chemical compounds (e.g. fungicides, fumigants). In general, if properly maintained, substrates can last for up to 2–3 years, while some inorganic substrates may last longer (e.g. 10 years for polyurethane) (Benoit and Cuestermans 1995; Gruda et al. 2013).

4 Water in Horticultural Soilless Culture Systems

Water is considered a valuable resource in a growing number of areas throughout the world, and represents one of the most important political, social and economic issues (Pignata 2015; Rosegrant et al. 2009; Rouphael et al. 2005). Agriculture is the major water user, and probably the sector that is managed the least efficiently because of technicalities concerning its distribution and the maintenance of irrigation facilities (Abou Hadid 2013). The reduced availability of irrigation water, quality water and salinity, and environmental regulations are drawing attention to the problem of water criticality, even in the horticultural sector. This trend is driving many horticultural companies towards a crossroads. On the one hand, they are choosing a reduction in the water supply or the utilisation of water with relatively high salt concentrations, thus reducing both yields and product quality; on the other hand, they are moving towards improved systems and cultural techniques (Savvas et al. 2007).

Water availability and consumption is directly affected and determined by the efficiency of the growing system. Water efficiency in TCS, in open fields, is determined by the combination of the losses due to evaporation, transpiration, evapotranspiration, soil percolation, run-off and water consumption by weeds. Among these factors, transpiration and evapotranspiration are the two main factors that are responsible for the high water utilisation in agriculture. Transpiration, which is mainly linked to the opening of the leaf stomata, can reach 98% of the total amount of water absorbed by the plants, and can consequently affect nutrient absorption. Because of the absence of soil and weeds, the quantity of water necessary for the crop in SCS is the sum of the water necessary for plant growth and for transpiration. Only a negligible amount of water is actually lost through evaporation from the substrate. The amount of water lost through evaporation can be further reduced by covering the substrate with plastic film (Castilla 2013).

It is crucial to know the profile of the water used in SCS for horticultural production, although the water composition and contamination level can vary unpredictably. Having information available concerning water quality is useful to:

(a) formulate appropriate and specific HNS, on the basis of the initial water composition, by modulating the integration of the macro-, meso- and micronutrients;
(b) reduce the fresh produce safety risk, which is closely related to the microbiological quality of the irrigation water;
(c) vary the water source according to needs (Adams 2002; Jones 2005; Silber and Bar-Tal 2008; Sonneveld 2002).

Regardless of the quality of water available for cultural purposes, farmers who use SCS should implement a series of actions to protect and properly manage water sources. These actions should be implemented to reduce the sources of contamination by providing buffer zones, protecting water openings and accesses, and cooperating with nearby farms to avoid groundwater contamination.

5 Formulation of the Hydroponic Nutrient Solution

Fertilisers are provided in SCS by means of fertigation, which is based on mixing and distributing mineral elements through irrigation water, thus via an HNS. In order to guarantee successful plant growth, the HNS formulation should be defined considering:

(a) the chemical, physical and biological characteristics and properties of the irrigation water;
(b) the needs of the species, according to the phenological stage of the plants;
(c) the media that are used;
(d) the HNS supply system that is adopted;
(e) environmental factors and the cultivation season;
(f) leaching and drainage (Colla and Saccardo 2003; Enzo et al. 2001; Silber and Bar-Tal 2008; Somerville et al. 2014; Tognoni et al. 2005; Zekki et al. 1996).

5.1 Macro-, Meso- and Micronutrients in Soilless Culture

Plants absorb many elements through their roots, but not all of these are considered essential elements. Essential macro-, meso- and micronutrients are defined as those that are required for the plant growth cycle whose role cannot be assumed by another element (Hussain et al. 2014; Silber and Bar-Tal 2008). Macronutrients are those that are required in relatively large amounts, because they are the main structural elements, that is, carbon, hydrogen, oxygen, nitrogen, phosphorus and potassium. Mesonutrients are those that are required in moderate amounts, but which are essential for the main plant activities, that is, calcium, magnesium and sulphur. Micronutrients are those that are required in small amounts, because they are needed for a few enzyme activities, that is, iron, manganese, chlorine, boron, copper, molybdenum, zinc, sodium and selenium (Marschner 1995). Most of these nutrients are absorbed by roots as cations or anions, except for boron, which is absorbed as boric acid or as the borate ion, depending on the pH (Silber and Bar-Tal 2008). Thus, HNS are composed of mineral salts, acids and bases dissolved in water (Le Bot et al. 2001; Sambo and Pimpini 2001). Their solubility and compatibility with the substrate and the irrigation water should be considered (Silber and Bar-Tal 2008).

As in TCS in open fields, the nitrogen requirements in crops grown in SCS are high during the juvenile stages and before fruit expansion. Nitrogen is supplied through fertigation as urea, $N\text{-}NO_3^-$ (N in nitric form) and $N\text{-}NH_4^+$ (N in ammoniacal form), because it is absorbed differently by the roots and has different functions in the various metabolic processes. Urea is the cheapest nitrogen source, and the most concentrated nitrogen fertilizer. It is highly soluble and easily distributed with the HNS, but it is not taken up directly by plants. Urea is only available to plants after hydrolysis time-dependent reactions, which lead to the formation of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$. For this reason, urea is not commonly used in SCS (Silber and Bar-Tal 2008). The nitric form is rapidly absorbed and stored by the plant. It is useful in cases of waterlogging to reduce the incidence of cold damage (Giardini 2004; Sambo and Pimpini 2001).

Nitrogen is usually supplied in nitric form in the HNS as nitric acid, potassium nitrate, calcium nitrate, zinc nitrate, copper(II) nitrate or ammonium nitrate.

$N\text{-}NH_4^+$ absorption does not require reduction, prior to plant utilisation, and this results in energy savings (Gorbe and Calatayud 2010). High concentrations of the ammonium form in HNS are toxic to most plants, particularly in conditions of high root temperatures and salinity (Britto and Kronzucker 2002; Sonneveld 2002). $N\text{-}NH_4^+$ has a negative effect on calcium leaf tissue accumulation, thus suggesting that its concentration should be reduced to 10–15% of the total nitrogen supply to susceptible crops, such as tomatoes and sweet peppers (Adams 2002; Silber and Bar-Tal 2008). Moreover, $N\text{-}NH_4^+$ enhances phosphate absorption (Lewis 1992). Nitrogen in the form of ammonium is supplied to HNS as ammonium sulphate, ammonium dihydrogen phosphate, diammonium phosphate, ammonium molybdate or ammonium nitrate.

The presence of nitrates in vegetables is considered a threat for human health, not so much due to their toxicity, which is low, but because they can convert in the organism to the more toxic nitrites (Lundberg et al. 2004; Pannala et al. 2003). Young plants are prone to accumulating more nitrates than older plants, and their accumulation tends to be higher in the outer leaves and in the petioles than in the laminae (Cárdenas-Navarro et al. 1999; Fontana and Nicola 2008; Krohn et al.

2003; Maynard and Barker 1979; Siomos et al. 2002). Low nitrate amounts are accumulated under growing conditions with high amounts of available radiation, because of the high light-dependent activity of the nitrate reductase enzyme in reducing the nitrate taken up by the plants (Burns et al. 2004; Conte et al. 2008; Konstantopoulou et al. 2010; Proietti et al. 2004; Riens and Heldt 1992; Ysart et al. 1999). Because of the tendency of some leafy vegetables to accumulate nitrates accordingly to the growing conditions, the maximum amount of nitrate allowed to accumulate in lettuce, spinach and different rocket species is regulated in Europe by EU Regulation No. 1258/2011, in function of the growing period and growing system.

In vegetables, and in particular in leafy vegetables, the nitrogen supplied as nitrate during growth is inversely correlated to the dry matter, and directly correlated to the nitrate content in the edible portion (Fontana et al. 2004; Tei et al. 2000). Consequently, SCS can be used to regulate nitrogen by varying the total nitrogen concentration and the N-NO_3^-/N-NH_4^+ ratio in the HNS (Fontana and Nicola 2008). The nitrate concentration in vegetable plant tissues can be reduced by reducing or disposing of the nitric content in the HNS, by varying the N-NO_3^-/N-NH_4^+ ratio or by replacing the HNS with water some days before the harvesting time (Nicola et al. 2015). Different N-NO_3^-/N-NH_4^+ ratios have been studied extensively to understand their effects on several horticultural crops, such as rocket, garden cress, spinach, bladder campion, purslane, fennel, celery, Swiss chard and endives, and the results have been different shoot and root growths, yields, dry matter and toxicity symptoms (Fontana et al. 2006; Fontana and Nicola 2008; Nicola et al. 2015; Santamaria and Elia 1997; Santamaria et al. 1999).

Phosphorus, which is easily leached in SCS, can be supplied to HNS as phosphoric acid, ammonium dihydrogen phosphate, diammonium phosphate, potassium dihydrogen phosphate, potassium phosphate tribasic, iron(II) phosphate or iron(III) phosphate. Phosphorus absorption is influenced by the pH and the temperature, and it decreases under conditions of $pH > 6.5$ and temperatures <13 °C (Sambo and Pimpini 2001).

Potassium absorption is related to sodium absorption. Under saline-sodic conditions, high levels of Na^+ in the HNS or in the substrates interfere with K^+ acquisition in the roots, and may disrupt the integrity of the root membranes, thus altering their selectivity (Grattan and Grieve 1998; Silber and Bar-Tal 2008). In the HNS formulation, potassium can be supplied as potassium nitrate, potassium sulphate, potassium chloride, potassium dihydrogen phosphate or as potassium phosphate tribasic.

Significant raw material and economic losses of horticultural crops have been related to inadequate calcium nutrition. This is due not so much to a low calcium concentration in the HNS and in the substrates, but to the pH conditions, and the ratio with other cations in the substrate, such as ammonium, potassium, sodium and magnesium (Sambo and Pimpini 2001; Somerville et al. 2014). The presence of Ca^{2+} influences K^+/Na^+ selectivity by shifting the plant uptake ratio in favour of K^+ at the expense of Na^+ (Grattan and Grieve 1998). Calcium can be supplied as calcium hydroxide, calcium nitrate or calcium chloride.

Magnesium is immobilized at $\mathrm{pH} < 5.5$, and is very competitive with potassium and calcium cations. Magnesium can be supplied to HNS as magnesium sulphate.

Sulphur is usually present in HNS in a ratio of 1:10 with nitrogen. Sulphur is supplied as potassium sulphate, ammonium sulphate, magnesium sulphate, iron (II) sulphate, iron(III) sulphate, zinc sulphate, copper(I) sulphate or copper (II) sulphate (Sambo and Pimpini 2001).

Iron absorption is affected by a $\mathrm{pH} > 7.0$, and the presence of manganese, with which it is in competition for root absorption (Tomasi et al. 2015). Iron can be supplied as iron(II) phosphate, iron(III) phosphate, iron(II) sulphate, iron(III) sulphate or iron chelate.

Manganese absorption is affected by an alkaline pH, and by competition with cations. It is supplied to the HNS used in SCS as manganese sulphate (Sambo and Pimpini 2001; Somerville et al. 2014).

Chlorine is a mobile element in the plant, which is soluble and easily absorbable. A Cl^- uptake increase and accumulation is often coupled with an $N\text{-}NO_3^-$ decrease in the shoots (Grattan and Grieve 1998). Chlorine is supplied as potassium chloride, calcium chloride, zinc chloride, copper(I) chloride or copper(II) chloride.

Boron, which is usually supplied as sodium tetraborate, is easily absorbed by crops, if the HNS pH ranges between 4.5 and 5.5. Boron can compete with calcium, and can result in a boron plant deficiency.

Copper is absorbed to a great extent at a pH of 5.5–6.5. Toxicity phenomena may arise in a crop at a $\mathrm{pH} < 5.5$, while copper absorption is reduced at a $\mathrm{pH} > 6.5$. It is supplied as copper(II) nitrate, copper(I) chloride, copper(II) chloride, copper (I) sulphate or copper(II) sulphate.

Molybdenum is available more for crops grown in SCS at a pH close to neutrality than in other pH conditions. It can be supplied to the HNS as ammonium molybdate or sodium molybdate.

Zinc absorption is influenced by the pH, temperature, substrate humidity and phosphorus competition. Zinc can be supplied as zinc nitrate, zinc sulphate or zinc chloride (Sambo and Pimpini 2001).

The bicarbonates contained in the HNS should be neutralized using acidic solutions, such as nitric acid, sulphuric acid or phosphoric acid, because:

(a) bicarbonates affect the HNS pH by promoting sub-alkaline conditions, thus reducing the solubility and absorbability of the elements;
(b) calcium bicarbonate and magnesium bicarbonate can be accumulated in intensive evaporation conditions, thus favouring the availability of sodium;
(c) bicarbonates can promote the formation of whitish spots on the surface of the plant tissue, in different intensities, according to the crop: the damage is mostly aesthetic in ornamental species, while it can provoke phytotoxicity in baby-leaf vegetables (Enzo et al. 2001).

5.2 *Dosage of the Hydroponic Nutrient Solution*

The current recommendations on fertiliser use and dosage in TCS in open field cultivations are usually inappropriate and not transferable to SCS, because of the different functioning criteria and dynamics (Grattan and Grieve 1998). The HNS in SCS are mainly prepared at high concentrations for technical reasons:

(a) the HNS is usually automatically prepared from stock solutions that have been concentrated up to 200-times, using systems that are not always very accurate or maintained properly;
(b) farmers prefer an adequate and constant nutrient supply to the root zone to guarantee horticultural production (Lazzarin et al. 2001; Tognoni et al. 2005).

The latter point is supported through the use of a closed-cycle hydroponic system, which increases the water and nutrient efficiency. Nevertheless, in SCS, as in TCS in open fields, one of the main problems concerning the excessive supply of nutrients or the utilisation of an open-cycle hydroponic system is nitrate leaching (Thompson et al. 2002).

6 Indicators Used in the Soilless Culture System

An incorrect HNS management can damage plants, thus ruining the cultivation and productivity (Hussain et al. 2014). The utilisation of chemical indicators for water and HNS composition control and checking represents one of the most important instruments for a proper SCS horticultural production. Using indicators can lead to improvements in both the safety and nutritional characteristics of the raw material (Tomasi et al. 2015). The main indicators used for the adjustment of the water and HNS in SCS are pH, salt composition, EC, oxygen content and temperature. pH and EC are the two main indicators that undergo changes during cultivation in SCS, while the HNS mineral ratios usually do not change.

Parallel to the evaluation of the HNS chemical indicators, measurements and analyses can be performed in substrates and plant tissues, as they can provide information on the nutrients that have been absorbed (Castilla 2013). pH and EC are two indicators that are used to check the HNS conditions in the substrates, both during cultivation and at the end of the growing cycle. Apart from the direct determination of the ion, macro-, meso- and micronutrient contents in the plant tissue, it is also possible to indirectly evaluate the physiological status by observing the plant symptoms. Any deviation from optimal levels of pH, EC and ratio between nutrients in both the substrate and HNS induces alterations or modifications in different organs of the plants (Enzo et al. 2001).

6.1 pH

pH is one of the most important parameters that has to be measured and checked during SCS cultivation, because it determines the availability of the essential minerals, and consequently affects the nutrient absorption by the root system (Castilla 2013). The pH tolerance range for most horticultural species is 5.5–6.5. This means that plants in conditions outside this range are not able to efficiently use the elements dissolved in the HNS, especially iron, calcium and magnesium. An acidic pH could damage the root membranes and increase the manganese and aluminium concentrations until they reach toxic levels. Values of $\mathrm{pH} > 7.0$ in the HNS may induce the precipitation of phosphates, calcium carbonate and magnesium. In this case, nutrient deficiencies result in visual defects of the plants and the development of toxicity symptoms (Adams 2002; Hussain et al. 2014; Sonneveld 2002; Taiz and Zeiger 2002). In order to avoid salt precipitation, which promotes the transport of salt towards the roots, micronutrients are added in solutions with chelating agents (Silber and Bar-Tal 2008).

The pH of the HNS changes constantly in SCS, in conjunction with the crop development, due to nutrient uptake and the interaction of the elements with those of the substrate. Although slightly acidic pH conditions are preferable, biological interactions between the plant root system and bacteria and fungi can occur, and this allows nutrient absorption to take place, even at a higher pH than the optimal one (Somerville et al. 2014). Fluctuations of pH of 0.1 are considered non-critical (Sengupta and Banerjee 2012). In the case of large pH variations, it is necessary to introduce strategies and actions to keep the pH within optimum values. Because of the low buffer capacity of SCS, pH correction of HNS should be executed daily (Urrestarazu 2004).

With a basic pH in the HNS, the following actions can be taken:

(a) correcting the pH using acidic or sub-acidic solutions;
(b) providing an HNS with a lower pH;
(c) changing the ratio between N-NH_4^+ and N-NO_3^-, that is, supplying N-NH_4^+ of up to 20% of the total nitrogen amount;
(d) increasing the amount of manganese and phosphorus, because they are less soluble at high pH;
(e) increasing the humidity of the substrate.

On the other hand, the following actions can be taken for a basic pH in the HNS:

(a) correcting the pH using basic or sub-basic solutions;
(b) providing an HNS with a higher pH;
(c) changing the ratio between N-NH_4^+ and N-NO_3^-, that is, supplying N-NH_4^+ of less than 10% of the total nitrogen amount;
(d) reducing the amount of micronutrients dissolved in the HNS;
(e) reducing the humidity of the substrate.

Apart from improving nutrient solubility, correcting the pH to within an optimal range also allows specific elements to be provided, according to the solution that is used to correct the pH of the HNS (Santamaria and Valenzano 2001).

6.2 *Electrical Conductivity*

EC is an indiscriminate indicator of the overall salt concentration that is commonly used in agriculture. However, this value alone is not sufficient to establish either the suitability of the water to be used for the HNS preparation or to define the punctual, real and individual nutrient components in the solution (Hussain et al. 2014; Le Bot et al. 1998; Tomasi et al. 2015). Most soilless grown crops require HNS with salt concentrations of 1–1.5 dS m^{-1}, which can reach up to 2.5–3.0 dS m^{-1} in the case of species grown for fruit. The effects of the salt concentration in the HNS on horticultural production are complex, because the crops are influenced by various factors and conditions (Greenway and Munns 1980). Salts directly affect plant nutrition, because the ion concentration can create uptake competition with specific ions, such as sodium and chloride, and can thus reduce nutrient uptake and translocation (Grattan and Grieve 1998). This may lead to toxicity conditions and antagonism between the single elements (Castilla 2013).

Salinity stress decreases yield, limits leaf expansion, decreases root growth and the relative water content, reduces fruit size, and causes blossom-end rot (Giuffrida et al. 2008; Meloni et al. 2004; Netondo et al. 2004; Rodríguez et al. 1997). A reduced growth of horticultural crops can be due to the high osmotic pressure that results from a high salinity, which in turn favours plant water stress and hinders HNS absorption (Hussain et al. 2014; Läuchli and Epstein 1990; Silber and Bar-Tal 2008). On the other hand, salinity increases the dry matter, the total soluble solids content, the organic acids content, the phytochemical compound content, such as vitamin C, and other antioxidants in fruit and vegetables. It can improve the organoleptic quality and the firmness of the fresh produce, and extend the shelf-life (De Pascale et al. 2003; Fanasca et al. 2006; Gruda 2009; Krauss et al. 2007; Pardossi et al. 1999; Tomasi et al. 2015).

In the case of excessive EC, the following actions can be taken:

(a) supplying HNS with a lower EC;
(b) supplying HNS in high volumes;
(c) increasing the drainage percentage;
(d) extending the HNS supply period per day;
(e) stimulating nutrient absorption;
(f) temporarily replacing the HNS with water to wash away the excess salts and washing the system.

In the case of a low EC, the following actions can be taken:

(a) supplying HNS with a higher EC;
(b) supplying HNS in low volumes;
(c) reducing the drainage percentage;
(d) shortening the HNS supply period per day;
(e) increasing the frequency of the HNS supply (Enzo et al. 2001; Hussain et al. 2014; Lieth and Oki 2008; Savvas et al. 2007; Sengupta and Banerjee 2012).

6.3 Oxygen

Horticultural crops require dissolved oxygen levels in the HNS of about 5–6 mg L^{-1} to favour root respiration. Oxygen deficiency stress in horticultural crops can manifest in the form of hypoxia, which consists of an insufficient supply of oxygen to the roots, or in the form of anoxia, which consists of a complete lack of oxygen (Blokhina et al. 2003). Hypoxia can occur in SCS, while anoxia is rather rare (Kläring and Zude 2009; Morard and Silvestre 1996). In both conditions, root development is reduced, and this affects the metabolic processes and nutrient absorption, but can also favour fungal growth (Incrocci et al. 2000; Morard et al. 2000). The visible symptoms include tissue wilting, senesce of the older leaves and defoliation (Morard and Silvestre 1996; Taiz and Zeiger 2002).

The effects of oxygen deficiency on plant tissues depend on the duration and severity of the oxygen deprivation, on the tolerance of the species and on the growth stage (Blokhina et al. 2003; Fukao and Bailey-Serres 2004; Gorbe and Calatayud 2010). Hypoxia is particularly acute in hot periods, when water temperatures increase, because the saturation level for oxygen in water decreases and the rate of root respiration increases (Morard and Silvestre 1996). In order to avoid any negative repercussions on yield, growers can aerate the NS to enrich it with oxygen (Nicola et al. 2015).

6.4 Temperature

The HNS temperature is usually a more critical factor than the growing environment temperature, because it directly influences the root temperature and growing conditions (Somerville et al. 2014). Moreover, conditioning the air of the whole greenhouse requires more energy, and is technically more complicated than varying the HNS temperature (Urrestarazu et al. 2008). Changes in the root temperature have shown pronounced effects on the uptake of water and nutrients, such as nitrate and phosphate, on shoot growth, yield and quality in melon, watermelon and tomatoes (Cornillon and Fellahi 1993; Gent and Ma 1998; Nkansah and Ito 1995; Urrestarazu et al. 2008). Temperatures of the root zone below 18 °C and above 28 °C can affect the root status by reducing the dry weight, inhibiting its growth and extension and negatively affecting the uptake of nutrients (Bar-Yosef 2008).

SCS allow an accurate control to be made of the root temperatures, as it is possible to vary the HNS according to the needs. Heating the HNS determines a reduction in the dissolved oxygen, but also increases the root respiration rate and favours salt solubilisation; cooling the HNS results in an increase in the dissolved oxygen, but also partial salt precipitation (Raviv et al. 2008; Silber and Bar-Tal 2008).

7 Open-Cycle or Closed-Cycle Hydroponic Systems in Soilless Cultures

Flows can be set up as open-cycle or closed-cycle hydroponic systems, according to the HNS drainage management practices.

7.1 The Open-Cycle Hydroponic System

In open-cycle hydroponic systems, plants are fed a specifically prepared HNS, without recovering the drainage that leaches out from the system. This implies an excess water and nutrient supply, which results in an input loss, surface pollution and possible groundwater contamination (Jensen 1997; Incrocci et al. 2006). This system is currently used less because it is not fully sustainable. In order to ensure that the crop receives the proper water and nutrient supply, an excess volume and concentration of HNS is supplied, compared to what is needed. Regardless of the type of crop, a fraction of drainage close to 20–30% is in general necessary to avoid substrate salinization. Leaching in open-cycle hydroponic systems can range from 20% to 70–80% of the total amount of supplied HNS in the case of an EC of 3–5 dS m^{-1}, or in the case of a reduction in the evapotranspiration demand (Santamaria and Signore 2004; Savvas et al. 2007). In some growing systems, the drainage obtained at the end of the open-cycle hydroponic system in SCS is used in TCS in open fields (De Pascale and Barbieri 2000).

7.2 The Closed-Cycle Hydroponic System

Closed-cycle hydroponic systems have been implemented to reduce the critical issues that arise when open-cycle systems are used (Castilla 2013; Zekki et al. 1996). The drainage that flows out from the SCS lines is collected in tanks and re-inserted into the system (Hussain et al. 2014). The drainage should periodically be subjected to analysis (Massa et al. 2011). HNS monitoring can be performed using simple and portable equipment or through more complex instrumentation, even automated and computerized, to provide timely results in both the growing area and in the laboratory (Tomasi et al. 2015).

The development of specific sensors for the measurements of HNS indicators has allowed the water and nutrient balance to be defined more precisely. The HNS can be integrated in an appropriate manner by introducing single macro-, meso- and micronutrients, water or a new HNS according to the expected or obtained results, the adopted SCS and the cultivated horticultural species (Lazzarin et al. 2001; Tognoni et al. 2005). In general, the same HNS can be used for several weeks before a correction of the composition becomes necessary (Enzo et al. 2001).

