BioGreenhouse

Soil fertility management in organic greenhouses in Europe

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Soil Fertility

Abstract

The management of soil fertility in organic greenhouse systems differs quite widely across Europe. The challenge is to identify and implement strategies which comply with the organic principles set out in (EC) Reg. 834/2007 and (EC) Reg. 889/2008 as well as supporting environmentally, socially and economically sustainable cropping systems. In this paper, written by a group of scientists of different geographical origin and with different background, the state of the art of the sector and the main characteristics of the European organic greenhouse cropping systems are described. The main bottlenecks and constraints are discussed with a particular reference to the regulatory framework in force. The most relevant issues that may influence the enforcement and future development of the sector have been identified as specific knowledge gaps. For each of them, the appropriate research needs were elaborated in a multidisciplinary perspective as forthcoming challenges for the whole sector. Although not exhaustive, given the wide heterogeneity of the implemented systems, this paper is able, for the first time, to give a structured outlook on soil fertility management in protected organic conditions on a European scale.

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Pictures

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Disclaimer

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Preface

In 2008, at the 16th IFOAM Organic World Congress in Modena (IT), about 25 participants expressed their interest in working together in the field of research and development for organic greenhouse or protected horticulture. A two-day workshop was organised in Cologne in 2009 to discuss the subject and to give further support to the collaboration. 45 people from across Europe and from Canada attended this workshop. It was decided to pursue joint efforts in the field of organic protected horticulture, with particular respect to planting material; soil fertility; composting; water management; disease and pest management; climate management and energy conservation; and sustainability. The group also agreed to submit a COST (European Cooperation in Science and Technology) Action on the same subject. The proposal ”Towards a sustainable and productive EU organic greenhouse horticulture‟, (BioGreenhouse), was submitted in mid 2011.

At the end of 2011, COST approved this proposal as COST Action FA1105 (see http://www.cost.eu/COST_Actions/fa/FA1105 and www.biogreenhouse.org), which set out to build a network of experts working in the field of organic protected horticulture. The aims of the Action are to develop and to disseminate knowledge of new and improved production strategies, methods and technologies for the support of sustainable and productive organic greenhouse/protected horticulture in the EU. This has involved coordinated international efforts and in total, 27 participating COST countries and two COST Neighbouring countries took part in the Action.

This Action offered the framework and funds for experts of the participating countries to meet and to work together in Working Groups focusing on the objectives of the Action. The objectives related to soil fertility were to develop efficient, sustainable and safe soil fertility management strategies using common guidelines which take into account the diversified pedo-climatic conditions.

A group of eight experts from different regions and backgrounds worked together on this topic. They have approached their task with commitment by reviewing the state of the art of organic protected cropping in Europe and its relationship with prevailing organic principles; by looking into the detail of soil fertility management tools; by describing the main characteristics of organic protected cropping systems in Europe from less intensive to high intensive; and by defining soil management criteria.

Together they wrote this booklet: **“Soil fertility management in organic greenhouses in Europe”**

I believe this booklet will be a unique source of information for all actors involved in organic protected horticulture: growers, researchers, students, teachers, consultants, suppliers and policy makers. This booklet could finally help to develop and implement more sustainable soil fertility strategies.

On behalf of the COST Action BioGreenhouse, I want to thank the team of the authors for the work they have done, their cooperative spirit and their perseverance. This work will definitely contribute to a more efficient and sustainable soil fertility management and will be a basis for developing a new R & D agenda on Organic Greenhouse Horticulture.

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Wageningen UR Greenhouse Horticulture
Chair, COST Action FA1105 BioGreenhouse

1 Introduction

During the last years, an increasing interest in organic greenhouse production has been shown by organic farming associations, researchers, and policy makers either at a national or at a transnational level. Representatives of IFOAM Europe produced their position paper (IFOAM, 2013), while the Expert Group for Technical Advice on Organic Production (EGTOP), under mandate of the European Commission, published their report on the main controversial technical issues regarding organic production in greenhouses (EGTOP, 2013). This booklet is the result of discussions between the members of a transnational group of researchers and is based on published and unpublished scientific studies. It is also based on the authors' scientific knowledge of European organic greenhouses and the main cropping systems used. It is focused on soil fertility management and aims to provide a deeper insight into one of the more controversial areas of protected organic production.

Specifically, the state of the art of the sector and the main characteristics of the European cropping systems have been described. The main bottlenecks and constraints are discussed with a particular reference to the regulatory framework in force. Finally, the more relevant issues that may influence the enforcement and future developments of the sector have been identified as specific knowledge gaps in the field of the soil fertility management in organic greenhouse horticulture. For each of them, the appropriate research needs are suggested in a multidisciplinary perspective as forthcoming challenges for the whole sector.

1.1 State of the art of organic protected cropping in Europe

There are no official statistics on the area of greenhouses that is managed according to the organic regulation in the EU. A very general inventory estimates the total area in Europe to be about 5,000 ha. The estimated areas covered by organic greenhouses, at a Country level, are reported in Figure 1.