An inadequate frequency of both the drainage control and correction can reduce the productivity and yield of closed-cycle hydroponic systems compared to open-cycle hydroponic systems. An HNS imbalance results in a low efficiency, due to an accumulation of ions, the release of root exudates or a reduced oxygen availability (Carmassi et al. 2005; Gorbe and Calatayud 2010). Similarly, the strength of the HNS recirculation and reuse can become a weakness, because it can favour the accumulation and the diffusion of undesirable organisms, such as microbes and pathogens, as well as toxic molecules. This condition may lead to a rapid spread of disease, and damage to the root system and later to the plants (Castilla 2013; Silberbush et al. 2005).

In general, the risk of microbial contamination increases proportionally with the increase in the size of the crop unit. Contamination risks are higher in those SCS that do not use a substrate than in those that do. This is due to:

(a) the direct contact between the HNS and the root system, while in SCS with a substrate, the latter acts as a buffer;
(b) the absence of physical separation between plants, although the continuous liquid flow that occurs in an SCS without a substrate favours contamination diffusion; in substrate-based systems, the defined and separated containers that host the crops limit this diffusion (Enzo et al. 2001).

7.2.1 Hydroponic Nutrient Solution in the Closed-Cycle Hydroponic System

SCS based on the recirculation of HNS require drainage sanitation systems, regardless of whether there is a substrate or not. The main sanitation systems are:

(a) sand or membrane filtration by means of septa, ranging from 0.01 to 10 μm in size. Because of the necessity of frequently cleaning the septa, the filtration is usually carried out by arranging the septa in series. Moreover, filtration allows the solids conveyed by the HNS, such as the residues of the substrate, roots, leaves, flowers, fruit or foreign bodies, to be physically separated;
(b) heat treatments using heat exchangers. A heat treatment is usually performed at 95 °C for 30 s in order to guarantee the sanitation effect. However, the utilisation of this technique is limited by the high energy costs;

(c) exposure to ultraviolet (UV) radiation in the 200–315 nm range. This is mainly performed in dark conditions on previously filtered HNS. This system is frequently used because it is effective against fungi, bacteria and viruses, although the exposure of HNS to UV radiation leads to iron precipitation and the need for its subsequent reintroduction;
(d) chemical treatments with chlorine, ozone, hydrogen peroxide or iodine in different concentrations to reduce microbiological contaminations (Incrocci et al. 2006; Savvas et al. 2013).

In order to ensure a high efficiency of the SCS using a closed- or semi-closed-cycle hydroponic system, the water utilised for the HNS preparation must be of high quality both as far as the chemical and microbiological contents are concerned (Montesano et al. 2007). When the total salinity of the HNS reaches a predetermined threshold value, it is necessary to provide the total or the partial replacement of the solution itself. In the case of partial replacement, the system is defined as semi-closed (Carmassi et al. 2005; Lazzarin et al. 2001; Silber and Bar-Tal 2008). In closed- or semi-closed-cycle hydroponic systems, thanks to the reduced environmental impact, the tendency is to supply 20–30% more of the HNS than the plant needs. This practice is introduced to prevent the crops from suffering from water stress, and to ensure a continuous leaching of the excess salt in the substrate (Santamaria and Signore 2004). The excess humidity that can arise, due to the high HNS frequency and the large quantity of HNS, might reduce the oxygen availability at a root level. The utilisation of a porous substrate with a high drainage capacity could reduce the root stress, thus favouring plant growth (Savvas et al. 2007).

In efficient closed- and semi-closed-cycle hydroponic systems, the supply and absorption of the water and nutrients are regulated to maximize the input and minimize the output (De Pascale and Barbieri 2000). The closed-cycle hydroponic system increases the efficiency of the use of input, by reducing the water loss by about 21% and the nutrients by about 17–35%, compared to open-cycle hydroponic systems. The disadvantages of closed- and semi-closed-cycle hydroponic systems are the greater structural investments and maintenance costs (Incrocci et al. 2006; Van Os 1999).

8 Planning the Nutrient Supply in Soilless Culture Systems

When planning the nutrient supply in SCS, it is important to determine:

(a) the HNS supply period per day, intended as the interval between the first and last treatments;
(b) the HNS volume supplied per unit area or per plant;
(c) the number of events per day (Enzo et al. 2001; Savvas et al. 2013).

These factors should be defined according to the SCS design, size and type. For instance, in substrate-based SCS, the volume and both the chemical and physical properties of the substrates have to be taken into account. Other factors that have to be considered are related to the species and to the phenological growth stage of the plant. Species grown in SCS can be divided into categories on the basis of their nutritional needs during the growing period:

- lettuce, chard, rocket, basil, mint, parsley, cilantro, chives, pak choi, cress, peas and beans have reduced nutritional needs;
- cabbage, cauliflower, broccoli, kohlrabi, beetroot, taro, onions and carrots have average nutritional needs;
- tomatoes, eggplants, cucumber, zucchini, strawberries and peppers have high nutritional needs.

Moreover, the environmental conditions have a direct effect on the HNS scheduling and needs (Sengupta and Banerjee 2012; Somerville et al. 2014).

8.1 Hydroponic Nutrient Supply Period per Day

The HNS supply period should occur concurrently with the photosynthetic activity. Its proper definition allows the efficiency of the uptake to be increased, thus reducing energetic costs for the HNS flow. Low light conditions and low temperatures limit the physiological activity of the plants, and thus reduce the water and nutrient consumption (Poorter and Nagel 2000). Exceptional interventions (e.g. during nighttime) could be carried out to correct critical situations, such as high HNS imbalances, high environmental temperatures, and low humidity of the substrate and of the root zone.

8.2 Hydroponic Nutrient Volume Supplied

The HNS volume supplied in each intervention should be sufficient to satisfy the needs of the plants and compensate for the absorption, transpiration, and water and nutrient losses in the substrates, if present, and to replenish its reserves (Castilla 2013). In substrate-based SCS, the supplied HNS volume should allow a drainage of about 0–5% during root expansion, 15–20% during the vegetative stage and 25–35% during crop growth (Lazzarin et al. 2001). An appropriate HNS volume is also important, because an excess dosage can cause structural damage to the tissues, such as cracking, increased susceptibility to physical damage, delayed maturity and a reduced soluble solids content (Luna et al. 2012; Peet and Willits 1995). HNS volume supplies depend on the irrigation system design. When designing the SCS system, the HNS volumes and scheduled automations should be planned so that the volume can be adjusted as necessary, during the growing cycle, to follow the crop needs and in order to avoid plant stress.

8.3 Number of Events per Day

The number of events per day should be defined and adapted to avoid plant stress and root damage, due to water stagnation or input losses. The water and nutritional needs of the crops are reduced immediately after transplanting, and the irrigation strategy should stimulate root expansion through a limited number of events. In the early crop stages, that is, in the first 2–3 days, the interventions should be aimed at facilitating and promoting a vertical root expansion. In a later phase, that is, after 5–10 days, the number and duration of the irrigation interventions should be minimized to favour a horizontal root expansion. Subsequently, during plant growth, the number of events should be defined according to the drainage volume and water, and to the nutritional needs of the crop (Enzo et al. 2001).

The effects of the irrigation frequency change during plant growth for the following reasons:

(a) during the early growth stage, the roots are mainly located at the top of the substrate, and are highly sensitive to drying and rewetting processes;
(b) the roots are more active in the early growth stage than in the later stages (Silber and Bar-Tal 2008).

In conditions of high temperatures or in which the HNS film that surrounds the root system is not changed frequently, it is possible to observe an increase in salinity close to the root zone, because the plant's demand for water increases more than that for nutrients (Le Bot et al. 1998; Pardossi 2003). In these cases, an increase in the numbers of HNS interventions is advisable. Reducing the time lag between successive fertigations allows a constant water content to be available in the substrate, and thus reduces variations in the nutrient concentrations and increases their availability. A high irrigation frequency favours P and K dissolution in the HNS and shortens the period during which salt precipitation takes place (Gorbe and Calatayud 2010).

The beneficial effects of high-frequency irrigations are considered an effective system to optimise the environment conditions of the roots. The irrigation frequency, and thus the water distribution in the substrate, both affect the root system by modulating its distribution, growth, density and architecture (Coelho and Or 1999; Liao et al. 2001). On the other hand, a too frequent irrigation leads to a wet substrate surface, which is subjected to continuous evaporation, thus causing nutrient accumulation in the top layer and reducing their availability to the roots (Sonneveld and Voogt 2009). Consequently, the nutrient concentrations in the substrate may be high or excessive immediately after the HNS supply, and then be lacking. An excessive irrigation frequency increases the leaching fraction (Lieth and Oki 2008).

9 Hydroponic Nutrient Solution Supply Systems

The methods used in SCS to deliver and distribute water and nutrients to horticultural crops vary in function of the growing system that is adopted. The HNS in SCS can be supplied from below the plant, using a sub-irrigation system and nebulisation, or from the top, using a drip irrigation system or sprinkling (Castilla 2013).

9.1 The Sub-irrigation System

A sub-irrigation system can be used in SCS, with or without a substrate, to exploit the capillary phenomenon in order to efficiently replenish the plant root system with water and nutrients (Vavrina and Hochmuth 1996). A sub-irrigation system has a unidirectional HNS flow from the bottom to the top of the container in which the plants are standing (Incrocci et al. 2006; Savvas et al. 2013). This unidirectional flow of the HNS improves the stability of the HNS itself, and results in reduced phytopathological risks. This condition allows the HNS to be analytically controlled, and the disinfection treatments that favour plant growth to be reduced. The HNS supply that takes place via a sub-irrigation system can be continuous, using static or dynamic volumes, with a partial or complete HNS flow in the cultivation modules, or discontinuous. A discontinuous sub-irrigation system ensures good root aeration. Sub-irrigation systems can be planned either with open- or closed-cycle hydroponic systems.

9.2 Nebulisation

Nebulisation is an irrigation practice that is used in aeroponic systems. It consists of the supply of HNS, as micro particles, directly to the roots of the plants (Lazzarin et al. 2001; Malorgio 2004). It is a highly innovative, discontinuous system. However, it requires precise calibration to provide the correct water and nutrient amounts, particularly in order to avoid root drying. Nebulisation is usually coupled with a closed-cycle hydroponic system.

9.3 The Drip Irrigation System

The drip irrigation system is a localized HNS supply system, which consists of the supply of water and nutrients close to the plants, thanks to the presence of a pipe system (Tognoni et al. 2005). A precise and punctual HNS distribution allows the water and nutrient losses to be reduced, because of the high efficiency of the system. Drip irrigation systems require high initial investments for the materials and the automation system that is necessary to perform the irrigation scheduling. The high initial costs are balanced by the high efficiency of the system itself (De Pascale and Barbieri 2000). An appropriate drip irrigation use for horticultural crops implies technical knowledge on high frequency, physical HNS flows and both reduced pressure and volumes (Silber and Bar-Tal 2008). It is necessary to set up the system in order to reduce salinization phenomena close to the crop root system, to avoid partial or total clogging of the lines and to enable an efficient use of the resources (Castilla 2013). A reduction in the humidity in the substrate may arise from a malfunctioning of the drip irrigation, and this could cause a discontinuous HNS supply, which in turn could induce an adaptation of the root system and a limited nutrient uptake by the crop. Drip irrigation can be performed using single or multiple drippers, according to the volume that needs to be transferred. The system can be set up in both open- and closed-cycle hydroponic systems.

9.4 The Sprinkling System

The provision of water or HNS via sprinkling is an over-head treatment that is rarely adopted in SCS for sanitary reasons. The reduced use of over-head irrigation in SCS is due to the risk of promoting microbial diffusion directly on the edible part of the horticultural products (Savvas et al. 2007; Sengupta and Banerjee 2012). Over-head irrigation is usually adopted at the nursery stage to favour seed germination and seedling emergence; it is also adopted during the crop cycle in particularly high temperature and low humidity conditions to acclimatise and restore the optimum growth conditions. In these conditions, the sprinklings should take place when the air temperature is low (Enzo et al. 2001).

10 Conclusions

The future of horticulture in a changing world is an important issue as far as environmental sustainability, and economic and social challenges and developments are concerned. The application of specialized and standardised growing techniques could be an efficient strategy to increase food security in a context in which both land and water are becoming scarce. The awareness of growers, supply chain partners, research institutes and governments of the technical and socio-economic factors pertaining to protected cultivation and SCS is crucial for horticultural production and profitability in modern dynamic and intensive systems. SCS allows the provision of water, nutrients and oxygen to be controlled and regulated, according to the needs of the root system, by means of HNS, on the basis of the crop stage and the punctual and real crop needs.

Some SCS use substrates or substrate mixes with specific chemical and physical properties. These substrates should be chemically stable to avoid the release of elements that could cause changes in the HNS salinity, could create problems for the filtering and sanitising systems, and could induce unwanted salt precipitation and phytotoxicity. The HNS in SCS should be formulated using microbiologically safe water. Macro-, meso- and micronutrients should be integrated precisely, on the basis of the chemical composition of the water, because they each have a specific function in the metabolism and pathway of the plants. It is necessary to consider a combination of the complex interactions that occur in the HNS formulation between the individual elements, which affect plant growth, crop yield and injury susceptibility. The availability of the macro-, meso- and micronutrients depends on the pH, EC, salt composition, species, SCS, substrate and on environmental factors. The ratio between the elements dissolved in the HNS does not usually change during plant cultivation, while major changes take place concerning the pH, EC and substrate humidity, with consequent relevant effects and responses in the plants. These indicators should be monitored periodically in order to provide appropriate corrective actions to re-obtain the optimal HNS values and composition. It is important to determine a specific HNS supply period per day, volume per unit area or per plant and number of events during the day in order to obtain a successful crop cultivation in SCS. These factors should be defined according to the design, size and type of the SCS, the species, the phenological growth stage, the absorption rate, the transpiration losses and the environmental conditions.

HNS, whether continuously or discontinuously distributed, according to which type of SCS is used, can be supplied directly to the root using a sub-irrigation system or a nebulisation system, or from the aerial part using a drip irrigation system or a sprinkling system. The sub-irrigation system implies a unidirectional flow of HNS from the bottom to the top of the container in which the plants stand, and thus implies an improvement in the HNS stability and a reduction in the phytopathological risks. Nebulisation enables a precise HNS supply, as micro particles, directly onto the root system, but it requires high technology and automation. Drip irrigation allows a localized HNS supply, thanks to a pipe system that consents a precise and punctual HNS distribution, and the reduction of water and nutrients losses. Sprinkling is seldom used for horticultural crops cultivated in SCS because of the safety risk, except during the nursery stages or in particular cultivation conditions.

The HNS supply in SCS can be set up with either open- or closed-cycle hydroponic systems. In open-cycle hydroponic systems, plants are fed with a specifically prepared HNS, without recovery of the drainage, and this results in input losses, surface pollution and possible groundwater contamination. In closed-cycle hydroponic systems, the drainage is collected in tanks and re-inserted into the system, after appropriate analysis, sanitation and nutrient integrations.

HNS control and the use of indicators can help improve the safety and nutritional characteristics of the raw horticultural material grown in SCS. Each horticultural crop has specific water and nutrient supply needs, which are induced by specific physiological responses. The content and dynamics of the absorption of elements by plants grown in SCS are valuable indicators of the quality and postharvest shelf-life of the raw material.

Glossary

DFT Deep flow technique
EC Electrical conductivity
EF Ebb-and-flow flotation
FGS Floating growing systems
FL Continuous flotation
GFT Gravel film technique
HNS Hydroponic nutrient solution
MGS Mobile gully system
NFT Nutrient film technique
NGS New growing system
N-NH$_4^+$ N in ammoniacal form
N-NO$_3^-$ N in nitric form
SCS Soilless culture systems
TCS Traditional culture systems
UV Ultraviolet

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Plant Breeding for Improving Nutrient Uptake and Utilization Efficiency

Antonio Ferrante, Fabio Francesco Nocito, Silvia Morgutti, and Gian Attilio Sacchi

Abstract Mineral nutrients are essential for plants where they play specific metabolic functions. Macronutrients are required in higher quantities, while micronutrients in smaller amounts. Deprivation or paucity of any macro- or microelement has negative effects on plant development and yield, potentially impairing the plant capability of reaching and completing the reproductive phase. Therefore, the evolution of mechanisms able to maintain the tissue mineral nutrient homeostasis in response to changes in their availability in the growth substrate is a key factor under both the evolutionary (biological) and agricultural (yield performance) points of view.

The supply/availability/plant intake and assimilation of mineral nutrients are often limited by extrinsic (i.e., environmental) and intrinsic (developmental, biochemical, physiological), plant-related factors. Since all of the latter are under genetic control, use of efficient plant breeding procedures for improving the complex trait of plant nutrient utilization efficiency is of paramount importance. This issue is made more compelling since intensive agriculture, necessary to satisfy the increasing food demand on Earth's scale, requires, in order to reintroduce into the soil the mineral nutrients removed with plant harvest, the use of large amounts of fertilizers posing serious soil, air and water pollution concerns.

Nitrogen, with phosphorus and potassium, is the macronutrient that more deeply affects crop production.

The chapter presents a survey of the main molecular aspects determining the biochemical and physiological bottlenecks that limit Nutrient/Nitrogen Use Efficiency (Nu/NUE) in crop plants, with particular focus on leafy vegetables. The most innovative molecular approaches applicable to overcome these restraints, based upon the use of novel genome- and transcriptome-based technologies, are reviewed.

Keywords Fertilizers • Mineral nutrition • Molecular markers • Nitrogen • Next generation sequencing • Quantitative trait loci

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1 Introduction

Mineral nutrients in plants have specific functions and are essential for metabolism. Some of them are required in high quantities and are called macronutrients, while others, indispensable in small amounts, are defined as micronutrients. In order to cope with the negative effects on their biological cycle of the deprivation/paucity of any macro- or microelement, plants have evolved mechanisms aimed at maintaining the tissue homeostasis of mineral nutrient ions upon changes in their availability in the growth substrate.

Intensive agriculture requires the use of large amounts of fertilizers in order to reintroduce into the soil the mineral nutrients removed with plant harvest. Among the different mineral nutrients, those that most affect crop production are nitrogen, phosphorus and potassium. To date, the global fertilizers consumption is estimated about 194 m metric tons (of which, 16 as N, 45 as P_2O_5 and 33 as K_2O) and it is forecast that it will increase in the next future of an average 2% yearly rate (Food and Agriculture Organization of the United Nations 2015). Although the volatility and fluctuation of energy prices in the last years have decreased, the expense for fertilizer purchase is one of the main input costs for farmers.

Only a minor fraction of the nutrient provided to the soil as fertilizer is taken up by the crop (AR: Apparent Recovery) and, in turn, only a fraction of the absorbed amount is assimilated (PE: Physiological Efficiency) finally influencing yield. AR and PE are calculated as follows (Craswell and Godwin 1984):

$$\mathrm{AR} = 100\,(\mathrm{N_F} - \mathrm{N_{nF}})/\mathrm{F} \tag{1}$$

$$\mathrm{PE} = 100\,(\mathrm{A_F} - \mathrm{A_{nF}})/\mathrm{F} \tag{2}$$

where: F is the dose of nutrient supplied with fertilizer; N_F and A_F are the total amounts of the nutrient taken up and assimilated by the crop if fertilized, respectively; N_{nF} and A_{nF} are the amounts of the nutrient taken up by the crop from the soil natural reserves and assimilated, respectively.

The average AR values for the main crops are not higher than 35% in the case of nitrogen (Raun and Johnson 1999), range between 10 and 30% for phosphorus (Malhi et al. 2002) and are at maximum 50% for potassium. The limited efficiency of a crop in taking up and assimilating mineral macronutrients is due to both environmental (i.e., soil characteristics) factors and the genetically determined potential performance of the plants, and generates environmental and economic concerns.

The parameter that more clearly links plant yield to availability of a mineral nutrient is the Agronomic nutrient Use Efficiency (AUE). It is defined as the ratio dY/dF, where: dY is the infinitesimal increase in yield due to the infinitesimal increase in availability of the nutrient supplied with fertilization (dF). The AUE value can also be calculated as the product of crop Removal Efficiency (RE) times crop PE. The RE is in turn defined as the ratio dU/dF, where U is the nutrient adsorbed from the crop, while PE is the ratio dY/dU. Therefore, the equation is:

$$\mathrm{AUE} = \mathrm{RE} \times \mathrm{PE} = dU/dF \times dY/dU = dY/dF \tag{3}$$

In the past 50 years, the important outcomes of intensive agriculture have been dependent on the adoption of high-yield crop genotypes requiring increasing addition to the soil of industrially-produced nitrogen and phosphorus fertilizers, and have been accompanied by a dramatic drop in the AUE of the two nutrients (Tilman et al. 2002).

Under the point of view of environmental sustainability, it should be stressed that significant amounts of both nitrogen and phosphorus supplied as fertilizers are lost from agricultural systems, with the consequence of negatively affecting the quality of surface- and underground water and, in the case of nitrogen, inducing air pollution for the emission of gaseous nitrogen oxides from the soil. In order to limit further potential environmental damages and risks for the safety of living organisms, included humans, the European Union issued a specific directive (91/676/EEC, 2 December 1991) regulating fertilization practices in the so-called nitrate-vulnerable zones.

Concerning AUE, and in particular the *dY/dU* term (Eq. 3), some distinctive considerations concerning leafy vegetable crops with respect to other crops must be done. Indeed, all the genetic, physiological, environmental and/or agronomical variables included in the process, that in major crops affect the remobilization of N taken up before flowering and its contribute to the yield and protein tenor of the harvested organs, are negligible for leafy vegetables. For the latter, in fact, it is determinant the efficiency of the conversion of the nitrogen acquired by the plant into total plant biomass. For leafy vegetable crops the remobilization of N becomes important, even if within certain limits, for what concerns the relationship between the not completely developed leaves, that act as sinks for both C and N, and the older or senescent leaves, that act as sources for both C and N.

In the case of leafy vegetables, an additional issue concerning the AUE of nitrogen fertilization should be taken into account. In these produces, a correct balance between the amount of nitrate taken up from the soil (N_F, Eq. 1) and the entity of its assimilation (A_F, Eq. 2) has to be searched for, in order to avoid excessive accumulation of this anion in the vacuole of leaf cells. Indeed, high nitrate dietary intakes are associated with the onset of gastrointestinal cancer and other diseases (Cavaiuolo and Ferrante 2014; Santamaria 2006).

From the above issues, it results evident that economic and environmental reasons stimulate the urgent development of novel crop genotypes and improved crop management practices aimed at increasing the Nitrogen Use Efficiency (NUE) of agricultural systems.

Considering its importance for crop yield, its limited availability in soil and the impressive global demand for fertilizers (foreseen to be, in the next future, around 120 m metric tons; Food and Agriculture Organization of the United Nations 2015), it is reasonable that the majority of the research efforts aimed at improving crop nutrient use efficiency have been focused on nitrogen. In this chapter, the molecular and physiological bottlenecks limiting nutrient use efficiency in plants, as well as the current and novel approaches to overcome them, are synthetically listed with a particular focus on nitrogen.

2 Physiological, Biochemical and Molecular Traits Affecting Nitrogen Uptake by Roots

2.1 Root Development and Morphology

The acquisition of mineral nutrients by plants is the result of bi-univocal root-soil interactions. Root growth and biochemical/physiological activity affect the physical, chemical and microbiological features of the soil volume (rhizosphere) in their proximity and are, in turn, markedly affected by soil properties.

The spatial root arrangement in the soil (assessable on the basis of root depth, lateral root expansion, and root length densities), together with the variety of the components (roots and root segments) that make up the root system and their mutual relationship (topology) define the so-called Root System Architecture (RSA; Hodge et al. 2009).

Different RSA ideotypes have been proposed for optimal soil mineral nutrient capture, able to confer to the plant a better NUE. The Steep, Cheap, and Deep (SCD) ideotype consists in root phenes (i.e., individual genetically determined traits, such as shallow growth angle, small diameter, high number lateral roots and long root hairs) able to enhance the ability of roots of exploring and exploiting deeper soil horizons, where availability of nitrate, the dominant form of N in most agricultural soils, is higher. Several components of this ideotype apply to maize and, in general, to monocotyledonous crops, but they can be considered valid also for dicotyledonous crops (Lynch 2013). Roots of most crops take up N from the soil, other than nitrate, in the forms of amino acids, urea or, when the plant grows on acidic and anaerobic soils, ammonium (NH_4^+). Since NH_4^+ is relatively immobile in the soil, the RSA ideotype for this cation resembles that of K^+, with intense lateral rooting, production of root hairs, and particularly high root length density. In this framework, mathematical models have been developed in several crops, including vegetables such as leek, red beet and cabbage, to simulate root growth and nutrient uptake (Pedersen et al. 2010).

The natural ability of plants to invest energy in root development to explore the soil in depth or laterally ensures nutrient supply and survival in extreme environments (Robinson 1994). The root penetration ability in the soil and root density have been studied in several crops to estimate their potentiality for nitrogen uptake (Delgado et al. 2000).

2.2 Nitrogen Uptake by Roots and Systemic Fluxes Within the Plant

In order to increase AUE of nitrogen in plants, a deep knowledge of how they take up the nutrient from the soil is fundamental.

More than 98% of total nitrogen in the soil is present as organic compounds. Only a minor fraction of these nitrogen forms (i.e., amino acids and some peptides) is directly taken up by the roots. Biological processes driven by soil microorganisms mineralize organic N into nitrate (NO_3^-) and NH_4^+, that are the two inorganic N sources taken up by root systems.

In aerobic soil conditions, NO_3^- is the predominant fraction of inorganic N present in the circulating soil water solution. Its concentration can spatially and temporally vary in the range 100 μM–20 mM, depending on the balance between inputs, due to microbial mineralization activity and the possible addition of inorganic fertilizers, and outputs, consisting in the amounts taken up by the roots plus those leached (since the negatively charged NO_3^- is not adsorbed on the surface of the soil minerals) towards deeper soil horizons.

In order to cope with the dynamic variations in the concentrations of NO_3^- in the soil solution, plants have evolved several root uptake systems with different affinity for the anion. When the concentration of NO_3^- in the soil solution is higher than 1 mM, the activity of the so-called Low-Affinity Transport System (LATS) operating by transporters localized on the plasma membrane (PM) of root cells is dominant. These transporters are encoded by elements belonging to the *NRT/PTR* (Nitrate Transporter/Peptide Transporter) gene family, recently renamed as *NRT1/PTR Family* (*NPF*; Léran et al. 2014). The values of the apparent K_M (Michaelis Menten's constant) of these transporters for NO_3^- average in the mM range; they mediate the active influx of the anion by a symport mechanism driven by the proton electrochemical gradient generated across the PM by the activity of the PM H^+-proton pump. When the concentration of NO_3^- in the soil solution is lower than 1 mM, the activity of the so-called High-AffinityTransport System (HATS), mediated by transporters controlled through the *NRT2* gene family, becomes prominent. The apparent K_M for NO_3^- of these proteins, operating by a H^+-coupled mechanisms, averages in the μM range. The *NRT2* gene family includes inducible elements (*iHATS*), expressed in response to low NO_3^- availability, as well as constitutive elements (*cHATS*), that are not nitrate-inducible (Miller et al. 2007; Okamoto et al. 2006).

NRT1, that belongs to the subgroup of nitrate/nitrite transporters (Pao et al. 1998), transports nitrate, histidine, and nitrite; NRT2, that belongs to the subgroup of H^+-dependent oligopeptide transporters (Galvan and Fernandez 2001), transports peptides, amino acids, nitrate, chlorate, and nitrite. Both the NRT1 and the NRT2 transporters mediate the active movement of NO_3^- across the plasma membrane through an H^+-symport mechanism, energized by the proton electrochemical gradient generated by the activity of the PM H^+-ATPase pump (Crawford and Glass 1998; Forde 2000, 2002). It has been proposed that in both systems two H^+ cross the plasma membrane per each NO_3^- taken up, and that this mechanism is tightly regulated by cell pH (Ritchie 2006).

The molecular basis of the transport systems involved in the absorption of NO_3^- from the soil and its systemic fluxes within plants, as well as that of their complex regulatory network, are coming to light in the model plant *Arabidopsis thaliana*. Nevertheless, knowledge of the orthologous genes in crops, with particular regard to vegetable ones, is still scanty.

In *A. thaliana* roots, the complex activity of the protein encoded by the *NRT1.1* gene has been widely studied providing a paradigm that is currently under investigation in other species. *NRT1.1* acts as both a low-affinity NO_3^- transporter (K_M approx. 5 mM; Huang et al. 1999) and a sensor able to activate the expression of NO_3^--related genes (Ho et al. 2009). In particular, when bound to the anion, *NRT1.1* triggers a regulatory cascade pathway that leads to the auxin-related development of root architecture traits able to optimize the capture of the anion from the soil and its assimilation in the plant (Ho and Tsay 2010; Krouk et al. 2010). Moreover, *NRT1.1*, thanks to the specific phosphorylation of the Thr residue in position 101 operated by the CIPK23 (CBL-Interacting Protein Kinase 23) protein under nitrogen shortage, shifts its affinity for NO_3^- to the μM range, behaving as a high-affinity transporter (Ho et al. 2009).

Recently, Hu et al. (2015) demonstrated that in the rice *OsNRT1.1B* gene, homologue of *AtNRT1.1*, a Single Nucleotide Polymorphism (SNP) causes the substitution in the encoded protein of the Thr residue at position 327 with a Met. This substitution is responsible for the higher nitrate uptake (and in turn NUE) of the cultivars belonging to the subspecies *indica* in comparison with that of the subspecies *japonica*. *NRT1.1.* could therefore represent an interesting target in crop breeding for improved NUE.

A primary role in the constitutive component of the LATS is played by the transport protein NRT1.2, localized in the root hairs and endodermis of the primary roots as well as in the fully differentiated region of roots.

The root-to-shoot long-distance nitrate translocation involves mainly *NRT1.5*, *NRT1.8*, *NRT1.9*, three members of the NRT1 family (Bai et al. 2013; Dechorgnat et al. 2011).

The iHAST is sustained by proteins encoded by members of the *NRT2* gene family, and in particular by the high-affinity transporter NRT2.1, localized at the plasma membrane of rhizoderm, cortex and endodermis cells of fully differentiated primary roots. Expression of this transporter is stimulated when plants are grown under N shortage conditions; the protein is active only in a tetrameric configuration consisting in two NRT2.1 subunits associated with two subunits of a smaller peptide, encoded by the *NAR2* (*Nitrate Assimilation Related*) gene, whose function is to address the NRT2.1 subunits towards the plasma membrane. To date, in *A. thaliana* seven *NRT2* genes have been identified. In this species, knockout mutants of *NRT2*.1, *NRT2*.2, *NRT2*.4 and *NRT2*.7 have been used to demonstrate their involvement in NO_3^- transport (Bai et al. 2013), with particular regard to root cells. Among these transporters, *AtNRT2*.7 was more expressed in shoots than in roots (Wang et al. 2003), suggesting a role for the related protein in the NO_3^- translocation activity.

In *A. thaliana*, under N limitation the levels of both *NRT1.1* and *NRT2.1* mRNAs are augmented in roots as a response to increased photosynthate allocation to this organ (Lejay et al. 1999). It has been recently shown that overexpression of a vascular H^+-translocating pyrophosphatase (PPase) improves NUE in romaine lettuce by enhancing, under NO_3^- limitation, the allocation of photosynthates (sucrose) to the roots and the expression of the lettuce *NRT2.1* gene (Paez-Valencia et al. 2013). Angiosperms show four *NRT2* elements on average and more than 50 members of the *NPF* family (von Wittgenstein et al. 2014).

Most nutrients are actively taken up, via specific transporters, in the roots and translocated via the xylem to the leaves, where they are utilized. Nevertheless, presence of an efflux movement of NO_3^- across the plasma membrane has also been demonstrated. This passive efflux is mediated by the excretion transporter Nitrate Excretion Transporter1 (NAXT1) encoded by a gene belonging to a sub-family of the *NRT1* family (Segonzac et al. 2007). The physiological role of this efflux remains unknown, even if, under biotic and abiotic stress, it has been observed to increase up to overcoming the total NO_3^- influx. The root stele localization of some NAXT proteins allows to hypothesize their involvement in NO_3^- xylem loading. Increasing evidence supports the involvement, in *A. thaliana*, of different members (AtNRT1.3-9) of the NRT1 family in loading and unloading of NO_3^- from the xylem vessels, thus participating to the systemic distribution of the anion within the plant (for an overview, see Wang et al. 2012).

The cytosolic concentration (1–5 mM) of NO_3^- is quite stable independent from the anion availability. It is the resultant of the net anion uptake into the cell (i.e., the balance between its influx and efflux across the plasma membrane), its reduction to nitrite and then to ammonium (see below), and its compartmentation into the vacuole. The vacuolar NO_3^- pool plays different physiological roles, being involved in maintaining cell turgor (Miller and Smith 2008), providing the anion to the cytosol facing possible N limitations, avoiding undesired high NO_3^- cytosolic concentration for exceeding NO_3^- availability. Within the cell, other NO_3^- pools can be found in the chloroplast (approx. 5 mM in spinach leaves; Schroppelmeier and Kaiser 1988) and in the endoplasmic reticulum (Siddiqi and Glass 2002).

In *A. thaliana*, sequestration of NO_3^- into the vacuole is mediated by a $NO_3^-/2\ H^+$ antiporter mechanism operated by two distinct but related transporters, AtCLCa and AtCLCb, encoded by two elements belonging to the *ChLoride Transporters* (*CLC*) gene family (von der Fecht-Bartenbach et al. 2010). Interestingly, the activity of the AtCLCa transporter is finely regulated, in a coordinated way, with the expression of both *NRT1.1* and *NRT2.1*, in order to maintain the cytosolic NO_3^- concentration within a physiological value (Monachello et al. 2009; Wang et al. 2009). Excessive amounts of NO_3^- stored in the vacuole result in reduced NUE of the plant. This result was recently confirmed by Han et al. (2015) who, analyzing two *Brassica napus* cultivars characterized by high and low NUE, showed that this difference was related to the activity of both types of vacuolar proton pumps (vH^+-

ATPase and vH$^+$-PPase) that generate the H$^+$ electrochemical gradient across the tonoplast. In particular, in the low-NUE cultivar the activities of the two pumps in the root cells are particularly pronounced and induce a substantial accumulation of NO_3^- into the vacuole, thus reducing the amount of NO_3^- translocated by NRT1.5 and NRT1.8 towards the shoot, where it is eventually assimilated.

When the value of soil redox potential is low, the prevailing form of inorganic nitrogen shifts from NO_3^- to NH_4^+. Plants take advantage in absorbing N as NH_4^+ since its assimilation needs less metabolic energy compared to NO_3^-. Nevertheless, on one hand excess NH_4^+ in the soil can be toxic for plants (Britto and Kronzucker 2002); on the other hand, in aerobic soils the cation added as a fertilizer is rapidly converted to NO_3^- by soil nitrifying bacteria. When both forms are available as N source, plants prefer NH_4^+ than NO_3^- (von Wirén et al. 2000). This discrimination occurs as a direct negative effect of NH_4^+ on the NO_3^- uptake systems (Kronzucker et al. 1999a) and as a positive effect of NO_3^- on the NH_4^+ uptake systems (Kronzucker et al. 1999b).

In many plant species, including vegetable crops such as *Lycopersicon esculentum* (Lauter et al. 1996; von Wirén et al. 2000), *Brassica napus* (Pearson et al. 2002) and *Phaseolus vulgaris* (Ortiz-Ramirez et al. 2011), several Ammonium Transporters (AMTs) have been identified and characterized. They operate through an H^+/NH_4^+ uniporter or ammonia channel (Khademi et al. 2004; Ortiz-Ramirez et al. 2011). In order to avoid the risks of toxic ammonium accumulation in the cell, AMTs undergo a NH_4^+-induced phosphorylation of a Thr residue leading to a negative modulation of their activity (Lanquar et al. 2009). Domestication has drastically reduced the variability in *AMT* alleles in crops and thus the actual chances to obtain new cultivars with increased *dU*/dF for NH_4^+ rely on generating new specific variability by biotechnological approaches and/or identifying interesting alleles in wild species related to the specific crops.

Due to its high N tenor, urea is the N fertilizer most widely utilized in agriculture, by soil fertilization and/or foliar application. Microbial soil urease catalyzes the hydrolytic scission of urea into CO_2 and two molecules of NH_3/NH_4^+, that become in turn available for root uptake or nitrification by soil microbiota. By feeding roots with ^{15}N-urea, Safeena and co-workers (Safeena et al. 1999) verified that, in roots of rice plants grown in submerged, up to 10% of the nitrogen deriving from applied urea is taken up in the form of intact urea. Experimental evidence about the uptake of external urea by plant cells is described also for soybean (Stebbins et al. 1991) and potato (Witte et al. 2002).

Although urea transporters have long been identified in bacteria and animals, only in the last years evidence of the existence of urea-permease proteins at the plasma membrane of plant root cells has emerged (Wang et al. 2008). Two types of plant plasma membrane urea transporters have been described. The former one, belonging to the class of the Major Intrinsic Membrane Proteins (MIPs), mediates a passive influx of urea into the cells; the latter one, known as DUR3, mediates the high-affinity (K_M approx. 75 μM) influx of the molecule. In rice roots, the *OsDUR3* transporter is upregulated under N shortage (Wang et al. 2012). Recently, Zanin and co-workers (Zanin et al. 2014) identified and functionally characterized the

OsDUR3 orthologues in maize, reporting experimental evidence that these high-affinity urea transporters, whose transcript levels increase in root cells of plants experiencing N shortage, probably operate through an H^+/urea co-transport mechanism. Currently, no evidence exists, to our knowledge, about the presence of *DUR3* orthologues in vegetable crops. It is reasonable to presume that the urea transport pathways might be an interesting target for improving dU/dF in plants.

The need for reducing the input of inorganic N fertilizer in crop production has switched on again the interest on plant organic N nutrition. The soil solution may contain several soluble organic compounds, such as peptides, proteins and free amino acids. Free-living soil microbes, mycorrhizal fungi and plant roots release into the soil proteolytic enzymes that hydrolyze peptides releasing amino acids. The concentration of the different amino acids in the plant rhizosphere depends on their mobility in the bulk soil (positively charged amino acids like L-Arg and L-Lys are less mobile than neutral ones) and on their uptake by soil microbes and fungi. All major mycorrhizal types and non-mycorrhizal plant species are able to take up amino acids from the soil (Lipson and Näsholm 2001) at concentrations lower than 10 μM (Näsholm et al. 2009). The plant root systems involved show apparent K_Ms for the different amino acids in the range 10–300 μM. At the molecular level, putative plant amino acids transporters are encoded by members of at least five gene families. Experimental evidence shows that neutral and acidic amino acids are taken up into the roots by the LHT1 (Lysine HistidineTransporter 1) transporter, belonging to the gene family *Aminoacid Transport Family* (*ATF*) at the plasma membrane of rhizoderm, cortex and endodermis root cells of nonmycorrhizal plants (Näsholm et al. 2009). On the contrary, the uptake of basic amino acids, i.e., L-Arg and L-Lys, into the same root cells of non-mycorrhizal plants is operated by the AAP5 (Amino Acid Permease 5) transporter (Näsholm et al. 2009). To date, it is not possible to exclude that other transporters could be involved in amino acid absorption by plant roots.

For the majority of plants, the short-term rates of amino acid uptake by roots result lower than that of NH_4^+, but significantly higher than that of NO_3^-. Nevertheless, for different reasons including their diffusion rate in the soil, in the field the relative concentrations of the three absorbable N sources at the rhizosphere level can differently favour their relative uptake into the roots.

Currently, direct evidence of the direct contribution of organic N to plant nutrition in agro-systems and, in particular, of the possibility to manage its absorption pathways in order to increase crop NUE is still lacking.

2.3 Nitrogen Assimilation Pathway

The dY/dU term in Eq. 3 defines the infinitesimal increment in productivity per the infinitesimal increment in the amount of nutrient in the plant due to fertilization. In other words, it represents the Nitrogen Use (assimilation) Efficiency, i.e., the fraction of plant-acquired N converted to total plant biomass or grain yield.

The pathway of nitrogen assimilation is to date well characterized and the key enzymes involved, as well as their regulation, have been extensively studied in both model plant species and crops. The NO_3^- taken up from the soil is in part assimilated in the roots, but the majority of NO_3^- is loaded into the xylem and translocated to the leaves, where it is eventually assimilated. In the cytosol of root or leaf cells NO_3^- is reduced to nitrite (NO_2^-) by the finely regulated activity of Nitrate Reductase (NR). Then, NO_2^- crosses the inner membrane of plastids or chloroplasts of root or leaf cells, respectively, via a not yet identified transporter and it is reduced to NH_3 in the stroma by the activity of Nitrite Reductase (NiR).

Nitrate Reductase is a homodimeric protein in which each subunit, encoded by the nuclear *NIA* genes, is associated with three prosthetic groups: haeme, FAD (Flavin Adenine Dinucleotide) and the Mo cofactor. In barley and maize roots, a plasma membrane-bound NR (PM-NR) has also been identified. NR activity is finely tuned at transcriptional (NO_3^-- and light-induced; repressed by relatively high levels of amino acids and C-starvation), translational, and post-translational (protein degradation and phosphorylation) levels (Lillo 2008).

Finally, the NH_4^+ produced by the activity of NiR is assimilated into glutamic acid by the Glutamine Synthetase (GS)/Glutamine-2-OxoGlutarate Amino Transferase (Fd-GOGAT) cycle. In leaf cells, the reducing equivalents necessary to sustain the reaction are directly supplied by the photosynthetic electron chain through the reduced form of ferredoxin (Fd_{red}), whereas in root cells they are supplied by plastidial NAD(P)H [Nicotinamide Adenine Dinucleotide(Phosphate) H]. Two isoforms of GS exist: one (GS2) is active in the stroma where it is involved in the GS2/Fd-GOGAT cycle, whereas the second one (GS1) is active in the cytosol, where it participates to the GS1/NAD(P)H-GOGAT cycle responsible for the reassimilation of NH_4^+ ions released by protein degradation and/or amino acid deamination, relevant processes during leaf senescence. Moreover, the GS2/Fd-GOGAT cycle is responsible for the so-called secondary N assimilation, that consists in the reassimilation of the NH_3 released from the photorespiratory (C2) cycle during the methylene tetrahydrofolate-mediated synthesis of serine from two glycines (Rachmilevitch et al. 2004). The NH_4^+ ions directly taken up from the soil by the AMT system, as well as those released by the hydrolysis of urea in root cells by the Ni-dependent plant urease, are assimilated by the plastidial GS2/Fd-GOGAT cycle. When the concentration of NH_4^+ ions raises, the mitochondrial NADH-Glutamate Dehydrogenase (GDH) can incorporate NH_4^+ into glutamate (Masclaux-Daubresse et al. 2010). Glutamate is the primary form of assimilated N and, through the catalytic action of different aminotransferases, its amino group is bound to specific carbon skeletons. Glutamine and glutamate are systemic-mobile, and transport amino groups to the different plant organs via the vascular system of the plant. In senescing leaves, before being translocated, via the phloem, from senescing leaf cells, the γ-amino group of glutamine is often transferred, by the activity of Asparagine Synthetase (AS), to aspartate, generating the basic amino acid asparagine, endowed with a higher N/C ratio than glutamine, that is finally loaded into the phloem. However, among the N-metabolites translocated within plants, the highest N/C ratios are shown by ureids, such as citrulline. Carbamoyl-phosphate, the precursor of these compounds, is synthesized in the plastids from HCO_3^-, NH_4^+ and ATP by the activity of Carbamoyl Phosphate Synthetase (CPSase), a heterodimeric enzyme whose two subunits in *A. thaliana* are encoded by the *carA* and *carB* genes (Potel et al. 2009).

Among the traits able to affect AUE and concerning the assimilation process of N, the existence of a satisfactory inter- and intraspecific variability has been described (Chardon et al. 2010; Dawson et al. 2008). Probably due to the complex post transcriptional, translational and post translational regulatory mechanisms of NR, it is very difficult to identify possible relationship(s) between variability in AUE and specific allelic variants in different plant species and in different genotypes within the same species. For the same reason, no biotechnological intervention aimed to obtain overexpression of the *NIA* genes showed significant positive effects on AUE.

In lettuce, the positive effect expected by overexpression of the *NIA2* gene under the control of *CaMV 35S* (*Cauliflower Mosaic Virus 35S*) promoter, including the expected reduction of NO_3^- accumulation in plants grown under high NO_3^- availability, was limited by problems related to post transcriptional regulation of NR (Curtis et al. 1999). Nevertheless, more encouraging results were obtained by the same approach in tobacco and potato (Djennane et al. 2002, 2004).

In rice, an interesting relationship between levels of GS2 activity and amount of photorespiratory NH_3 emission from the leaves has been described, with a presently still unknown regulatory mechanism of GS2 activity supposed to be at the basis of the different amounts of NH_3 released from two cultivars (Kumagai et al. 2011). Drought and high temperature can increase the photorespiratory NH_3 release from the crop canopy; it has been evaluated that up to approx. 40 kg of N per hectare can be lost from staple crops during a season (Raun et al. 1999). It can be concluded that higher GS2 activity should become a target in future breeding programmes aimed at increasing crop NUE: in greenhouse-cultivated leafy vegetable crops this trait could assume a particular interest since they often experience environmental conditions that favour the photorespiration process.

2.4 Nitrogen Remobilization

The *dY/dU* term of Eq. 3 includes the continuous utilization of the plant N for sustaining dry mass growth or yield of the harvestable organs. This avoids that the not yet assimilated N is lost with leaf senescence and abscission. Indeed, an important amount of assimilated N flows, at vegetative stage, from senescing to expanding leaves or, at reproductive stage after flowering, to developing seeds (Diaz et al. 2008; Malagoli et al. 2004, 2005). The efficiency of this remobilization process (NRE: Nitrogen Remobilization Efficiency) significantly affects N-AUE, and, in the case of the flow from older to younger leaves, strictly depends on severity of leaf senescence (Diaz et al. 2008).

In cereals, oilseed rape and legumes, the remobilization from senescing leaves of the assimilated N accounts for the large majority of N content in harvested seeds. This is a consequence of the downregulation, after flowering, of the root transporter involved in the uptake of N from the soil, that makes the nutrient insufficient for the high demand of developing seeds (Cliquet et al. 1990; Diaz et al. 2008; Malagoli et al. 2005). The importance of remobilization particularly increases when plants are grown under low N availability (Lemaître et al. 2008). Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase (Rubisco) and other photosynthesis-related enzymes are the main sources of N from senescing to expanding leaves or to reproductive organs. Their degradation, together with that of other leaf proteins, is tightly regulated by senescence-activated chloroplastic or vacuolar proteases. Moreover, onset of leaf senescence is concomitant with activation of some GS1, GDH and AS isoforms involved in the reassimilation of NH_4^+ ions released from protein catabolism (Masclaux-Daubresse et al. 2010).

In cereals, functional genomics and QTL (Quantitative Trait Loci) approaches put in evidence a fundamental role for GS1 in N remobilization and plant NUE (Bernard and Habash 2009; Habash et al. 2007; Kichey et al. 2007). In rice, as well as in *A. thaliana*, GS1 is encoded by multigenic families that include differently regulated elements, expressing enzyme isoforms with different tissue localization and kinetic properties (Bernard and Habash 2009; Ishiyama et al. 2004). This makes to date unclear the actual contribution of each enzyme isoform in the total N remobilization (for a review, see Masclaux-Daubresse et al. 2010). Similarly, the multigenic nature of the gene family (*ASN*) encoding AS currently does not allow identifying surely which isoform(s) (*ASN1-3*) is/are more implicated in establishing NRE (Diaz et al. 2008; Masclaux-Daubresse et al. 2010).

Although they probably play a fundamental role in the allocation of the reassimilated N, the role of specific members of the large gene family encoding the amino acid transporters that load amino acids into the phloem is not clear (Okumoto and Pilot 2011). Nevertheless, in this group interesting traits for improving N-AUE could be searched for.

2.5 C-Metabolism and N-Assimilation Cross-Talking

It is evident that in plants N-assimilation and C-metabolism are tightly interconnected (Neuhäuser et al. 2007) due to the need of the former process for metabolic energy, reducing equivalents and carbon skeletons supplied by the latter one. Organic acids, with particular regard to 2-Oxo-Glutarate (2-OG), are important crossroads of the interconnection between the two pathways (Sweetlove et al. 2010). Moreover, it is now largely accepted that in both dicots and monocots N-assimilation depends on photorespiration (Bauwe et al. 2010; Rachmilevitch et al. 2004).

The mitochondrial NAD-dependent Isocitrate Dehydrogenase (IDH) is the heteromeric enzyme catalyzing, in the Tri-Carboxylic Acids (TCA) cycle, the

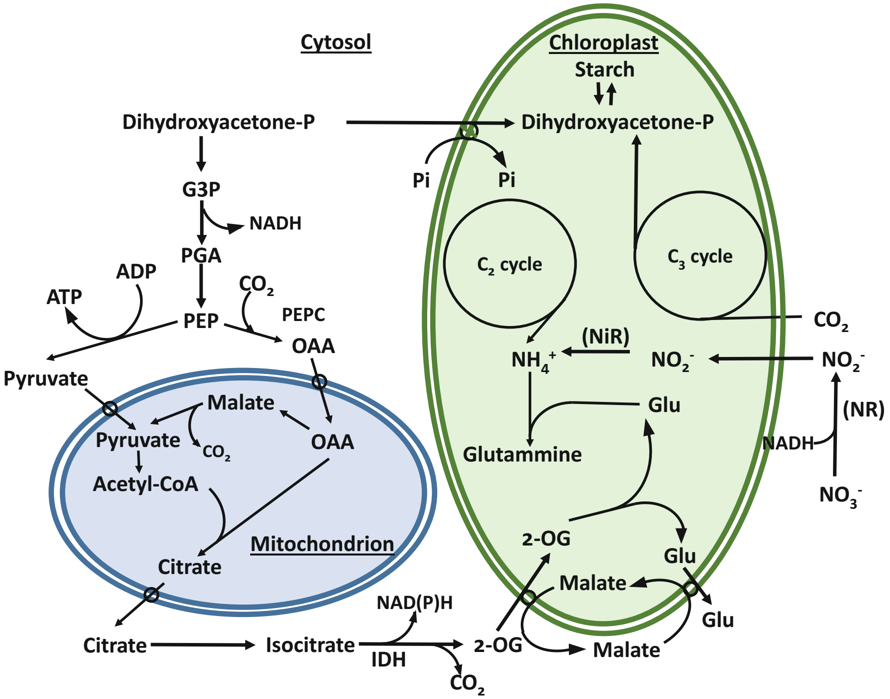

Fig. 1 Metabolic origin and subcellular localization of the carbon skeletons and enzymes involved in nitrogen assimilation. IDH Isocitrate Dehydrogenase, NR Nitrate Reductase, NiR Nitrite Reductase, PEPC Phospho*enol*pyruvate Carboxylase, 2-OG 2-Oxo-Glutarate, G3P Glyceraldehyde-3-Phosphate, OAA OxaloAcetic Acid, PEP Phospho*enol*Pyruvate, PGA Phosphoglyceric Acid

oxidative decarboxylation of isocitrate to 2-OG. In addition to this activity, a NADP-dependent IDH represented by a monomeric protein found in several cell compartments, such as cytosol, plastids, mitochondria and peroxisomes, has been identified (Hodges et al. 2003). Currently, it has not been definitively clarified which of the two forms is responsible for the synthesis of 2-OG for NH_4^+ assimilation. Nevertheless, some co-expression and reverse genetic approaches carried out in *A. thaliana* grown under different N regimes seem to favour the NAD-IDH activity (Foyer et al. 2011 and references therein) even if other experimental results suggest a role also for NADP-IDH (Fig. 1).

Under illumination, the activity of the TCA cycle in leaf cells is reduced by 80%, making the level of 2-OG not sufficient for N-assimilation that, on the contrary, is activated by light. This apparently inconsistent behaviour has been recently solved demonstrating, by experiments with isotopic $^{13}C/^{15}N$ double-labelling, that 2-OG derives from the malate or citrate stored during the night, when the TCA cycle is active. Consequently, the activity of the Dicarboxylate/Tricarboxylate Carrier (DTC) of the inner mitochondrial membrane, that exports 2-OG or citrate from the mitochondrion, could reasonably be considered an interesting target trait for the manipulation of NUE (Foyer et al. 2011). In rice plants, the 2-OG required for the assimilation of NH_4^+ ions is produced by the activity of the-light induced Osppc4 isoform of the enzyme Phospho*enol*Pyruvate Carboxylase (PEPC) (Masumoto et al. 2010).

The tight positive correlation between photorespiration and N-assimilation resides in the photorespiratory-induced activation of the malate/oxaloacetate shuttles at the chloroplast envelope, that increases the NADH/NAD ratio in the cytoplasm thus favouring the reduction of NO_3^- to NO_2^- (Rachmilevitch et al. 2004). Consequently, in C3 plants the selection for reduced photorespiration, as well as the adoption of growth conditions drastically reducing the C2 cycle, could negatively affect crop NUE.

Although only indirectly related to the cross-talk between C- and N- metabolism, growth under sulphate-limited availability reduces the plant NUE. The effect is mainly due, other than to the scarcity of cysteine for protein synthesis, to a reduction in the glutathione pool (GSH plus GSSG) involved in the cellular redox homeostasis. Shortages in Mg, Fe and Mo availability also negatively affect NUE since these mineral elements participate as cofactors in the NR and NiR activities.

3 New Approaches for Improving Nutrient Use Efficiency in Plants

Breeding programmes able to provide new crop genotypes with improved Nutrient Use Efficiency (NuUE), i.e., able to better take up and use minerals for improved yield, are needed in order to face the increasing need for food at a global level (Han et al. 2015). These programmes shall more and more take into account also the probable effects of the already ongoing climate changes on the soil processes that affect mineral nutrient availability and, eventually, plant physiology (Pilbeam 2015).

Concerning leafy vegetables such as lettuce, rocket and spinach, breeding programmes for improved NuUE need to be specifically planned as a function of the type of cultivation adopted in order to enhance the appreciable features of the crop (Fig. 2). For example, if these crops are grown in hydroponic conditions, the size of their root systems should be quite limited in order to avoid the high biomass-induced limitation of circulation of the nutrient solution and the high cell material turnover-induced increase in organic matter in the nutrient solution, with consequent problems to the fertirrigation system. On the contrary, if a same species is grown on soils poor in mineral nutrients, its root system should be able to explore a wide volume of soil, and, in this case, the development of a large root system with peculiar and specific architectural traits would be crucial (de Dorlodot et al. 2007).

Breeding programmes aimed at enhancing plant NuUE can be focused on either single specific genes or gene groups (Fig. 3). The preferable strategy is surely the

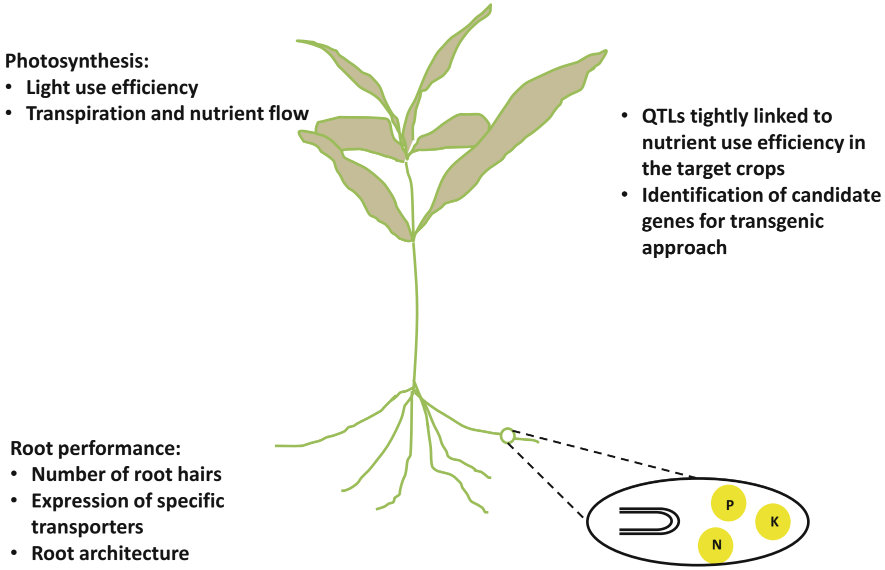

Fig. 2 Potential traits that, if enhanced, may improve NuUE in plants and be a source of molecular markers for molecular breeding. The related strategies should be focused to root system architecture and leaf functionality traits

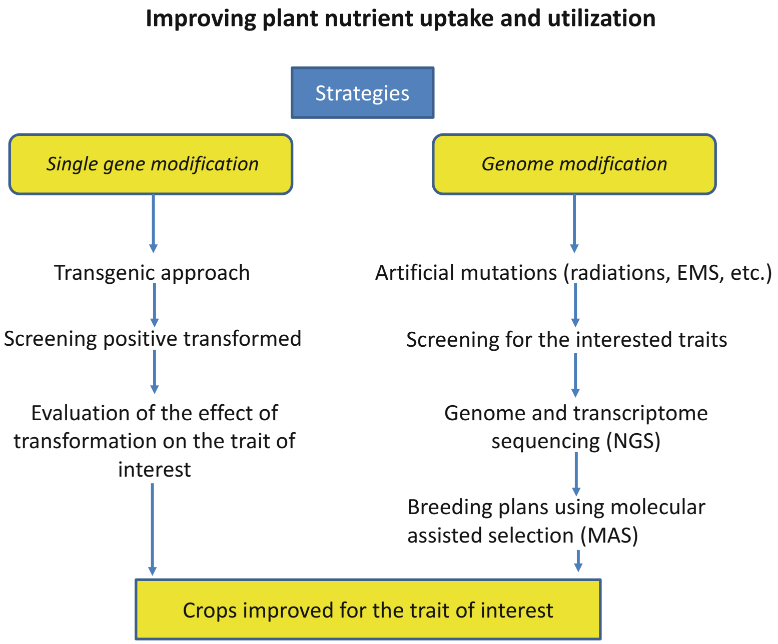

Fig. 3 Simplified working scheme using different approaches for improving plant nutrient uptake and utilization, involving identification of a single gene able to enhance NuUE/NUE in plants, or large genome modification with selection of mutants to be used in breeding programmes. Ethyl Methane Sulfonate (EMS)

use of a single gene encoding for a key trait of the crop, since in this case the introgression of the improved trait into the gene pool of the new genotype will be easier. Unfortunately, the enhancement of only one specific gene often proves unsuccessful in improving the plant NuUE. Intrinsic genetic, morphological, biochemical and physiological traits and their interactions with intrinsic (environmental) factors (i.e., soil pH, water availability, temperature, light intensity, agronomic management, soil biological properties, and fertilizer inputs) should be taken into account to really improve the NuUE of a crop. Improvement of mineral nutrient uptake and assimilation in plants could therefore be achieved by considering entire biochemical pathways or physiological processes, and this approach seems particularly promising for the specific case of nitrogen. Indeed, in spite of the numerous transgenic approaches (McAllister et al. 2012) adopted in recent years to improve NUE by manipulating the expression of single candidate genes putatively involved in N absorption and metabolism (for a review, see Xu et al. 2012), the effectiveness of this approach in cultivation in the field still has to be convincingly demonstrated.

Several to date available genomic tools and approaches open up new perspectives for the genetic improvement of NuUE. In the following lines, a brief presentation and discussion about some of these tools are reported.

3.1 The Quantitative Trait Loci Approach

The identification of genes that cosegregate with NuUE is not easy and is a time- and labour-consuming task. The analysis of gene combinations cannot be achieved with traditional breeding tools, but it necessarily requires transcriptome and genome sequencing information.

Since uptake and utilization of mineral elements are regulated by several genes, most of which not yet identified, QTL analysis and their mapping in the genome of target species can be of great help in genetic improvement strategies (Collard et al. 2005). QTLs may be used in order to identify genes involved in the determination of NuUE and in the growth and development of the root system, and to determine how these genes are transferred to the progeny. The availability of collections of Near-Isogenic Lines (NILs) will accelerate the usually laborious and time-consuming mapping of QTLs on chromosomes; the localization on the chromosomes of these genes in positions very close (tightly linked) to the NuUE genes may be exploited in a Marker-Assisted Selection (MAS) framework of molecular breeding.

For what specifically concerns nitrogen, several QTLs for NUE have been identified mainly in staple crops, such as wheat (Quraishi et al. 2011), barley

(Mickelson et al. 2003), rice (Obara et al. 2004) and maize (Gallais and Hirel 2004). To date, QTLs for NUE in vegetable species are beginning to be available (Chan-Navarrete et al. 2015). QTL analysis for NUE, with particular regard to the metabolic processes linked to nitrogen assimilation, identified several loci that co-segregate with GS1 and NADH-GOGAT (Obara et al. 2001). QTL analysis for genes involved in the development and architecture of the root system can also provide useful information for improving the efficiency of plant mineral uptake. These genes may be further utilized in breeding programmes with specific objectives, such as enhanced root branching or root hair formation.

3.2 Next Generation Breeding

The availability of Next Generation Sequencing (NGS) tools allows fast and accurate transcriptome and genome sequencing. By NGS, in a short and reasonable time it will be possible to gain the transcription profiles or the genome information of different species, as well as of specific mutants. These data, correlated with biochemical, metabolomic, proteomic, and physiological information, will facilitate the identification of the molecular basis of specific phenotypic traits, allowing the identification of key genes as well as the development of molecular markers useful for MAS of novel crop cultivars.

The availability of reference genomes among crop species is rapidly increasing. Partial or complete re-sequencing of different accessions within a species produce datasets of high-density SNPs correlated with quantitative trait variations. These data are exploitable in Genome-Wide Association Studies (GWAS) for QTL mapping in plants, for the development of genomic selection programmes, for the identification of interesting mutations in mutagenized populations, and, finally, for the targeted modification of specific genes by means of genome editing technologies (Barabaschi et al. 2016). GWAS are proving very useful in plants to exploit both the existing natural variation and that induced by generation, through the breeding of adequate parentals, of RIL (Recombinant Inbred Line) populations in order to dissect the mechanisms that control complex biochemical/physiological traits, including NUE (Atwell et al. 2010; Harper et al. 2012; Koprivova et al. 2014). GWAS have been used not only in model species, but also in several crops thanks to the availability of genotyping by sequencing data (Huang and Han 2014).

The so called “Targeted Genome Editing” using artificial nucleases as the CRISPR/Cas9 system (Bortesi and Fischer 2015) is a very interesting technology that promises to accelerate plant breeding by allowing the precise and predictable manipulation of specific genes. In spite of the current debate about the advisability of considering genome editing as a GMO (Genetically Modified Organism) technology or not, examples of the suitability of the use of this technology in plant breeding are increasing. In the authors’ knowledge, to date no example of a Targeted Genome Editing approach to increase NuUE is available. Although the scientific community is more and more engaged towards this goal (Research

Council UK 2016), the challenge remains the identification of the gene(s) to be manipulated for a stable and in-field valid improvement in NuUE concerning (a) specific nutrient(s).

3.3 Overcoming the Phenotyping Bottleneck

The need of a very large number of plant accessions for phenotyping specific traits is the actual bottleneck in the exploitation of Next Generation Breeding approaches (Brown et al. 2014). Currently, interdisciplinary efforts are devoted to develop high-throughput phenotyping platforms, many of which exploited for the selection of genotypes with increased resource use efficiency (Fiorani and Schurr 2013). By using non-invasive technologies, these platforms allow rapid and continuous screening of the responses of a large number of accessions, under both controlled and field conditions, to environmental changes. Cameras and stereo-cameras sensitive in the visible or infrared (IR) range of the electromagnetic spectrum, fluorescence cameras, near-IR spectrometers or cameras, and hyperspectral cameras are the most widely used sensors for the non-invasive analysis of plant morphology, plant shoot growth dynamics and physiological status in phenomic platforms.

Phenotyping for NuUE means measuring the effect of growing *dF* on the increment in plant biomass/yield (*dY*) or, alternatively, on the plant physiological status. In the former case, sensors able to follow in continuous, by imaging, single plant or canopy development are suitable; in the latter, it is usually possible to resort to indirect but related (proxy) evaluation of the physiological parameter under investigation. For example, the concentration of chlorophyll in leaves is considered a proxy measure of the nitrogen nutritional status of a crop (Samborski et al. 2009 and references therein; Schlemmer et al. 2005). Several instruments able to analyze the spectral properties of leaf tissues for the estimation of their chlorophyll content (optical chlorophyll meters) have been developed to evaluate the need for agricultural N applications as well as the efficiency of different genotypes in using the nutrient (for a critical review, see Maghrebi et al. 2014). The same instruments can be used as sensors in phenomic platforms.

Concerning roots, the simplest non-invasive method consists in the use of camera-equipped rhizotrons to record root profiles, while other recurring methods (ground-penetrating radar, electrical resistance measurements, and impedance tomography) consist in the evaluation of the growth of the root system by the indirect evaluation of its effects on the soil physical properties. When root architecture is the phenotypic trait investigated, as in the case of selection for NuUE traits, two techniques, i.e., X-ray Computed Tomography and Magnetic Resonance Imaging, are more suitable. Nevertheless, in the case of field experiments, the combination of shovelomics and imagine elaboration techniques for the quantification of the root system features proves more suitable (Bucksch et al. 2014).

4 Conclusion

Agricultural systems are evolving towards more environment-friendly growing strategies able to reduce chemical inputs. Therefore, crops must enhance their NuUE. To this aim, several strategies, involving crop management in the short period, and genetic improvement in the long one, should be adopted. Hence, breeding should be oriented to increase traits that improve NuUE/NUE under different growing conditions. The increasing knowledge about the molecular and physiological bases of a complex trait as NuUE and the development of innovative emerging molecular technologies for the study of the genome and transcriptome will provide useful tools for supporting the modern breeding programmes. Under a general point of view, other than for staple crops, strong efforts for improving NuUE in vegetable, and in particular leafy, crops should be planned.

Glossary

2-OG 2-Oxo-Glutarate
AAP5 Amino Acid Permease 5
AMT Ammonium Transporter
AR Apparent Recovery
AS Asparagine Syntethase
ASN *Asparagine Synthetase*-encoding gene family
ATF *Aminoacid Transport Family* gene family
AUE Agronomic nutrient Use Efficiency
CaMV 35S Cauliflower Mosaic Virus 35S
cHATS constitutive *HATS* elements
CIPK23 CBL-Interacting Protein Kinase 23
CLC *ChLoride Transporters* gene family
CPSase Carbamoyl Phosphate Synthetase
CRISPR/Cas9 Clustered Regularly Interspaced Short Palindromic Repeat/CRISPR-associated9
DTC Dicarboxylate/Tricarboxylate Carrier
EMS Ethyl Methane Sulfonate
FAD Flavin Adenine Dinucleotide
Fd Ferredoxin
G3P Glyceraldehyde-3-Phosphate
GDH Glutamate Dehydrogenase
GMO Genetically Modified Organism
GOGAT Glutamine-2-OxoGlutarate Amino Transferase
GS Glutamine Syntethase
GSH Glutathione, reduced

GSSG Glutathione disulphide
GWAS Genome-Wide Association Studies
HATS High-Affinity Transport System
IDH Isocitrate Dehydrogenase
iHATS inducible *HATS* elements
IR Infrared
K_M Michaelis-Menten's constant
LATS Low-Affinity Transport System
LHT1 Lysine Histidine Transporter 1
MAS Marker-Assisted Selection
MIPs Major Intrinsic Membrane Proteins
NAD Nicotinamide Adenine Dinucleotide, oxidized
NADH Nicotinamide Adenine Dinucleotide, reduced
NADP Nicotinamide Adenine Dinucleotide Phosphate
NAR2 *Nitrate Assimilation Related* gene
NAXT1 Nitrate Excretion Transporter1
NGS Next Generation Sequencing
NH_4^+ Ammonium
***NIA* gene** *nitrate reductase* gene
NIL Near-Isogenic Line
NiR Nitrite Reductase
NO_2^- Nitrite
NO_3^- Nitrate
NPF Nitrate Transporter 1/Peptide Transporter gene family
NR Nitrate Reductase
NRE Nitrogen Remobilization Efficiency
NRT Nitrate Transporter
NUE Nitrogen Use Efficiency
NuNUE Nutrient/Nitrogen Use Efficiency
NuUE Nutrient Use Efficiency
OAA OxaloAcetic Acid
PE Physiological Efficiency
PEPC Phospho*enol*Pyruvate Carboxylase
PGA Phosphoglyceric Acid
PM Plasma Membrane
PPase PyroPhosphatase
PTR Peptide Transporter
QTL Quantitative Trait Loci
RE Removal Efficiency
RIL Recombinant Inbred Line
RSA Root System Architecture
Rubisco Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase
SCD Steep, Cheap, and Deep
SNP Single Nucleotide Polymorphism
TCA Tri-Carboxylic Acids

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Water Management for Enhancing Crop Nutrient Use Efficiency and Reducing Losses

Jose L. Gabriel and Miguel Quemada

Abstract Strategies that enhance water and nutrient use efficiency in vegetable production may contribute to increase productivity and reduce diffuse (non-point source) nutrient pollution. A combination of optimal water management and applying fertilizer rates adjusted to crop requirements should not only reduce the risk of adverse environmental impact but also be the most profitable choice for the farmer. This chapter covers water management strategies oriented towards improving nutrient use efficiency in horticultural systems. Water management affects the mineralization process and the subsequent use of released nutrients, and is crucial in Mediterranean and semi-arid climates. This is particularly relevant when transforming rain fed cropping systems into irrigated ones, because the soil may increase mineralization and supply large amounts of nutrients during the transition period. Nitrogen losses occur mainly by leaching and, together with phosphorus, by erosion and runoff from open fields. Nitrate leaching is frequently the most important loss process in horticulture because large input of N fertilizer are applied to maintain high productivity, roots of many vegetable crops are superficial, and the N remaining in the field as crop residues after harvest is a large fraction of the plant N uptake. Losses by leaching and effluents from greenhouses may also be responsible for diffuse pollution. Water management greatly affects greenhouse gas emission and may help to design horticultural systems with low emissions of atmospheric pollutants. Water is also used for salinity control and irrigation can be used to mitigate some of the adverse effect of salinity on plant nutrition and growth. Therefore, an integrated fertilization program oriented towards reducing nutrient losses and maintaining farm profitability should rely on both, a rational fertilization and an efficient water management.

Keywords Diffuse water pollution • Nitrogen • Phosphorus • Salinity • Vegetable production • Water quality

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1 Water and Nutrient Management for Enhancing Crop Uptake and Use Efficiency

Water and nutrient availability remain globally the most limiting plant growth factors in intensive agriculture. Therefore, an important reduction of the yield gap might be achieved by improving nutrients and water management. Mueller et al. (2012) observed that closing maize yield gaps to 50% of attainable yields in Sub-Saharan Africa could be done solving nutrient deficiencies, but closing to 75% would require increases in water and nutrient applications. In addition, co-limitation of nutrients and water was observed across East Africa and Western India for maize (*Zea mays* L.), in areas of the USA Great Plains and the Mediterranean Basin for wheat (*Triticum* spp.), and in Southeast Asia for rice (*Oryza sativa* L.). This limitation is even more evident when the cropping system involves vegetables, more sensitive to the lack of water and nutrients (Quemada et al. 2013). However, increments in food production should be achieved without further undermining the integrity of the Earth's environmental systems (Godfray et al. 2010). As water is one of the most important drivers of human activity, increasing water use efficiency is a major challenge for ensuring the sustainability of intensive agricultural production.

A linear relationship exists between crop biomass production and crop transpiration, so crop water deficit leads to yield and biomass reduction and therefore diminishes the crop nutrient uptake (Fereres et al. 2003). Continuous water deficit with variable intensity is a common strategy in modern irrigation to reduce biomass production changing its partitioning in favor of yield or product quality. Potential yield losses are compensated with higher commercial value and lower uses of water and external inputs. On the other hand, excessive water application enhances leaching losses and soil conditions that favor denitrification. Generally, in commercial farming the nutrient use efficiency of crops is low and linked to the water use in most horticultural systems. Crop recovery is usually reported as 30–50% of applied N (Mosier et al. 2004) and even lower of applied P (Sims and Sharpley 2005). Nutrient from agricultural systems are lost through lixiviation, erosion/runoff or gaseous emissions. All these processes are driven by water. In irrigated agriculture, water application is a management option that the farmers may use to enhance nutrient use efficiency. Most nutrients lost through leaching and runoff are finally accumulated in the inland water bodies or the oceans. The recovery of these nutrients is difficult and inefficient, so new nutrients are added in the form of organic or synthetic fertilizers. Most synthetic fertilizers derive from mining or require energy for their fabrication. A more efficient use of nutrients and water is becoming a major concern and was identified in the European communication "Roadmap to a Resource Efficient Europe" (EC 2011) as one of the key topics to attain a sustainable development in the EU.

The environmental consequences of nutrient losses from agricultural systems, particularly of N and P, is a major societal concern resulting in government legislation in developed countries. The European Union has established frameworks for action in the field of water policy (Directives 2000/60/EC (EC 2000) and 2008/105/CE (EC 2008)) and the USA have identified regions affected by excessive nutrient contamination and have passed legislation to prevent it (Rabalais et al. 2002; USA Congress 1978). In China, concern about water quality is increasing with special attention to aquifer contamination by nitrate (Ju et al. 2006). In all countries, irrigated horticultural areas were identified as particularly susceptible to groundwater pollution because vegetable crops are abundantly fertilized and occasionally overwatered because of their higher yield potential (Vázquez et al. 2006). The relative contribution of agriculture to N oxides and ammonia emissions is reflected in the various international agreements concerning air quality and global warming (Gothenburg Protocol 1999; IPCC 2007).

Several studies showed that a combination of optimal water management and applying fertilizer rates adjusted to crop requirements should not only reduce the risk of environmental impact but also be the most profitable choice for the farmer (Mosier et al. 2004; Quemada et al. 2013). This chapter covers water management strategies that proved to be effective at improving nutrient use efficiency in horticultural systems.

2 Effect of Water Management on Soil Nutrient Mineralization (Nutrient Supply)

Horticultural systems are often characterized by soils with high organic matter content to ensure soil fertility and structure stability. The mineralization of organic matter can be an abundant source of nutrients and this topic is addressed in chapter "Organic matter mineralization as a source of nitrogen". In this section, the importance of the water management on the mineralization process and the subsequent use of the nutrients released will be emphasized.

Water supports most of the reactions taking place in the soil. Microorganisms release extracellular hydrolytic enzymes to the media that carry through the decomposition process (Jarvis et al. 1996). If the soil is dry, the enzymes hardly reach the organic matter molecules and the mineralization stops. If the soil is flooded, anaerobic processes are enhanced and mineralization rate slows down. In flooded soils, the availability of many nutrients is reduced, either because losses increase (i.e. N losses by denitrification, sulfur losses as SH_2) or metals are retained in less available forms (i.e. iron, zinc, copper, manganese or molybdenum). Therefore, the best scenario for organic matter mineralization is a moist and well drained soil.

In many semi-arid and Mediterranean climate zones, mineralization is limited by a lack of moisture during the dry season (Zdruli et al. 2004). When water is supplied through irrigation, the mineralization and nitrification rates may greatly increase under the thermic and hyperthermic conditions characteristics of these areas. A comparison of N mineralization rates in soils from various locations in Spain showed that the potential mineralization rate determined from aerobic incubation in the laboratory was similar or slightly larger for soils from rain fed than from irrigated fields (Table 1). Nevertheless, the apparent N mineralization rate obtained in field experiments was greater under irrigated than under rain fed conditions, due to the optimal soil moisture and temperature in the irrigated fields. This is particularly relevant in newly irrigated areas or in fields in which a vegetable alternates with a rain fed crop, a common practice in open field vegetable production (Tei et al. 2002; Vázquez et al. 2005). The transformation of rain fed into irrigatedcropping systems enhances organic matter mineralization. During this transition period, soil may supply large amounts of nutrients and very large N mineralization rates have being reported for irrigated fields (Table 1; Díez and Vallejo 2004; Vázquez et al. 2006). The soil organic matter content will eventually stabilize after various years depending on the C inputs. Likewise, in sandy soils and in newly constructed greenhouses based on artificial soil systems, the added manure is likely to provide these soils with a high N mineralization potential that might last for various years (Thompson et al. 2007). Making allowance for this nutrient supply by mineralization when developing fertilizer programs could provide appreciable savings to the farmers. In many cases, this N supply is not accounted for with resultant accumulation of large quantities of nitrate (NO_3^-) in the soil profile that is susceptible to leaching.

3 Effect of Water Management on Nutrient Losses and Water Quality

Nutrient losses occur mainly by leaching, erosion and runoff from open fields and in the form of leaching and effluents from the greenhouses (Fig. 1). Topography, soil and hydrological characteristics of each site will determine the main pathway of nutrient losses. Land use, water management and agricultural practices can be designed for increasing the nutrient efficiency in the field and mitigate pollutions problems.

3.1 Leaching

Many nutrients are leached down the soil profile but differences in the ionic/molecular radius and electric charge make a difference in their mobility. Most soils colloids have a net negative charge so cations are retained easier than anions. Molecules or ions with small radius and positive charge (K^+ or NH_4^+) are very soluble. For instance, two typical molecules in soils as KCl or NH_4NO_3 present solubility constants around 180 g K L^{-1} and 430 g NH_4 L^{-1}, for water at 20 °C. However, these cations are usually retained in the soil cationic exchange complex,

Table 1 Relationship between the N potential mineralization rate (k) determined from aerobic laboratory incubation, and the apparent soil N mineralization rate (k*) observed in field experiments for various soils from either irrigated or rain fed cropping systems at different locations in Spain

			k	k*
Location	Soil classification	g C kg^{-1}	mg N kg^{-1} d^{-1}	
Irrigated systems				
Valdegón	*Typic Xerofluvent*	11.3	0.39	0.24
Montañana	*Typic Xerofluvent*	5.9	0.29	0.14
Gimenells	*Petrocalcic Calcixerept*	9.5	0.40	0.14
Tallada-2	*Oxyaquic Xerofluvent*	9.9	0.47	0.20
Average			**0.39**	**0.18**
Rain fed systems				
Gauna	*Vertic Endoaquol*	14.9	0.48	0.08
Aranguiz	*Vertic Endoaquol*	10.6	0.43	0.03
Beriain	*Typic Calcixerept*	11.6	0.41	0.06
Tajonar	*Fluventic Haploxerept*	14.0	0.38	0.01
Average			**0.42**	**0.05**

Adapted from Quemada (2006), Quemada and Díez (2007), and Vázquez et al. (2006)

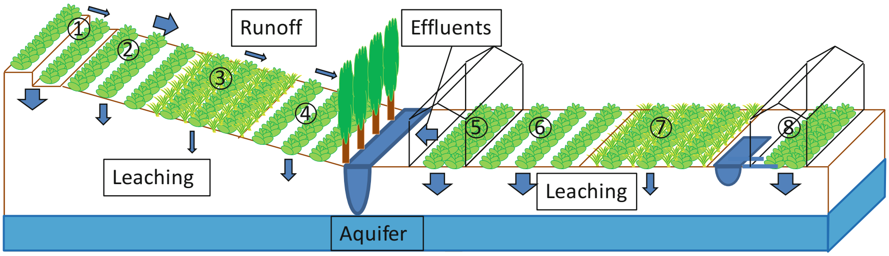


Fig. 1 Effect of various agricultural practices on nutrient leaching, runoff and effluents in flat or sloped fields. *Larger arrows* reflect larger effect. *1* terrace cropping, *2* contour cropping, *3*cover cropping in slope fields, *4* buffer strip on the edge of the field, *5* greenhouse, *6* cropping in flat areas, *7* cover cropping in flat fields, and *8* greenhouse with effluent recirculation

so small losses by leaching are expected in most soils. Others cations with a larger radius (Ca^{2+} or Mg^{2+}) are often displaced from the soil cationic exchange complex by the smaller and are easier to leach. Some nutrient molecules and ions with negative charge, like NO_3^-, are easily leached because they are weakly retained by the soil. Other nutrients like phosphorus, iron, bore, zinc, copper or molybdenum present limited mobility because they are prone to precipitation in many soils, particularly when pH > 7.5. The removal of $SO_4^{=}$ from most soils is explained by adsorption rather than precipitation. However, leaching of P, S or metals may occur in certain soils with low reactivity or after application of large amount of organic matter, that may affect redox conditions and produce chelates.

Excess NO_3^- in water is one of the major environmental impacts of agricultural production, resulting in decreasing groundwater quality and increasing eutrophication of surface inland water and coastal marine environments (McIsaac et al. 2001). Societal concern regarding the environmental consequences of these N losses is reflected in the current legislation in developed countries aiming at preserving good water quality. The EU nitrate Directive (EC 1991) aims at reducing and preventing the contamination of subterranean and superficial water bodies from NO_3^- derived from agricultural activity. All members state have identified Nitrate Vulnerable Zones (NVZ); these are regions in which the water is affected (more than 50 mg NO_3 L^{-1}) or at risk of being affected by NO_3^- pollution, and approved legislation describing the crop management practices that should be implemented in these NVZ. Nitrate leaching is frequently the most important loss process in horticulture because in addition to the high mobility of NO_3^- in many soils, large input of N fertilizer are applied to maintain the high productivity of many horticultural systems. Other reasons that contribute to the high potential of horticulture for high NO_3^- leaching losses are:

1. roots of many vegetable crops are superficial, increasing the risk of water and nitrogen to be lost below the active rooting depth
2. the N remaining in the field as crop residues after harvest is for many vegetable crops a large fraction of the plant N uptake, that is easily mineralized to leachable forms.

Nitrate leaching imposes a cost on both the farmer and the environment, so it is imperative to reduce quantities of NO_3^- delivered from cropland to ground and surface water. In addition, NO_3^- losses are a good indicator of the efficiency of the cropping systems. In most cases where fertilizer causes NO_3^- pollution, it is due to excessive application or to poor management practices (Follet et al. 1991), and usually mismanaged agricultural systems are prone to high NO_3^- leaching losses. Therefore, it is crucial to identify horticultural systems with high N losses and establish the best management practices aimed at their reduction. In general, the following recommendations for reducing NO_3^- leaching are also applicable to many nutrients and agrochemical products.

Strategies related to water application are particularly relevant when horticultural crops are irrigated. Excessive water application increase NO_3^- leaching, leading to a vicious circle were low crop N availability is compensated by increasing fertilizer rates. Because of that the first recommendation to increase nitrogen use efficiency and mitigate the deleterious impact on water is to adjust water application to crop needs. As an example, crop evapotranspiration (ETc)-based irrigation scheduling improved NUE and limited N loss to the environment in bell pepper (*Capsicum annuum* L.) in Florida (Zotarelli et al. 2007). Moreover, even without a difference in the amount of water applied, a further increase in NUE can be pursued by improving the irrigation schedule. Nitrate leaching is particularly important during the crop establishment period, when the plantlets' roots explore only a small volume of soil and their water absorption capacity is small (Vázquez et al. 2006). Yet at that time, irrigation amounts applied for crop establishment are

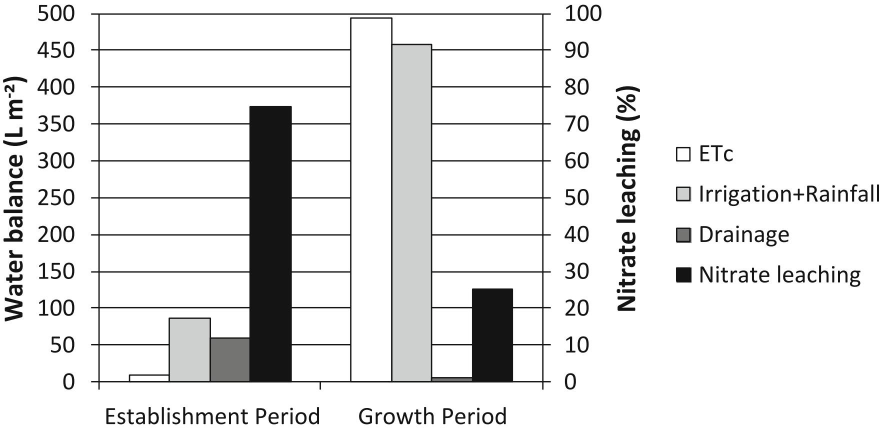


Fig. 2 Average water balance and nitrate leaching observed in two tomato crop seasons, divided in two growth periods, based on Vázquez et al. (2006) results

above ETc. Consequently, excess water is commonly applied to maintain low soil water potential to ensure survival of plantlets. In a field trial with processing tomato (*Solanum lycopersicon* L.) in the Ebro Valley (Spain), Vázquez et al. (2006) observed than 75% of NO_3^- leaching occurred during the establishment period (Fig. 2). Irrigation frequency was shown to be a major management variable to mitigate N losses and maintain plant survival and yield. Once the crop is established, soil or plant moisture sensors can be used to control irrigation and adapt water application to crop demand, being more feasible a reduction in water percolation below the root depth and a mitigation of NO_3^- leaching (Wadell et al., 2000; Zotarelli et al. 2011). Hence, irrigation technology has a role on reducing the impact of horticultural practices on water quality, as trickle or sprinkle irrigation is better adapted to programming and high frequency water application than surface irrigation.

Because the risk of N leaching during the establishment period of vegetables is high, agricultural practices that lead to an accumulation of soil mineral N content at (or before) planting should be avoided. In Mediterranean climates, large quantities of NO_3^- in the fallow soils are common by the beginning of spring, as rain is insufficient to cause leaching of the N mineralized during fall and winter. Replacing the winter fallow by cover crops that would take up soil mineral N and reduce the risk of NO_3^- leaching during the establishment period has been shown to be an efficient technique (Gabriel et al. 2012a, b; Tosti et al. 2012). Even more, appropriate use of the cover crop kill date may ensure low NO_3^- leaching risk and mitigate pre-emptive competition with the subsequent cash crop (Alonso-Ayuso et al. 2014). Another strategy to reduce NO_3^- leaching losses is delaying the first N fertilizer application until the end of the establishment period. Crop N demand is low during the first growth stages and the soil supply is enough to meet crop requirements. This technique is easy to implement by fertigation and it can be adapted to other fertilizer programs as well. Finally, if N is added before planting with the starter fertilizer it is recommended to use technologies that delay the release of NO_3^- to the soil, either by mean of nitrification inhibitors, coatings or chemicals forms of different solubility (Cui et al. 2011). When N is applied in organic form, it is also recommended to avoid application of fresh organic materials before planting that can lead to a rapid N release, and to use cover crops to enhance N recycling into the cropping systems (Benincasa et al. 2011).

Improved fertilizer management should be a priority when designing strategies to control nutrient leaching. Over-fertilization, either with organic or synthetic fertilizers, is a common practice in many horticultural systems and appeared as the main cause of nutrient leaching after water management in a meta-analysis of irrigated areas (Quemada et al. 2013). Adjusting fertilizer application to crop demand and accounting for nitrogen coming from mineralization of the organic matter and previous crop residues, are very efficient way to reduce nutrient leaching. In chapter "Tools and strategies for sustainable nitrogen fertilisation of vegetable crops" of this book, different approaches to optimized fertilizer application are discussed (Table 2).

Another strategy that involves both water and N management, and that might help to control NO_3^- leaching, is accounting for the N supply with the irrigation water when calculating the fertilizer rate of a crop. It might be particularly relevant when the water is pumped from wells in aquifers with high NO_3^- content. Also, when the water is re-used either in the circuit of a greenhouse or from the drainage channel of a watershed (Isidoro et al. 2006).

In irrigated systems, the technology use for water delivery may also have an effect on nutrient leaching (Waddell et al. 2000). In general, equipment that allow increasing water use efficiency at a field scale may also increase nitrogen use efficiency and reduce nutrient leaching losses. In surface irrigation systems, application of excess water is a common practice to ensure a wet soil profile in the whole farm. Water percolation in the areas closer to the source of water delivery is frequent and so are nutrient leaching losses. Drip irrigation, if properly managed, allow increasing water and N use efficiency, particularly if fertigation is used. When comparing two onion fields in New Mexico, Sharma et al. (2012) greatly increased water use efficiency and reduced by half nutrient leaching losses (from 150 to 76 kg NO_3-N ha^{-1}) using drip instead of furrow irrigation systems. Poh et al. (2011) also observed in tomato fields that increasing the length of drip irrigation time by reducing the operating pressure can lead in reduced water drainage. Sprinkle and center pivot systems present intermediate opportunities for reduction in nutrient leaching, but if care is taken in adjusting water and N application to crop requirements they may be equal to drip irrigation in mitigating nutrient leaching (Quemada et al. 2013).

Table 2 Summary of the techniques that can reduce nitrate leaching by proper N fertilization and water management

Technic	Brief description and expected reduction	Some references
Adjusting water application to crop needs	The crop grows at its potential but water drainage (and then N leaching) is reduced	Zotarelli et al. (2007) and Vázquez et al. (2006)
Improving irrigation schedule	Coupling the water applied with each irrigation event to the water necessities of the plant based on the phenology and reducing the amount applied per event (i.e. increasing irrigation frequency)	Vázquez et al. (2006), Wadell et al. (2000), Zotarelli et al. (2011), and Poh et al. (2011)
Improving water delivery system	Systems that increase water application homogeneity or placement are easier for adjusting water application. (drip>sprinkle>furrow)	Wadell et al. (2000), Sharma et al. (2012), and Quemada et al. (2013)
Avoiding residual soil mineral N	Using cover crops to catch N from the soil in periods without crop, and releasing during the next crop.	Gabriel et al. (2012a, b) and Tosti et al. (2012)
Delaying first fertilizer application	Avoid soil mineral N accumulation when the small crop is not able to uptake it.	Quemada et al. (2013)
Using controlled release N fertilizers	Control N leaching by diminishing or delaying nitrate accumulation.	Cui et al. (2011)
Avoiding organic fertilizers before planting	Avoid N excess in the soil prone to be leached because the crop cannot uptake it.	Benincasa et al. (2011)
Avoiding over fertilization	The excess of N is prone to be leached because the crop cannot uptake it.	Quemada et al. (2013)
Considering N mineralised from soils or crop residues	Making allowance for N supply by mineralization when developing fertilization programs	Gallejones et al. (2012) and He et al. (2007)
Considering N in the irrigation water	Correct N fertilizer rate by the nitrate apply with irrigation water. Relevant in regions with high levels of N in irrigation water or with recirculation systems.	Isidoro et al. (2006) and He et al. (2007)

3.2 *Erosion, Runoff and Effluents*

Nutrient losses from horticultural areas to water bodies also occurs through runoff and erosion from open fields and through effluents or leachates from greenhouses. Erosion and runoff of phosphorus (P) and N are a major concern because of the soil fertility loss and the large environmental impact. Horticultural systems are often characterized by P surpluses because of high fertilization rates and low exports

(Yan et al. 2013). Large P accumulation in soils, frequent in horticultural cropping systems, enhance the risk of P loss from fields to surface waters. Phosphorus is often the limiting factor for plant growth in aquatic ecosystems so it triggers eutrophication of water bodies. In the EU as in many other parts of the world, agricultural soils are a major contributor to P diffuse pollution so there is a need to optimize fertilization and reduce P losses (Ott and Rechberg 2012). A promising strategy to increase crop P uptake efficiency and reduce the environmental impact is to combine lower P content in soils with techniques to increase P availability (myccorhizae symbiosis, fertilizer placement) and mitigate soil losses (Senthilkumar et al. 2012).

A priority when designing practices to reduce soil erosion is increasing ground cover with cover crops or with crop residues. Soil erosion control is promoted by various ways: (i) avoiding the direct impact of water drops on the soil surface and so on structural degradation, (ii) reducing runoff velocity due to increasing soil microrelieve, (iii) increasing infiltration and therefore, in many cases, enhancing plant water availability and crop growth (Langdale et al. 1991). One of the main cover crop functions is to reduce soil losses and they have being used successfully to cover the ground between trees in permanent orchards or to replace the traditional bare fallow between cash crops (Bowman et al. 2000). A cover crop optimized for erosion control should present rapid and high level of ground cover and leave slowly decomposable residues remaining in the field (Ramírez-García et al. 2015). Many grasses showed these characteristics and are often used, sole or mixed with other species, when the aim is controlling erosion.

The use of moldboard plough and other inversion tillage techniques is common in many horticultural crops that require a thorough soil preparation to be cultivated. Soil losses and runoff can be greatly reduced by mean of conservation tillage and have being developed in many arable crops (Meyer et al. 1999). For horticultural production systems, conservation tillage techniques are starting to be developed and still need machinery capable of dealing with technical problems. Strip-tillage is gaining attention in recent years as it combines a high degree of soil protection and flexibility to respond to the specific needs of vegetable crops (Evans et al. 2010). Agro-textiles woven and non-wovens fabrics applied in agriculture, have also being used to reduce the risk of soil erosion for certain crops under specific conditions (Olle and Bender 2010).

The irrigation systems may also have an effect on erosion and runoff (Sojka et al. 1998, 2007). Erosion and runoff induced by surface irrigation has being broadly studied and pointed as one of the main reasons for diffuse pollution in irrigated areas. In surface irrigation, the soil is hydrated faster than in most rain events and the soil structure is often disrupted, leading to an enhancement of runoff and risk of soil loss. Sprinkle or center pivot irrigation is similar to rain in many aspects, so if properly managed, it may diminish soil and water losses out of the field. Nevertheless, care should be taken when either soil or water quality can induce soil crusting, as the risk of nutrient loss from the system may greatly increase. Drip irrigation is the least erosion prone of irrigation systems, even in steep fields, and can achieved uniform water application (>95%) with technics as pressure compensating emitters.

Important nutrient enrichment of surface and subsurface water is frequently observed near greenhouses. Losses have being reported from either soil-based (Thompson et al. 2007; Min et al. 2011) or soilless vegetable and ornamental crops (Berckmoes et al. 2013). Leachates and effluents from water surplus in fertigated greenhouses are identified as the main cause. Strategies to mitigate losses are adjusting irrigation and fertilization to water needs, and recirculation of the leaching fraction.

In many countries, vegetated buffer strips represent an effective best management practice for mitigating diffuse pollution (Ballestrini et al. 2011). The vegetated strip is usually established on the edge of the field or adjacent to streams or wetlands. One drawback is the buffer strips may take land out of production. Buffer strips can remove more than 75% of N and P from inflowing water depending on width, vegetation type and maintenance. Their effectiveness is dependent also on site-specific characteristics as soil type, and subsurface hydrology (Muñoz-Carpena et al. 2007).

Ideally, vegetable production should be using appropriate practices so that as much as possible N and P losses from the field are captured and recycled. However, even if all these strategies are implemented, some risk of N and P pollution of water remain, particularly due to heavy rainfall. Because of that, strategies that deals with management of runoff, drainage and effluents from production areas have being proposed. These strategies are called "end of pipe" solutions and are the last resort to the problem of nutrient pollution, when all other practices to conserve and recycle nutrients on the farm have been exhausted. Sedimentation ponds and artificial wetlands have been the most successful. Care should be taken to ensure the efficiency of these strategies, as they might increase the problem of pollution swapping (i.e. enhanced denitrification) or act just as a temporary solution, as nutrient accumulated in this traps may be released later (Dorioz et al. 2006).

4 Effect of Water Management on Gaseous Losses

The relevant nutrients that may be lost from the agro-system through gaseous emissions are N and sulfur (S). Nitrogen can be lost as NH_3, N_2O, NO or N_2, and sulfur as SH_2.Without an appropriate management, N gaseous losses may be very important, affecting fertilizer use efficiency and greenhouse gaseous emissions (GHG's). Agricultural practices such as fertilization, irrigation or residue management, are known to be driving forces in the emission of GHG's (IPCC 2007). Most losses occur in the soil surface, although they may also come from deeper horizons or even from plant leaves as NH_3 or volatile amine usually associated to excessive N fertilization (Schjoerring et al. 2000).

Agricultural soils are identified as one of the major sources of nitrous oxide (N_2O), a GHG that constitutes 6% of the anthropogenic greenhouse effect and also contributes to the depletion of stratospheric ozone (IPCC 2007). In general, agricultural practices that avoid accumulation of mineral N remaining in the soil and reduce water-filled pore space during long time, mitigate N_2O emission during both the fallow and cropping period (Sanchez-Martín et al. 2010). Surface irrigation is characterized by near-saturation conditions for a few days after irrigation, leading to one or various large pulses following water application (Kallenbach et al. 2010). In contrast, drip irrigation maintains water content around field capacity in the wet bulb and promotes a small but steady flux of N_2O throughout the cropping season. In a field study with melons (*Cucumis melo* L. cv. Sancho) Sánchez-Martín et al. (2008) reported that drip irrigation reduced total N_2O emissions by 70% and NO by 33% with respect to furrow irrigation (Fig. 3). Furthermore, due to the different soil water content regime, the most important source of N_2O was nitrification when drip irrigation is used whereas it was denitrification with furrow irrigation. Therefore, proper water management greatly affects GHG emission and may help to design horticultural systems with low emissions of atmospheric pollutants (Snyder et al. 2009; Aguilera et al. 2013).

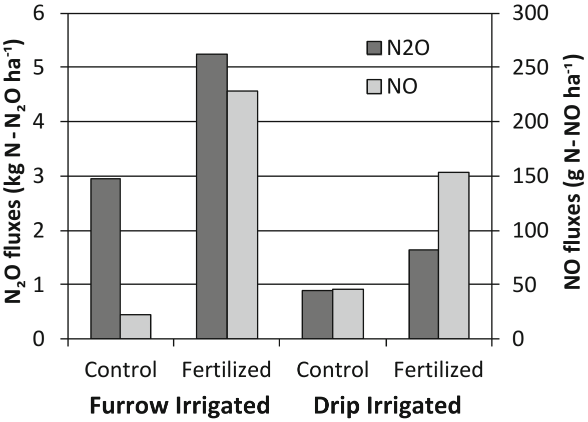
Under dry conditions and after surface applications of urea-containing fertilizers, N losses due to NH_3 volatilization may be relevant (Meisinger and Randall 1991). Large losses may occur in a few days and the soil NH_3 presence follows the equation (Connor et al. 2011):

$$NH_3 + H^+ + OH^- \leftrightarrow NH_4^+ + OH^-$$

The equilibrium is regulated by the soil pH. Under conditions close to $pH = 5$ only 0.004% of the N is present as NH_3. However, this relationship increases around ten times by each increment of 1 in the pH, resulting in a 40% of the N as NH_3 when $pH = 9$. Therefore, soils with high pH are prone to high ammonia losses and fertilization techniques that raise the pH in the surrounding of the fertilizer, either organic or synthetic, should be avoided. Under these conditions, application of NO_3^--based fertilizers is recommended. If urea-based fertilizers are applied, techniques that encourage the NH_4^+ entering the soil will drastically reduced ammonia emission (Quemada et al. 1998). Because of that, small irrigation pulses (~12 mm) after urea application is an efficient strategy to mitigate ammonia losses (Fenn and Escarzaga 1977). Subsurface drip fertigation is also a technique that reduces volatilization as fertilizer is directly incorporated below the soil surface in the wet bulb.

The chemical equilibria involved in sulfur volatilization process are similar to those in N (Blanes-Vidal et al. 2009). The volatile molecule is SH_2, and the process involved is: organic S => SH_2 => S => SO_4^{2-}; but, under reductive conditions, SO_4^{2-} can be reduced again to SH_2. Sulfur emissions may be important when organic fertilizers are not incorporated to the soil, under reductive conditions, and during the decomposition of crop residues rich in S (i.e. *Brassicas*). Nowadays, sulfur emission is not a major concern in vegetable production.

Fig. 3 NO and N_2O fluxes observed in a melon crop with two different irrigation methods, with or without fertilization (Based on Sánchez-Martín et al. 2008)



5 Effect of Water Management on Salinity Control

High salinity conditions induce nutrient imbalances in crops, either by decreasing nutrient availability, increasing competitive uptake, modifying transport or partitioning within the plant, or rising the internal crop requirement for a specific nutrient (Grattan and Grieve 1999). Salt-free water is crucial for salinity control, because it determines soil salt concentration and it is the driver for solute movement in the soil profile. Therefore, water management can be used to temporarily mitigate some of the deleterious effect of salinity on plant nutrition and growth.

Salinity has already affected large areas of arable land in the world and it is a principal cause of yield reduction and even land degradation in many regions (Feng et al. 2005; Lambers 2003; Wichelns and Oster 2006). In addition, in soil-less growing systems it is a requirement to maintain the salinity of the root zone solution at levels that are not detrimental to crop production (Sonneveld and van der Burg 1991). A common approach to control salinity in vegetable production is giving an additional amount of irrigation water (i.e. leaching fraction) to wash soluble salts out of the root zone (Oster 1994). Care should be taken, as watershed studies showed that return flows from irrigated agriculture are a major diffuse contributor of salt contamination in water bodies (Aragüés and Tanji 2003). To keep over-watering sustainable in the long term, the leaching fraction should be reduced to a minimum. This can be achieved by controlling or calculating the water and salt inputs and outputs and keeping the salt balance close to zero (Gabriel et al. 2012a, b). Another strategy is to apply a large leaching fraction only during the initial growth stage of the crop, when is usually more sensitive to salinity, and to avoid over-watering after fertilizer application. In soil-less systems, the recommendation is to increase recirculation of drainage water to reduce salt discharge (Sonneveld and van der Burg 1991). A key aspect to minimize the leaching fraction without drastically damaging crop yield is to rely on soil and water analysis for decision taking.

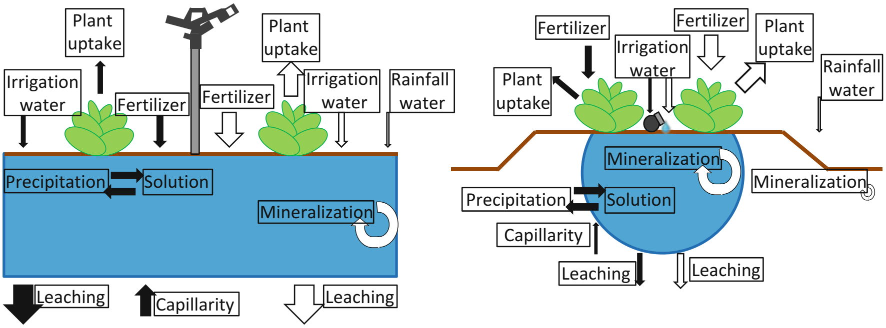


Fig. 4 Effect of sprinkler and drip irrigation on the main components of the salt (*black arrows*) and nitrogen (*white arrows*) balances. *Larger arrows* reflect larger effect

Crop growth responds to salt concentration in the soil solution, so for a fixed salt content less yield reduction would be induced in a wet than in a dry soil. Therefore, irrigation systems or schedules that maintain adequate soil water availability can greatly reduce the damage of salinity (Paranychianakis and Chartzoulakis 2005). Irrigation frequency is a major management variable that may be used to maintain high soil water content and control the osmotic potential of the soil solution to a minimum. Because of that, the characteristic wet bulb developed under drip and trickle irrigation is more suitable for keeping a low salt solution concentration level around the root system and enhance nutrient uptake (Fig. 4).

Increase in soil temperature produced by many synthetic mulches may enhance upward movement of water by capillarity (Gran et al. 2011). Salts from subsurface horizons rise up with the water and tend to precipitate in the soil surface. When the mulch is removed the electrical conductivity of the topsoil is high and in some cases even salt accumulation on the surface is visible. Rainy events during the non-cropping season or irrigation are required to wash salts down the profile. Sprinkle or surface irrigation homogenized the upper soil layers and have a high leaching efficiency if apply as pulses to avoid flooding (Ayers and Wescott 1985).

Irrigation with low-quality water (i.e. reclaimed water or treated wastewater that is reused) deserves special attention and it will not be covered in this chapter. Low-quality water may interact with mineral nutrition (i.e. PO_4^{3-} and K^+ uptake is more difficult if large amount of Ca^{2+} are present) and in some cases present specific problems of crop toxicity (Magán et al. 2008; Parida and Das 2005). Addition of specific accompanying nutrients to water may enhance the uptake and transport of another nutrient and alleviate the salinity damage, even if most mineral fertilizers increased the electrical conductivity of a solution (Zhu 2001). Supplemental fertilization of K^+, Ca^{2+} and NO_3^- correct physiological unbalance and stimulates growth under saline conditions. Particularly, adequate K^+ level in tomato may increase salt tolerance and fruit quality (Grattan and Grieve 1999).

6 Conclusion

In most horticultural systems there is a strong interaction between water- and nutrient-use efficiency. In addition, water is the driver of the various environmental problems causes by excess nutrients such as contamination of aquifers, eutrophication of surface waters or increasing atmospheric concentration of greenhouse gasses. Therefore, an integrated fertilization program oriented towards reducing nutrient losses and maintaining farm profitability should rely on both a rational fertilization and an efficient water management.

Glossary

k	N potential mineralization rate
k*	Apparent soil N mineralization
NO_3^-	Nitrate
NVZ	Nitrate vulnerable zones
ETc	Crop evapotranspiration
GHG	Greenhouse gases

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An Economic Analysis of the Efficiency and Sustainability of Fertilization Programmes at the Level of Operational Systems, with Case Studies on Table Tomato, Carrot and Potato in Central Italy

Gaetano Martino, Paolo Polinori, and Luca Turchetti

Abstract The objective of the study is to address an economic problematic area in the field of fertilization management: how the characteristics of the production system for a given vegetable crop influence the fertilization strategy effect of farm efficiency. The analysis is conducted at the farm level and framed into a conceptualization of the relationship between the decisional and operational systems. The conceptual framework emphasizes the importance of the response function approach, of sustainability principles and of organizational dimensions. Data on Table tomato, carrot and potato were collected from the European Union Farm Accounting Data Network system. Data Envelopment Analysis indicates the importance of operational systems organizational factors in determining crop efficiency. The evidence suggests considering the objectives of the fertilization programme in the context of the organizational dimensions of the operational system.

Keywords Operational systems • Crop efficiency • Response function • Data Envelopment Analysis

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1 Introduction

The production response to the level of use of a given fertilizer traditionally is the central problem considered in the field of fertilization management. Agricultural Economists conceptualized this issue in terms of the laws of productivity, seeking to address the point of view of the Agronomists. Agricultural Economists and Agronomists historically used two different conceptualizations and methodologies to approach the fertilization problem (Paris 1981). A key point is that whereas agronomists normally conducted fertilization experiments with a few combinations of nutrients and many replications, agricultural economists used many combinations with few replications. In this context, the early approach in Agricultural Economics contended that the well-known von Liebig hypothesis implied a linear response plateau (LRP) model. The hypothesis of linearity was challenged by Paris (1992a), who argued that the LRP must be thought of as only a first approximation. Starting from the original formulation of von Liebig, Paris (1992a, p. 1019) stated that the von Liebig hypothesis conveys the notions of both non-substitution between nutrients and of yield plateau. The analytical strategy of Paris is based on an econometric comparison of alternative specifications of potential yield functions. This strategy confirms that the hypothesis of non-substitution among the inputs and the plateau has the most interpretive power with respect to the data. Furthermore, the nonlinear von Liebig embodies decreasing marginal productivity and diminishing returns to scale (Paris 1992a, p. 1023) and thus is clearly connected to the basic principles of the economic analysis of productivity.

The Paris analysis originated a huge debate, and the analysis of the response of a crop to the fertilization strategy remains relevant in the context of farming system studies. Amon-Armah et al. (2015), for example, stressed the difference in functional forms and identified three main approaches: (a) fit input and output data to an individual mathematical model or functional form; (b) fit the production data to a generalized flexible functional form; and (c) fit input-output data to a set of competing mathematical models aiming at determining the model that best fits the data.

Reviewing the vegetation index method for evapotranspiration determination, Glenn et al. (2010) contend that based on the law of minimum, an increase in the complexity of the approach does not entail a concomitant increase in accuracy.

According to Paris (1992a, b), Zhang et al. (2007) addressed the problem of estimating the plant weight increments and uptake of each nutrient. They argued that Liebig's law of minimum type response explains much of the variation in the interaction among the effects of the nutrients in field experiments. As explained by Paris (1981), this line of reflection elaborated on early intuitions of agricultural economists and drove the study of the fertilization management towards a convergence between Agricultural Economists and Agronomists. Following this stream of analysis, a critical point concerns the necessity of addressing data that strictly relate to fertilization decisions without the interference of other variables (Paris 1992a).

In the analysis of the fertilization system, furthermore, the approach to the estimation of the production function is also associated with the design of the experiment. For example, Brorsen and Richter (2012) identified the characteristics of the optimal experimental design supporting the estimation of production functions and found that whereas a stochastic plateau model better fit the data use, equally spaced design seems to maintain their utility. A central aspect is that the Paris approach implied the efficiency criterion of the law of productivity; technical efficiency is achieved by selecting combinations of inputs that belong to production functions. Economic efficiency is then achieved by maximizing the crop profit, given the prices of inputs and of outputs.

Precision farming provides an innovative approach to fertilization decision-making. Following the von Liebig hypothesis approach (Chambers and Lichtenberg 1996; Paris 1992a), Färe et al. (2012) introduced a method for developing optimal site-specific nutrient management strategies in the case of multi-output crops (case study: orchard). This approach offers an interesting specification of the Data Envelopment Analysis (DEA) model in the case of fertilization management. In the DEA approach, efficiency is evaluated in relative terms and is concerned with the relative positions of the process studied. Crucially focusing on the crop season as production periods, the authors distinguish the variable inputs – the essential nutrients for crop growth – and the fixed input – the tree trunk, assuming that its size does not vary during the time period considered. Furthermore, the price of the outputs – crop product at various quality and size grades (multi-output production) – is assumed given. The study proposes to design a fertilization strategy based on the identification of the limiting influence of the nutrient on the yield. To this end, the authors suggest using the *nutrient responsiveness index* (Wang et al. 2006), which is defined as a ratio between the maximal revenue attainable in the case in which the availability of the nutrient, say x, is completely unconstrained to the maximal revenue attainable when the availability of the nutrient is constrained (Färe et al. 2012, p. 4370). Nutrient x is held to be limiting if the nutrient responsiveness index is greater than 1; x is considered non-limiting if the index is equal to 1. The approach based on the DEA model allows estimation of the concentration level of nutrient x, which would eliminate the revenue constraint that this nutrient imposes at a given production site. This information is considered central to the elaboration of a site-specific nutrient management (Färe et al. 2012, p. 4371). The approach reported shares the basic idea that the von Liebig hypothesis – the law of the minimum – is the best approach to fit experimental data on fertilization (Paris 1992b). Therefore, one should expect that the best suggestions as prescriptions to farmers should be based on such scientific knowledge.

The huge debate in recent decades about sustainability has encouraged systematic revisions of fertilization strategies (Beddington 2010; Kay et al. 2009) to identify principles and technological knowledge able to improve the relationship between agricultural and natural systems (Dobbs and Pretty 2004; Pretty 2008). Specifically, environmental stewardship – intended as careful and responsible management of natural resources and goods – progressively induced scholars to design fertilization strategies able to connect economic and environmental goals.

In this chapter, we assume that fertilization strategies and related implementation programmes are framed within the relationship between farm decision systems and vegetable operational systems. The aim of this chapter is to address a general, economic problematic area in the field of fertilization management: how the characteristics of the production system for a given vegetable crop influence the fertilization strategy effect of farm efficiency. For this study, we define the fertilization strategy as utilization of the main nutrients used in a productive agricultural context joined with principles on which the utilization decisions are based. This operational definition allows investigation of fertilization management with respect to a set of decisions normally made by farmers. We assume that a farm perspective is useful to identify the patterns of the economic and managerial behaviours of the famers and then to make attempts to evaluate these behaviours with respect to the main objectives of the fertilization strategy: the efficiency and the implementation of sustainable technologies. The main reason for such approach is the assumption that the farm organization plays a relevant role in framing the decision on the production process and fertilization management (Sèbillotte and Allain 1991; van der Ploeg 2008). This assumption is particularly evident in the case of vegetable crops, in which the correct allocation of the variable inputs is influenced by the farmer capability to perform the productive operations in the right time pattern, combining these inputs with the given availability of (household) labour and the land (Polidori and Romagnoli 1987). Conversely, fertilization management is crucially based on the capability of the farmer to implement the response functions based on indications in the practical context of the farm. Therefore, in the study of fertilization management, one must consider the standard conceptualization of the response functions. However, although different concepts of efficiency may be invoked to design the right management approach, the agronomic prescription clearly underlies the basis of the technological knowledge of the farmers. Conversely, the scientific knowledge itself is integrated in processes of knowledge creation in which the system of chain relationships plays an important role (Peterson 2002; Sporleder and Wu 2006).

A correct understanding of how the management of fertilization is designed and implemented thus requires considering how the codified and tacit knowledge are integrated in organizational dimensions of farming systems (Dunne 2007). Furthermore, fertilization management is currently facing many challenges from the perspective of sustainability. However, this view must be contrasted with both the necessity of implementing a technology adequate to sustain the achievement of other objectives – e.g., sufficient yields and with the identification of the real pattern of farmer behaviours.

Enhancing the sustainability of a crop system primarily requires reducing the use of fertilizers used when seeking to meet the crop requirements (Matson et al. 1997; Pretty 2008). Whereas there is increasing focus on dedicated technology design and implementation (see for example Goffart et al. 2011), a systemic perspective seems to offer effective opportunities of enhancement (Gabriel et al. 2013; Pretty and Bharucha 2014). The chapter is organized as follows.

The second paragraph introduces the objective of the study and the method adopted. We initially elaborate a brief literature review to identify the conceptual framework of the study. Then, we analyse the efficiency of groups of farms managing vegetable crops. In this analysis, we consider the role of fertilization strategies and of operational systems (Sèbillotte and Allain 1991). Paragraph 3 presents the conceptual framework and discusses the role of the response function approach, the importance of sustainability principles and the influence of organizational dimensions. The empirical analysis is illustrated and discussed in paragraph 4.

We performed an empirical investigation concentrated on an efficiency analysis of two vegetable crops: table tomato and potato. We considered data from two Italian regions, Campania and Abruzzi, where the vegetable crops are largely diffused. We concentrate on groups of farms whose size is strongly influenced by the data availability. Paragraph 5 provides final remarks.

2 Methodology Proposed

2.1 Research Question and Lines of Inquiry

First, we propose a conceptual framework that seems to account for the rationale of the question mentioned. Then, we perform an empirical investigation after having specified the general question for table tomato and potato.

These crops provide an interesting example of the management problem to be solved in farming contexts. We assume that the design and the implementation fertilization strategy is part of the farm management. This assumption implies that the content of the fertilization strategy cannot be thought of as fully independent from the entire set of farm-management decisions.

Our approach concentrates on three main themes: (a) the conceptualization of fertilization management in terms of production functions, (b) the role of farm organization and practices and (c) the design of sustainable approaches to fertilization in practical contexts.

After the identification of the conceptual framework, we perform an empirical analysis on data coming from the European Union Farm Accounting Database Network (FADN). The FADN is an annual sample survey established by the European Economic Commission (EEC) in 1965, with EEC Regulation 79/56 and updated with the EC Reg. 1217/2009, to support the Common Agricultural Policy (CAP) of the European Union (EU). The network evaluation activities consist of annual surveys performed by the Member States.

We performed an efficiency analysis of the production processes. The outcomes of this step are informative about how the fertilization strategies contribute to crop efficiency in economic terms. However, this analysis also shows how economic, organizational and environmental factors may influence these outcomes and introduces the study of these factors as the second step of the empirical investigation.

The conceptual approach proposed suggests a role from the response functions perspective. In farm management, fertilization strategies are designed and implemented within a complex framework of decision-making processes that consider many inputs and must cope with the time constraints of biological processes (Polidori and Romagnoli 1987). In other words, fertilization strategies are implemented in the context of a wider set of decisions. Furthermore, in practical contexts, e.g., at the farm level, isolating the variables directly involved (e.g., yield) is difficult. For these reasons, we concentrated on the analysis of the economic efficiency of production processes (crop).

2.2 Method of Data Analysis

Efficiency analysis is central to the analysis of the fertilization strategy from both an economic and technical point of view (Paris 1992a, b). DEA is a mathematical programming model applied to observational data providing empirical estimates of input-output relationships and efficiency analysis that was initially developed by Charnes et al. (1978). The sampled farms (Decision Making Units, DMU, in the DEA language) are systematically compared to ascertain their degree of efficiency. The specification of the efficiency concept in DMU emphasizes the relative importance of the units investigated and compared. A unit is considered efficient if further units in the sample do not exist that are able to produce a greater amount of output with the same level of inputs or use a smaller amount of inputs, yielding the same level of output. Therefore, determined efficiency levels are not concerned with absolute efficiency values – i.e., ideal levels associated with a theoretical production function. The DEA efficiency levels rather are concerned with the real production process observed.

The analysis was performed by a one and two stages process (Fried et al. 1999, 2002; Johnson and Kuosmanen 2012) that allows defining *bestpractices* frontiers.[1] The estimated efficiency degrees are defined with respect to these frontiers. The method allows weighting the efficiency ratio (*output*/*input*), regardless of input and output prices and according to a maximization procedure that considers each farm from the best evaluation perspective. Furthermore, note that the analysis is largely data-oriented and does not require specific assumptions in terms of theoretical background.

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[1] The production frontier is a common conceptual tool in the Theory of Production, indicating the combinations of the maximum amount of two outputs that can be produced with a given amount of resources.

Stages	Variables
First DEA estimation Determing the current level of efficiency	Output: *Crop gross product* Input: *Land, Labour, Capital, Fertilizers*
↓	
Correcting the level of input	Contextual variables: *Climatic, organizationa variables*
↓	
Second DEA estimation New level of efficiency	Output: *Crop gross product* Input corrected: *Land*, Labour*, Capital*, Fertilizers**

Source: authors

Fig. 1 Data envelopment analysis procedure (variables with *star* are corrected inputs) (Source: authors)

The method adopted in this study is the following (Fig. 1):

(i) *First stage DEA*

  (a) A multi-output and multi-input DEA is performed to determine both efficiency levels for each DMU and the amount of unused resources (*slack*) for each input and DMU.
  (b) A regression model is estimated in which the *slack* for each unit is the endogenous variable, and exogenous variables are factors expected to explain the inefficiency values of each input. The model allows adjustment of original input quantities.

(ii) *Second stage DEA* The adjusted input quantities obtained in step (b) are then used to calculate the new level of efficiency.

However, fertilization strategies implemented by the farmers are centred not only on the idea of achieving efficiency objectives. There is an increasing necessity to achieve and manage detailed information on the production process (Gabriel et al. 2013; Goffart et al. 2011) to improve the sustainability of cropping strategies.

A sustainable approach to cropping tends to shape both farming and cropping systems (Pretty 2008; Pretty and Bharucha 2014). Therefore, we assume that fertilization strategies are designed according to organizational needs that can be conceptualized in terms of the organization of the production process (Polidori and Romagnoli 1987) and of the influence of the cropping system (Sèbillotte 1992). Conversely, the principles shaping the fertilization strategies are fast evolving under the inducements of sustainability requirements (Fan et al. 2011; Mikkelsen et al. 2009; Pretty and Bharucha 2014; Pretty 2008).

2.3 The Source of the Data

The main role of the FADN is to determine income and provide business analyses of European farms. The FADN gathers accountancy data from farms for the determination of income results and for business analysis of agricultural holdings to measure the effect of the EU's agricultural policy and to support the on-farm decision-making process. The FADN is the only harmonized source of microeconomic data about agricultural holdings in the EU. Bookkeeping principles, for example, are the same in all countries. The applied methodology aims to provide representative data on three levels: (i) region; (ii) economic size; (iii) type of farming.

Data collected from individual farms are treated confidentially, and farmers are rewarded with detailed reports on their own farms and a comparison with other individual farms.

Holdings are selected to take part in national surveys based on sampling plans established at the regional level. The Italian FADN is based on a purposive sample of approximately 11,000 farms, structured to represent the different types of production and size in the national territory. The sample FADN allows an average coverage nationwide of 95% of the Utilized Agricultural Area (UAA), 97% of the value of Standard Production, 92% of Work Units, and 91% of Livestock Units.

The information framework of the Italian FADN, much wider than the institutional requirements of the European Commission, allows an analysis of various topics ranging from the productivity of farms to production costs and from environmental sustainability to the role of the family farm.

The Italian FADN (www.rica.inea.it) survey gathers different data on a yearly basis; accountancy data, structural characteristics and production of over ten thousand farms, and thousands of selected information items are organized and consolidated in a database. For every farm belonging to the FADN sample, a farm return is compiled, its basic structure outlined by specific regulatory measures of the European Commission. Over time, the return has undergone several changes and additions in response to new and greater information needs expressed by the EU.

The FADN database is also used by users external to the Community institutions: Ministry of Agriculture, Regions, universities and research institutes, and professional organizations and representatives of agricultural producers, which require information to define the context within which are implemented measures of agricultural policy and rural development. In this area, the FADN has provided a fundamental contribution to analysis and simulations concerning the various reforms of the CAP, both sectorial policies, and those of rural development.

3 Conceptual Framework

3.1 Sustainable Approach to Farming and Fertilization Strategies: Debating Ends and Means

The debate on sustainable agriculture challenged the strictly ‘input-output’ setting of the problem of fertilization and, to some extent, the effect of the role of economic efficiency in solving the related managerial problem. Agriculture has huge effects on natural systems because of the long-term trend towards industrialization (van der

Ploeg 2008). The reduction of fertilization quantities is becoming a necessary management principle (Beddington 2010), implying a need on the one hand to change the basic productivity relationship in the management approach and, on the other hand, to develop appropriate a conceptual framework to define innovative management principles. Scholars emphasize the inherent uniqueness of the agricultural sector because the sector directly affects many assets on which the sector in turn relies (Pretty and Bharucha 2014, pp. 1575–1576). Agricultural systems are artificial in nature and exhibit distinctive properties that sharply characterize them with respect to natural ecosystems. Sustainable agro-ecosystems are thought of as seeking to shift some of these properties towards natural systems without significant trade-offs in productivity (Pretty and Bharucha 2014, p. 1575).

The key principles for sustainability are to (Pretty 2008, p. 451)

(a) integrate biological and ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration, allelopathy, competition, predation and parasitism into food-production processes;
(b) minimize the use of those non-renewable inputs that cause harm to the environment or to the health of farmers and consumers;
(c) make productive use of the knowledge and skills of farmers, thus improving their self-reliance and substituting human capital for costly external inputs; and
(d) make productive use of people's collective capacities to work together to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management.

The principles should lead the transformation of the agroecosystems towards states more compatible with the maintenance of adequate flows of natural system services and society expectations. The technological knowledge is a crucial resource to face this challenge (Beddington 2010, p. 65; Pretty and Bharucha 2014, p. 1577). Sustainable agricultural systems exhibit many interesting properties (Pretty and Bharucha 2014, pp. 1577–1578): (a) they are multifunctional in nature because they jointly produce both private and public goods and services; (b) they are diverse, synergistic and tailored to their particular social-ecological contexts; (c) they often also manage complex mixes of domesticated plant and animal species associated with sophisticated management techniques; (d) finally, these systems strongly rely on systems of social relationships.

Sustainable systems also allow allocating agricultural resources in the context of a multifunctional strategy (Dobbs and Pretty 2004). From a system perspective in the field of fertilization strategy, sustainability implies modification of the aim and very content of fertilization technology. The concept of sustainability intensification helps explain this point. Table 1 offers a comparison between the conventional approach and sustainable intensification. The main point is concerned with the shift of farmers' goals from *increasing* towards *improving* crop and livestock yields. Second, a key point is the innovation role of knowledge creation, meaning that the specific experience of the farmers – their tacit knowledge (Polanyi 1966) – must be integrated into the definition of the fertilization program, as noted by recent contributions (Nesme et al. 2005).

Table 1 Differences between sustainable intensification and historically conventional forms of agricultural intensification

Features	Conventional forms of agricultural intensification	Sustainable intensification
Primary goals of farmers	Increase crop and livestock yield	Improve yield and incomes, improve natural capital in on – and off farm landscapes, build knowledge and social capital
Knowledge development	Tend to be solely ‘expert’ driven	Collaboration between ‘experts’ and other stakeholder as key to emergence of agro-ecological design; participatory research and development leads to new technologies combined and practices
Knowledge dissemination	Conventional extension chain from public or private research to farmers	Conventional extension combined with participatory dissemination via peer-to-peer learning
Steward ship of ecosystem services	Emphasis on provisioning services derived from agricultural landscapes; use of external inputs o substitute for regulating and supporting services; interactions with surrounding non-agricultural landscapes treated as externalities	Greater appreciation of the contribution of multiple ecosystem services provided by agricultural landscape and awareness of the two-way relationship between agricultural and non-agricultural components of landscapes

Source: Pretty and Bharucha (2014, p. 1579)

Nesme et al. (2005) underline the fact that farmers’ fertilization practices are not only a key factor in fostering sustainable approaches to fertilization systems but also differ to some extent from the approach suggested by agronomists and advisors. The analysis of Nesme et al. (2005) thus addresses the key point of the relationship between the experience of the farmers or, better, their tacit knowledge (Polanyi 1966) and scientific knowledge.

With respect to a given apple plot in a given area, the study estimated the amount of nitrogen fertilizer that should be applied to the crop area to supply the exact amount of nitrogen used (Nesme et al. 2005, pp. 299–301). Then, the real amounts of fertilizer supplied by farmers were observed and compared with model outputs. The subsequent analysis was then conducted in term of model discrepancy, defined as the difference between the model output and farmer practice. First, the authors found that model discrepancies become smaller as the complexity of the balance model increases, suggesting that the farmers’ experience would foster their capability to achieve a synthetic understanding of the determinants of fertilizer needs (Nesme et al. 2005, p. 310). Second, the study indicates that the within-farm homogeneity of model discrepancies implies the existence of an overall fertilization pattern for each farmer. Finally, the authors suggest that the model discrepancy should be considered a characteristic of cropping systems as defined by Sèbillotte

(1992) – a group of plots treated homogeneously, characterized by the nature of the crop and the crop management applied (Nesme et al. 2005, p. 311).

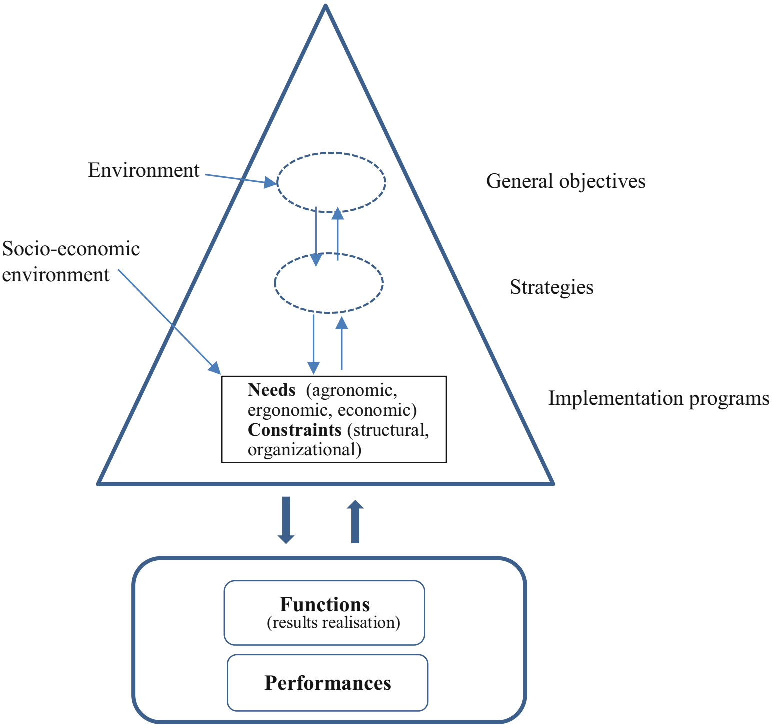
3.2 Farming Systems, Organization and Fertilization Programs

Sustainability principles are normally treated according to Environmental Economics perspectives. The brief discussion above shows that the specification and definition of a (sustainable) fertilization programme at the farm level implies an appropriate organization framework for the following reasons: First, there is the necessity to integrate the practical and the codified knowledge. Second, effectiveness practices are strictly components of the organizational framework of the production units (Grandori and Furnari 2008). Third, the organization itself solves specific problems of timely resource allocation, particularly in the vegetable crops (Polidori and Romagnoli 1987). Scholars recently provided evidence from systemic and organizational perspectives.

Gabriel et al. (2013) identified and ranked potential strategies related to the introduction of cover crops compared with standard rotation. The focus of the study was on the possibility of reducing nitrateleaching, and the approach aims at combining economic and environmental analyses. The authors used experimental data to estimate the probability distributions of the relevant outcomes including economic and environmental performance. Under this view, relevant outcomes also include effects on all the crops in the rotation. For the economic analysis, the authors considered two main management options: (a) leaving the cover crop to reside in the soil as green manure or selling the residues for animal feeding and (b) reducing the nitrogen fertilizer application based on the potential saving derived from the cover crop residues. Contrasting environmental (Nitrogen leaching) and economic (net befit per hectare) effects, the authors investigated the outcomes of Monte Carlo simulations conducted on the prominent variables, including crop prices and costs of the alternatives. Notably, the economic benefit outcomes appear characterized by a large variability, whereas selling residues appears a dominant solution in all cases considered (Gabriel et al. 2013, p. 29). Second, price variation seems not to influence the relative advantage of each scenario, although price variation does not vary the benefit range (Gabriel et al. 2013, p. 30). The approach proposed frames the fertilization issues within the farming system characteristics, although focused onrotation. The performance of the strategies considered therefore entails the outcomes of the related crops, but it also depends upon market possibilities, fertilization savings and the type of environmental indicator. Nowak (1992) categorized the main reasons why farmers adopt new technology. He first recognized that non-adoption is caused by two basic, not mutually exclusive reasons: farmers may be unable or they may not choose to adopt. Obstacles causing the inability to adopt may relate to lacking the cost of the necessary information, to the complexity of the technology, to high management or labour costs, to the availability of supporting resources or to the lack of control on the farmers' side. Nowak (1992, p. 15) states that a farmer may be unwilling to adopt a new practice because she/he has not been persuaded that the technology will work or is appropriate for the farmer's operation. Snapp et al. (2005) analysed the economic and environmental impacts of cover crops in various geographical contexts and contrasted evidence from the literature with tacit knowledge of the farmers. Among the objectives of the study, the analyses of the economic and environmental effects are prominent. A relevant point made by the authors is that the analysis must be performed with respect to both the key characteristics of the farming system and to the distribution between private and public stakeholders of the costs and benefits of alternative scenarios. Accordingly, Snapp et al. (2005) identified in the literature the main internal and external costs and benefits. Although the benefits appear better determined, a complex influence among crops appears to be at the basis of the external costs. The classification of the internal costs in indirect, direct and opportunity costs allows one to identify the main difficulties emerging in the different farming systems considered. The analysis is enriched by the comparison between the literature evidence and the outcomes of focus groups organized with farmers and aimed at addressing the main benefit and costs of the cover crops. Notably, the literature evidence (codified knowledge) and the farmers' assessments (tacit knowledge) tend to converge, providing rational bases for designing potential cropping strategies. From a wider perspective, Mikkelsen et al. (2009) explored the effects of a fertilization strategy with respect to the multiple-farming subsystem, emphasizing the complexity of the decision process and the necessity of framing multiple indicators to meet sustainability requirements.

Sèbillotte and Allain (1991, pp. 81–82) noted that an operational system in farming ensures the execution of the all types of operations (e.g., productive and administrative) by the entrepreneur. The operational system is particularly relevant in the implementation of the productive processes and establishes causal nexuses between the set of needs (agronomic, ergonomic and economic), how to perform productive operations and performance (Sèbillotte and Allain 1991, p. 82). Figure 2 illustrates the relationship between the decisional systems – internally articulated – the strategies level and the implementation programmes.

The figure shows that the level of strategies *must address a complex set of needs and constraints to specify the implementation programmes*. The real content and configuration of the production process (*functions*, in the figure) and their performance thus directly depend upon the formulation of the implementation programmes. To perform an empirical analysis at the farm level implies addressing the outcomes of the systemic relationships depicted in Fig. 2. This perspective suggests that the contribution of the fertilization strategy to farm efficiency is conditioned by the farm system characteristics. We consider this approach in the empirical analysis by considering the system characteristics a contextual variable in the analysis of crop efficiency.



Source: Sébillotte, Allain, 1991, p. 83

Fig. 2 Decision and operational systems

4 Empirical Analysis

The rationale for this approach is based on two considerations: (a) the approach offers significant evidence on how the fertilization management principles (efficiency, stewardship based) are implemented; and (b) it allows identifying how the organizational framework shapes the decisions made by the farmers.

For simplicity, we concentrate on table tomato and potato. To consider one crop, it is necessary to address coherent patterns of resource utilization. Considering two different crops helps highlight aspects of the fertilization programme that address different agronomic strategies.

We used FADN data and concentrate on farm activities in the Abruzzi and Campania regions (South Italy), implying a need to address a huge variability of climate and soil-based factors. We tried to capture the influence of these variables by specifying proxy variables available in the database (e.g., altitude, geographic coordinates and soil average characteristics).

4.1 Efficiency Analysis

The initial model includes six inputs:

Land, total Utilised Agricultura Area of the crop examined (ha);
Labour, total amount of human labour utilized in the crop *Land* (hour year^{-1});
Capital, total amount of equipements and dedicated machines used in the crop examined (Euro year^{-1});

and the amount of the three main fertilizers:

Nitrogen, total amount of nitrogen fertilizer used for the crop examined (kg);
Phosphorus, total amount phosphorus fertilizer used for the crop examined (kg);
Potassium, total amount of potassium fertilizer used for the crop examined (kg);

and one output (gross product of the crop considered). We assumed variable returns to scale, i.e., we assumed that the return of the productive processes increases (decreases) at a variable rate when all the inputs increase (decrease). The programming mathematical problem is the following:

$$TE^i = min_{\theta,\lambda}\theta \tag{1}$$

s.to:

$$-y_i + Y\lambda \geq 0; \quad \theta x_i - X\lambda \geq 0; \quad N1'\lambda = 1; \quad \lambda \geq 0$$

where $X_{(6*T)}$ is the input matrix, $Y_{(1*T)}$ is the output matrix *output* and x_i and y_i are the column vectors, which identify the *i*th DMU with $i = 1, \ldots, T$; $\lambda_{(T*1)}$ is a vector of constant parameters, $N1^{'}\lambda = 1$ represents the usual convexity constraint of the production theory, and θ indicates the efficiency level of the *i*th unit.

In this stage, we estimated a number of equations equal to the number of inputs considered. The outcome is, for each farm, the level of efficiency of the crop considered. These levels of efficiency are strictly related to the production function theoretical relationships.

The quantities of unused resources (*slack*) may arise from deviations from the production function combinations (*not radial slacks*) or from the profit maximization level (*radial slack*).

After having obtained a level of efficiency, we considered the fertilization strategies together with the influence of additional farm factors.

Actually, scholars (Coelli 1998; Fried et al. 1999, 2002; Muñiz 2002) noted that the economic environment in which the DMU operate can influence their performance. For example, factors not directly controlled by the management may have a negative influence on the evaluation of efficient performance.

In the field of our study, one such factor might be farmers not imposing sustainability strategies.

Table 2 Contextual variables

Variable	Label	Unit of measurement
Altitude	ALT	m. o.l.s.
Latitude	LAT	Degrees
Longitude	LONG	Degrees
Age of the enterpreneur	AGE	1 = young farmer, 0 = not young farmer
Size of the usable agricultural land of the whole farm	SCALE	(%)
Importance of the crop in the farming system	SPEC	(%)
Importance of the irrigated land with respect to the total farm land	IRR	(%)
N.of farming plots	PLOTS	Number/farm
Soil of average quality	SOILavg	ha

Source: authors

Following Coelli (1998), we considered further factors held to be able to explain the efficiency differences among the studied units (see Table 2).

These factors represent the contextual variables, which are thought to influence the technology but not the efficiency (Johnson and Kuosmanen 2012).

(i) *Altitude* (ALT) is a proxy of critical weather characteristics (such as temperatures) having direct influence on the crop; we measured the altitude using the FADN scale, with values from 1 (Mountain) to 5 (Plain). Actually, the true altitude of the farm in terms of metres o.l.s. is unknown; employing the FADN information, one may identify only the average altitude of the administrative area without any certain link with the farm altitude.

(ii) *Latitude* (LAT) and *Longitude* (LONG), considered proxies of the territorial conditions, are expected to influence the outcomes.

(iii) *Age of the entrepreneur* (AGE) is a proxy of farmer experience; the variable is dichotomous and assumes value 1 if the farmer is a “young farmer” according to the FADN classification and value 0 if she or he is not a “young farmer”.

(iv) *Size of the usable agricultural land of the whole farm* (SCALE) indicates the size of the economic organization and is captured by the area of land used as the main productive resource. We expect that increasing the scale increases the complexity of the management of activities, with potential negative effects on efficiency. The increase of scale actually allows farmers to achieve gains from unit cost reductions; however, potential negative effects may arise on the management side. Actually, the capability to manage units of increasing scale generates scale diseconomies due to an increasing inability to allocate resources efficiently, to manage the timing of production within biological constraints, to avoid excess financial costs and so forth.

(v) *Importance of the crop in the farming system* (SPEC) implies that more-important crops are associated with more-specialized farms for those specific crops and that farmers are expected to be more skilled with positive effects including efficiency.

(vi) *Importance of the irrigated land* (IRR) is the percentage of irrigated land with respect to total farmland. We expect that also in this case, as the percentage increases, the management of the productive operation becomes more complex, with potential negative effects on efficiency. Specifically, we expect that an increase in IRR may cause managerial issues at the farm level that in turn may overcome the benefits at the crop level.

(vii) *Farming land plots* (PLOTS) – for this variable, we expect that a larger number of plots is associated with more-complex productive operations.

(viii) *Medium texture soil* (SOILavg) – the type of soil is supposed to be influential on the farms' efficiency. We considered for this purpose the area of medium-texture soil.

Contextual variables might be used in two ways: (i) first o estimate the variables impact on the efficiency scores by a two-stage procedure; (ii) second, to correct input data by a three-stage procedure. In the first case in the second stage efficiency scores are regressed on the set of contextual variables using a Ordinary Least Square or Tobit model (Mc Donald 2009). Formally:

$$\theta_i = xe_i\beta + u_i \tag{2}$$

where u_i/xe_i are normally, identically and independently distributed with mean, zero, and variance, σ^2 , xe_i is a $1 \times k$ vector of observations on the constant and k–1 efficiency factor explanatory variables and β_i a $k \times 1$ vector of unknown coefficients.

In the second case a three stages procedure is applied and the second step is to use the coefficients estimated via the truncated regression to correct the original input data, eliminating the effects of the considered variables, and then obtain the new, corrected levels of input. Formally,

$$TSI_n^i = f_n\left(E_n^i, \beta_n, u_n^i\right) \tag{3}$$

where $i = 1, \ldots, T$ is the number of farms, $n = 1, \ldots, 6$ is the number of *inputs;*TSI_n^i is the sum of the *radial* and *no-radial slack* of the *i*th farm for the *n*th *input,*E_n^i is the matrix of contextual variables and u_n^i is the disturbance term. Having estimated the coefficients β_n in (3), it is possible to predict the levels of inputs of each farm:

$$\widehat{TSI_n^i} = f_n\left(E_n^i \widehat{\beta}_n\right) \tag{4}$$

Our approach puts all the farms in the worst levels of the contextual variables via the following correcting procedure:

$$x_n^{i,corr} = x_n^i + \left[max_n\left(\widehat{TSI}_n^i\right) - \widehat{TSI}_n^i\right] \tag{5}$$

with x_n^i indicating the current level of ith input and $x_n^{i,corr}$ indicating the correct level. Equation (5) allows one to substitute the correct inputs matrix into the original input matrix.

In the third stage, we simply calculate again the level of inefficiency of all farms based on the corrected input data. The association between the original and the corrected level of efficiency is measured by the Spearman rank correlation coefficient.

4.1.1 DEA: Table Tomato in the Abruzzi Region

We first considered the production of the Table tomato in the Abruzzi region (South of Italy) using a two stages approach. We considered 34 DMU and ran a single stage DEA considering inputs land, capital, labour, and the fertilization strategy (amount per hectare of nitrogen, phosphorus and potassium). The units are located in hill areas (low and high altitude) and change because of further contextual variables, namely, scale and specialization. The first stage DEA model results are illustrated in Table 3. The minimum value of the constant returns to scale efficiency is equal to 48.1% of the maximum value, whereas it is equal to more than 65% in the case of variable returns to scale. The distance between the first and second quartile is 0.202, but the interval between the median and third quartiles is only 0.06 in the case of constant returns to scale. In the case of variable returns to scale, the distance is smaller, 0.113 and 0, respectively.[2]

Assuming that the contextual variables influence the technology but not the efficiency, we then examined the role of the contextual variables of the degree of efficiency by running a simple linear regression taking the natural logarithm of *Theta* (*lTheta*) as the dependent variables (see Table 2). The estimated models yielded not statistically significant results except in the case of the model summarized in Table 4. The variables *ALT* (in this case, a dichotomous variable: 1 = low-hill area, 0 = high-hill area) and*SCALE* are both statistically significant at $P < 0.1$.

The marginal effect of *ALT* is positive, indicating that the low-hill environment influences efficiency. *SCALE* has a negative effect, which can be interpreted as managerial diseconomies due to the size of the farm (Penrose 1995). Notably, the other variables have no effect on efficiency, most likely because of the limited

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[2] A simpler case – not presented in detail – concerns 14 DMUs engaged in carrot production in Celano (Abruzzi, south Italy). In the case of constant returns to scale, the distribution of the efficiency levels is more concentrated towards the largest values. Actually, the distance between the first and the second quartile is small (0.028) compared with the distance between the second and the third quartile (0.214). In the case of the variable returns to scale, the results indicate a concentration of efficiency in the largest value areas. Because of the small number of units available, it was impossible to examine the effects of the contextual variables.

Table 3 Distribution of the technical efficiency level (Table Tomato – Abruzzi) – 1st stage

Technical efficiency			
Scores	Costant return of scale	Variable returns of scale	Scale efficiency
Min	0.481	0.656	0.480
1st quartile	0.712	0.887	0.784
2nd quartile	0.914	1	0.979
3rd quartile	1	1	1
Max	1	1	1
Mean	0.848	0.939	0.890
St. Dev.	0.173	0.101	0.134
C. V.	0.204	0.197	0.105
N. of DMU eff	10	22	10

Source: authors
DMU = 34; N. of output = 1; N. of input = 6. Efficiency scores: 1 = max efficiency; 0 = max inefficiency = 1
N. of DMU increasing return to scale = 15; N. of DMU decreasing return to scale = 9

Table 4 Table tomato (Abruzzi) – effects of the contextual variables (2nd Stage)

lTheta	Coef.	Std. Err.	T	P > t
ALT	1.323	0.653	2.03	0.056
LAT	−0.741	4.971	−0.18	0.857
LONG	0.131	3.634	0.04	0.972
SCALE	−0.147	0.074	−1.98	0.061
PLOTS	0.027	0.110	0.25	0.805
SPEC	0.046	2.188	0.02	0.983
SOILavg	0.031	0.064	0.49	0.631
_constant	2.638	2.185	0.12	0.905

Source: authors
N. of Obs. = 34 Adj $R^2 = 0.19$

range of the variables in the sample. The results indicate that a favourable environment positively influences crop efficiency, but this effect could be contrasted with the organizational characteristics of the cropping system.

Table 5 illustrates the Spearman correlation coefficients among the degrees of efficiency *(θ)*, the amounts of the inputs (Land, Capital, Labour) and the fertilizers utilized. These coefficients provide a measure of the coherence of the ranking of the units in terms of efficiency and of other factors. There is a significant coherence among efficiency degreeθ and other factors.

Notably, the connection between Nitrogen and efficiency is greater than is the correlation between Land, labour, capital and efficiency. This connection indicates the importance of the fertilization strategy to crop efficiency.

Table 5 Table tomato (Abruzzi) – Spearman correlation coefficients

	lTheta	Land	Capital	Labour	Nitrogen	Phosphorus	Potassium
lTheta	1.0000						
LAND	0.3789	1.0000					
CAPITAL	0.2298	0.6751	1.0000				
LABOUR	0.259	0.9364	0.6843	1.0000			
Nitrogen	0.4112	0.8329	0.7573	0.7099	1.0000		
Phosphorus	0.1615	0.7878	0.5873	0.6926	0.7851	1.0000	
Potassium	0.2914	0.7713	0.7824	0.6753	0.9373	0.6791	1.0000

Source: authors

4.1.2 DEA: Obtaining the Initial Levels of Efficiency for Potato in Abruzzi Region

The number of farms considered for the Potato case study in Abruzzi is 73 DMUs. We run the DEA estimation across all these units. The estimated levels of efficiency are presented in Table 6. We considered the technical efficiency in the case of constant and variable returns to scale and scale efficiency.

The minimum level of technical efficiency in the case of constant returns to scale is approximately 15.2% of the maximum level, whereas the mean is approximately 72.1% of the maximum value. The variation of the efficiency degree is very small moving from the second to the third quartile in the case of constant returns to scale. The variation of the efficiency degree is small moving from the second to the third quartile in the case of variable returns to scale. Conversely, there is a strong homogeneity level of scale efficiency. Table 7 shows Spearman correlation coefficients.

The results highlight that there is a divergence between rank in terms of efficiency and in terms of capital, nitrogen, phosphorus and potassium, although with a low correlation level; it seems that the efficiency of the crop is rather implemented by *Land* and *Labour*. We then run a truncated regression in which the dependent variable is the level of efficiency of the process and the covariate is the contextual variable: *ALT, AGE, SCALE, SPEC, and IRR*. We estimated one regression for each input considered in the analysis: *Land*, *Labour*, *Capital*, *Nitrogen, Phosphorus,* and *Potassium* (amount of fertilizers used per hectare). The latter also includes the total costs of the fertilization. The results are illustrated in Table 8.

Note that the coefficients of the truncated regression can be interpreted in the same manner as the Ordinary Least Square regression coefficient. Each of the coefficients in Table 8 indicates a predicted change in the dependent variable – the inputs in our case – due to a one-unit increase in the given independent variable (e.g., ALT), holding all remaining independent variables constant.

The *sigma* is the equivalent of the standard error of estimate in Ordinary Least Square regressions; the outcome is not small, but it appears acceptable. Altitude (*ALT*) and *AGE* are not statistically significant in any of the six models estimated.

Table 6 Distribution of the technical efficiency level (Potato – Abruzzi) – 1st stage

Technical efficiency			
	Costant return of scale	Variable returns of scale	Scale efficiency
Min	0.152	0.152	0.617
1st quartile	0.640	0.734	0.921
2nd quartile	0.718	0.836	0.990
3rd quartile	0.778	0.949	0.992
Max	1	1	1
Mean	0.721	0.813	0.949
St. Dev.	0.153	0.174	0.071
C. V.	0.212	0.215	0.075
N. of DMU eff	7	11	7

Source: authors

DMU = 73; n. output = 1; n. input = 6. Efficiency scores: 1 = max efficiency; 0 = max inefficiency

N. of DMU increasing return to scale = 38; N. of DMU decreasing return to scale = 35

Table 7 Potato (Abruzzi) – Spearman correlation coefficients

	Theta	Land	Capital	Labour	Nitrogen	Phosphorus	Potassium
Theta	1.0000						
LAND	0.3155	1.0000					
CAPITAL	−0.0469	0.3205	1.0000				
LABOUR	0.1365	0.6768	0.8040	1.0000			
Nitrogen	−0.0696	0.5606	0.5065	0.6374	1.0000		
Phosphorus	−0.1225	0.4709	0.4318	0.5055	0.9244	1.0000	
Potassium	−0.1501	0.4695	0.4971	0.5791	0.9368	0.9416	1.0000

Source: authors

SCALE has a positive effect on input slack in the case of the model for *Land*, *Nitrogen, Phosphorus,* and *Potassium.*

The results indicate that, as the scale of farm activities increases, the organization of the production processes becomes more difficult, giving rise to management difficulties. As for the fertilization strategy, the effect of these difficulties is greater than in the case of Nitrogen fertilization. Conversely, our results indicate that as the scale increases, the farmer appears to be more able to manage labour and capital. Farmers seek to implement better use of labour and capital because scale causes management difficulties. The specialization (SPEC) of the crop strongly influences the inputs used. Input slacks are positively influenced by the growth of specialization. Nitrogen fertilization exhibits the largest effect not only with respect to *Land*, *Labour* and *Capital* but also with respect to Phosphorus and Potassium fertilization strategy. The explanation of this evidence is that as specialization increases, despite the necessary gain of efficiency in terms of technology and skills, managerial diseconomies (Penrose 1995) become important. Notably, the largest effect of the specialization is concerned with *Capital* and *Nitrogen.*

Table 8 Truncated regressions, dependent variables = input slacks

Independent variables	Land		Labour		Capital		Nitrogen		Phosphorus		Potassium	
ALT	0.06		−20.34		−31.20		252.07		20.73		7.05	
	0.04		*13.26*		*24.92*		*185.45*		*55.87*		*5.94*	
AGE	−0.04		103.68		163.61		260.33		−9.98		69.18	
	0.04		*69.52*		*99.49*		*169.15*		*7.65*		*43.21*	
SCALE	0.02	**	−16.18	**	−32.48	**	107.56	**	12.14	**	5.81	**
	0.01		*7.92*		*15.85*		*45.48*		*4.75*		*2.25*	
SPEC	0.16	*	474.57	***	1236.23	*	1619.01	*	98.75	***	157.01	*
	0.09		*159.10*		*639.64*		*913.50*		*35.32*		*85.86*	
IRR	0.10	*	102.53	**	275.26	*	649.61	**	38.71	**	141.27	**
	0.06		*47.35*		*156.41*		*326.06*		*18.28*		*62.14*	
Constant	−0.21	**	83.55	*	104.46	*	−1187.69	*	−98.79	**	−43.52	*
	0.11		*43.64*		*58.91*		*706.66*		*47.99*		*23.57*	
Sigma	0.37	***	240.73	***	967.82	***	1382.20	***	144.22	***	281.22	***
	0.03		*19.92*		*80.10*		*114.39*		*11.94*		*23.27*	
logLH	−544.51		−503.89		−605.46		−631.48		−466.49		−515.24	
Obs.	73		73		73		73		73		73	
Wald chi^2(6)	27.45		25.40		30.52		31.83		23.51		25.97	

Source: authors

Note. Significance: *p < 0.1 , **p < 0.05, ***p < 0.001. Std. error in Italics

The relative importance of the irrigated land (IRR) exhibits a similar pattern of effects. The largest positive effect on the input slacks concerns *Capital* and also nitrogen strategy in this case.

Summarizing the results for the case of the potato crop in Abruzzi, note that the variable related to farm organization has a statistically significant effect on the input slacks. These effects are positive except for *Labour* and *Capital* in the case of SCALE. Therefore, as for the fertilization strategies, we contend that the organizational variables associated with the production system (Sèbillotte 1992) have an effect greater than the physical conditions as captured by the proxy variable ALT.

We corrected the level of the input assuming the worse input conditions for each farm.

Therefore, we applied Eq. (4), which does not modify the input availability for the worst farm. This is the DMU for which the term $\left[max_n\left(\widehat{TSI}_n^i\right) - \widehat{TSI}_n^i\right]$ has a null value, penalizing all remaining DMU for which $\widehat{TSI}_n^i$ is less than the maximum value predicted by the regression model coefficients. Figures 3, 4, 5, 6, 7 and 8 illustrate the original and corrected levels (*) of the inputs (Table 9).

Both the minimum and the mean values decrease, indicating a reduction of efficiency. Moreover, the interquartile distance increases, indicating that the variability also increases with respect to the first stage. In summary, we found that the organizational variables have an effect, reducing the degree of efficiency.

4.1.3 DEA: Obtaining the Initial Levels of Efficiency for Potato in Campania Region

In Table 10, we report the results of the first DEA in the case of the Potato crop in Campania. The sample includes 33 units. On average, the technical efficiency is greater than in the case of Abruzzi (0.822 vs. 0.674). The technical efficiency increases in the cases of both constant and variable returns to scale. The minimum level of efficiency is equal to 32.6% of the largest values in the case of constant returns to scale and 37.3% in the case of variable returns to scale. The mean value is high and almost equal in the two cases (82.2% and 85.5%).

The variability of the efficiency level is large. Within the 50% of the units included between the first and the third interquartile, the level of efficiency has a total variation equal to 30.8% (interquartile distance) of the largest efficiency value for the case of constant returns to scale and equal to 24.2% in the case of variable returns to scale. Table 11 shows that all inputs have a negative correlation with degree of efficiency, indicating that the input uses and the fertilization strategy are not coherent with the efficiency level and that there is room to correct the resources management.

The models addressing the input slacks are presented in Table 12. The picture is complex. The variable ALT has a negative small influence on land (−0.0104), whereas the remaining parameters are not statistically significant. The variable AGE has a clear effect on input use except for that of *Labour*. Only the influence

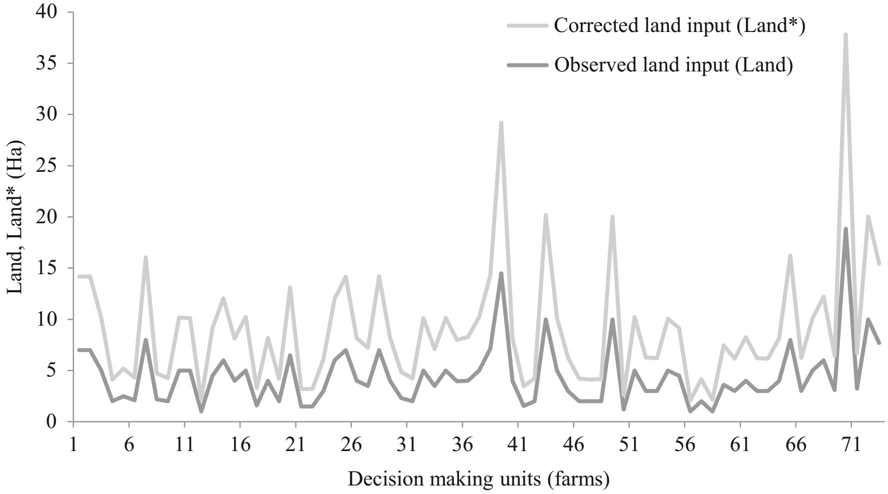

Fig. 3 Potato production process (Abruzzi) – Observed land input (*Land*) and land input corrected (*Land**) by through the Data Envelopment Analysis

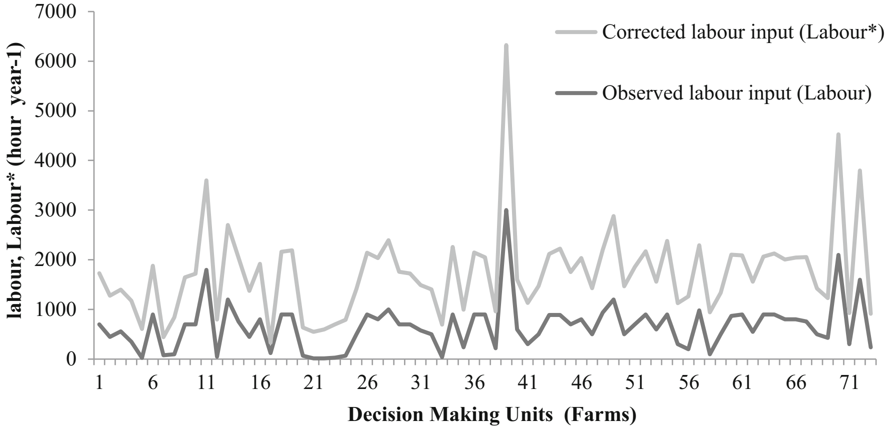

Fig. 4 Potato production process (Abruzzi) – Observed labour input (*Labour*) and labour input corrected (*Labour**) by through the Data Envelopment Analysis

on *Land* is positive, whereas AGE is negative on *Capital*, *Fert_N*, *Fert_P* and *Fert_K*.

Notably, the SCALE of the activity has a negative, small influence on *Land* and on *Labour*; however, SCALE has a positive influence on the fertilizer inputs Nitrogen and Potassium. The specialization has a positive effect on input slacks (except for *Land*), particularly for Nitrogen fertilization; in this case, the effect is almost three times the input on labour, whereas the effects on *Fert_P* and *Fert_K*

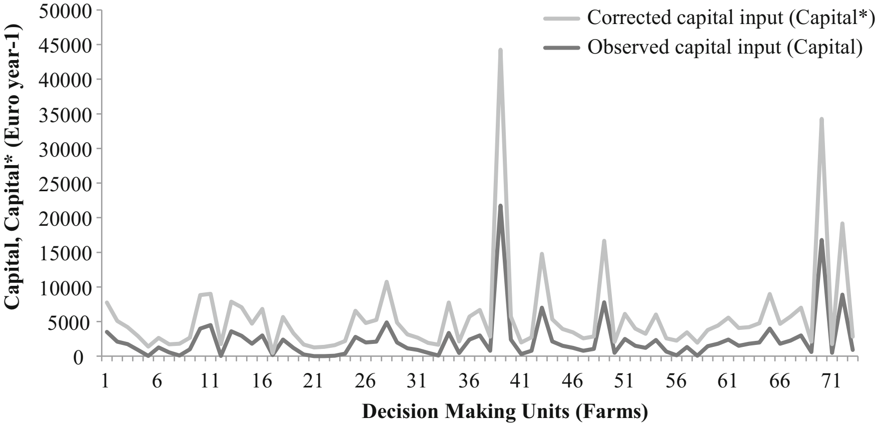

Fig. 5 Potato production process (Abruzzi) – Observed capital input (*Capital*) and capital input corrected (*Capital**) by through the Data Envelopment Analysis

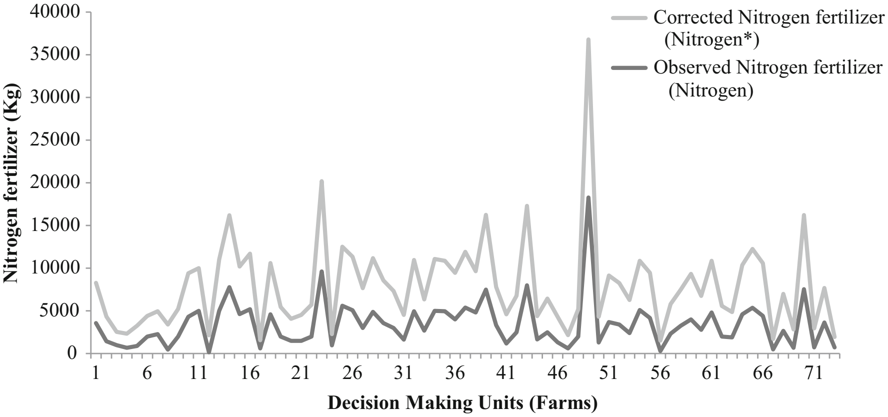

Fig. 6 Potato production process (Abruzzi) – Observed Nitrogen fertilizer input (*Nitrogen*) and Nitrogen fertilizer corrected (*Nitrogen**) by through the Data Envelopment Analysis

are less important. The effect of IRR has a similar but less pronounced pattern. Table 13 presents the level of efficiency based on the corrected inputs.

Both the minimum and the mean values decrease, indicating a reduction of efficiency. Moreover, the interquartile distance increases, indicating that the variability also increases with respect to the first stage. In summary, we found that the organizational variables have an effect, reducing the degree of efficiency.

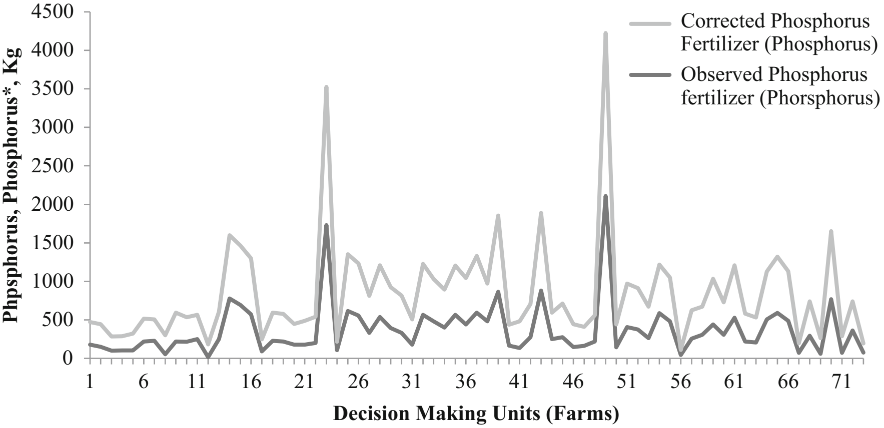

Fig. 7 Potato production process (Abruzzi) – Observed Phosphorus fertilizer input (*Phosphorus*) and Phosphorus fertilizer corrected (*Phosphorus**) by through the Data Envelopment Analysis

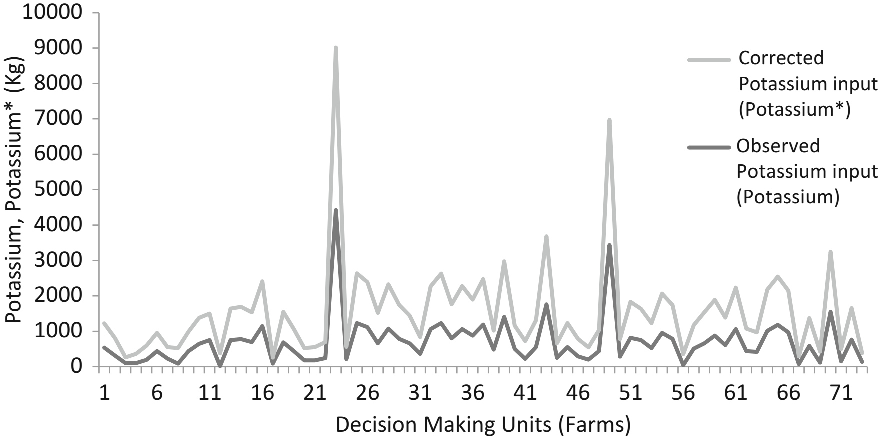

Fig. 8 Potato production process (Abruzzi) – Observed Potassium fertilizer input (*Potassium*) and Potassiums fertilizer corrected (*Potassium**) by through the Data Envelopment Analysis

4.2 Discussion

The first point to be underlined is that the contextual variables have an effect according to the conceptualization of the cropping operational system. Thus, the fertilization strategy must be considered within this system. Second, the fertilization strategy has a positive effect on crop efficiency in the case study of table tomato, indicating that there is room for revision of the fertilization strategy. Third, the specialization of the crop (in terms of percentage of UAL) tends to decrease the levels of efficiency. The specialization of an activity is normally expected to

Table 9 Technical efficiency (Potato – Abruzzi) – 3rd stage

	Technical efficiency		
	Constant return of scale	Variable return of scale	Scale efficiency
Min	0.053	0.053	0.686
1st quartile	0.574	0.661	0.871
2nd quartile	0.666	0.787	0.926
3rd quartile	0.749	0.959	0.991
Max	1	1	1
Mean	0.674	0.769	0.916
St. Dev.	0.157	0.203	0.077
C. V.	0.232	0.264	0.084
N. DMU eff	5	9	8

Source: authors
N. of DMU increasing return to scale = 58; N. of DMU decreasing return to scale = 7
DMU = 73; n. output = 1; n. input = 6. Efficiency scores: 1 = max efficiency; 0 = max inefficiency

Table 10 Technical efficiency (Potato-Campania) – 1st stage

	Technical efficiency		
	Constant return of scale	Variable return of scale	Scale efficiency
Min	0.326	0.373	0.809
1st quartile	0.692	0.758	0.936
2nd quartile	0.918	1.000	0.988
3rd quartile	1	1	1
Max	1	1	1
Mean	0.822	0.855	0.956
St. Dev.	0.223	0.212	0.061
C. V.	0.272	0.248	0.064
N.of DMU eff	13	17	13

Source: authors
N. of DMU increasing return to scale = 5; N. of DMU decreasing return to scale = 13
DMU = 33; n. output = 1; n. input = 6. Efficiency scores: 1 = max efficiency; 0 = max inefficiency

provide efficiency advantages. Our interpretation of the evidence is that as the size of the crop increases relative to the farm, managerial diseconomies arise at the level of implementing productive operations. The point is relevant in vegetable crops because, although the farm may gain advantages from specialization in terms of equipment investments and also competencies creation, management of the productive operation may suffer from the possibility of allocating resources (e.g., labour) in the right space-time coordinates. Our results are coherent with this view. Goffart et al. (2011) explored the pattern of nitrogen fertilization in the Potato crop. The fertilization strategy analysed is based on application of 70% of the total recommended Nitrogen rate and on the subsequent evaluation of the state of the crop. The status evaluation leads the decision to apply the remaining 30% of the

Table 11 Potato (Campania) – Spearman correlation coefficients

	lTheta	LAND	CAPITAL	LABOUR	Nitrogen	Phosphorus	Potassium
lTheta	1						
LAND	−0.1338	1					
CAPITAL	−0.322	0.6751	1				
LABOUR	−0.3159	0.9364	0.6843	1			
Nitrogen	−0.0726	0.8329	0.7573	0.7099	1		
Phosphorus	−0.1125	0.7878	0.5873	0.6926	0.785	1	
Potassium	−0.1998	0.7713	0.7824	0.6753	0.9373	0.679	1

Source: authors

nitrogen rate. To this end, the Authors consider various methods with respect to accuracy, sensitivity, specificity and feasibility and conclude that the remotely sensed above-crop reflectance measurement appears to be the most promising approach. This analysis clearly indicates that improvements of the fertilization strategy require gathering detailed information about critical characteristics of the crop. These types of information exceed a simple input-output analytical nexus and focus on characteristics that can be considered being dependent upon the farming system characteristics. Accordingly, Schröder et al. (2000) states that site-specific nitrogen management requires indicators for the soil-crop system. Such types of indicators provide information that captures the outcomes of a fertilization strategy. If a strategy can be implemented which satisfies the crop requirements – according to some indicators – the crop output will tend to be optimal. The increase of fertilizer utilization is the basis of agriculture intensification and the related reduction of system biodiversity (Matson et al. 1997). From this perspective, our results confirm that characteristics of the cropping operational system may have an effect not only in terms of private efficiency but also in terms of societal expectations. In designing fertilization strategies, there is increasing focus on information concerning the status of the crop. At the level of the farming system, a challenge is how to frame the information gathering and the fertilization decision in a coherent strategy. With respect to our context of analysis, we note that an improvement of the availability of information on a crop system should allow the farmer to enhance the degree of efficiency.

The role of experience – accounted for by the variable *AGE* in our analysis – is coherent with this picture; lack of experience reduces efficiency in using the land in the case of Potato in the Campania region, directly positing the problem of space-time allocation of resources. The importance of the organizational variable is also confirmed by the absence of any influence of altitude, soil types and latitude. The fertilization programmes exhibit an articulated picture, but overall, their effects appear smaller than do those of the organizational variables.

Finally, following Boote et al. (1996), we note that our approach can provide information on groups of production units in a given geographic area and may be refined to account for the role of a satisfying number and number of types of farming system characteristics. However, in the example provided, the models

Table 12 Truncated regression, LHS = input slacks (POTATO-Campania region)

RHS	LAND		LABOUR		CAPITAL		Nitrogen		Phosphorus		Potassium	
ALT	−0.010	*	−69.50		−6.58		−253.17		−14.03		−41.86	
	0.006		*48.40*		*13.77*		*327.21*		*25.57*		*51.13*	
AGE	0.100	***	−84.58		−4.05	**	−207.84	*	−20.29	*	−14.07	*
	0.036		*66.03*		*1.98*		*105.41*		*12.54*		*8.34*	
SCALE	−0.001	*	−2.96	*	−0.17		7.98	**	0.86	*	1.07	
	0.001		*1.47*		*1.66*		*3.53*		*0.49*		*0.68*	
SPEC	0.014		535.10	**	45.87	*	1581.65	*	84.06	**	262.89	*
	0.030		*242.55*		*26.59*		*912.23*		*39.10*		*158.16*	
IRR	0.019		297.00	*	20.34	*	795.98	*	44.69	*	138.61	*
	0.020		*159.94*		*11.08*		*457.48*		*22.16*		*80.30*	
Const	0.026	**	−181.24	*	−10.59	**	−420.67	**	−24.41	*	−70.54	**
	0.014		*105.10*		*4.06*		*189.84*		*12.98*		*35.92*	
Sigma	0.046	***	370.36		65.03		1545.65		120.78		241.51	
	0.006		*47.04*		*8.26*		*196.30*		*15.34*		*30.67*	
logLH	−107.61		−227.34		−173.41		−271.63		−192.60		−214.08	
Obs.	33		33		33		33		33		33	
Wald chi^2(6)	10.12		15.14		11.55		18.09		12.83		14.26	

Source: authors

Note. Significance: *$p < 0.1$, **$p < 0.05$, ***$p < 0.001$. Std. error in Italics

Table 13 Technical efficiency (Potato-Campania) – 3rd stage

	Technical efficiency		
	Constant return of scale	Variable return of scale	Scale efficiency
Min	0.315	0.315	0.777
1st quartile	0.534	0.608	0.913
2nd quartile	0.757	0.809	0.991
3rd quartile	0.996	1	1
Max	1	1	1
Mean	0.742	0.775	0.955
St. Dev.	0.244	0.243	0.060
C. V.	0.329	0.313	0.063
N. of DMU eff	8	12	8

Source: authors

N. of DMU increasing return to scale = 22; N. of DMU decreasing return to scale = 2

DMU = 33; n. output = 1; n. input = 6. Efficiency scores: 1 = max efficiency; 0 = max inefficiency

estimated do not allow one to discriminate crop-soil characteristics accurately and may result in a loss of information about the differences in the fertilization strategies observed.

In this study, we analysed the influence of a fertilization programme on crop efficiency at the farm level. The rationale for this approach is provided by the conceptualization of the relationship among the decisional farm system and the operational systems by which the fertilization programmes are implemented. We assumed that fertilization strategies are sustained by criteria of efficiency related to the response function approach and to the organizational framework of the farm, but they are also fostered by the sustainability principle, which is becoming of increasing importance. Although a sustainable intensification approach (Pretty and Bharucha 2014) seems to be promising for designing innovative technologies also based upon the integration of scientific and tacit knowledge, the results indicates that organizational factors tend to have an important effect upon crop efficiency. Although the response function approach provides leading indications for purposes of the definition and implementation of fertilization programs, these indications should be framed in the context of the operational system to achieve efficiency improvements and to innovate the approach towards sustainability objectives.

5 Conclusions

In this study we analyzed the influence of the fertilization program on the crop efficiency ad farm level. The rational for this approach is provided by the conceptualization of the relationship among the decisional farm system and the operational systems by which the fertilization programs are implemented. We assumed that the fertilization strategies are sustained by criteria of efficiency related to the response function approach and to the organizational framework of the farm, but also they are fostered by sustainable principle which are becoming of increasing importance. While a sustainable intensification approach (Pretty and Bharucha 2014) seems to be promising for designing innovative technologies also based upon the integration of scientific and tacit knowledge, the results indicates that the organizational factors tend to have an important impact upon the crop efficiency. Albeit the response function approach provide leading indications to the purposes of the definition and the implementation of fertilization programs, these indication should be framed in the context of the operational system in order to achieve efficiency improvements and innovate the approach towards objectives of sustainability.

Glossary

CAP	Common Agricultural Policy
DEA	Data Envelopment Analysis
DMU	Decision Making Units
EEC	European Economic Commission
EU	European Union
FADN	Farm Accounting Database Network
LRP	Linear Response Plateau
UAA	Utilized Agricultural Area

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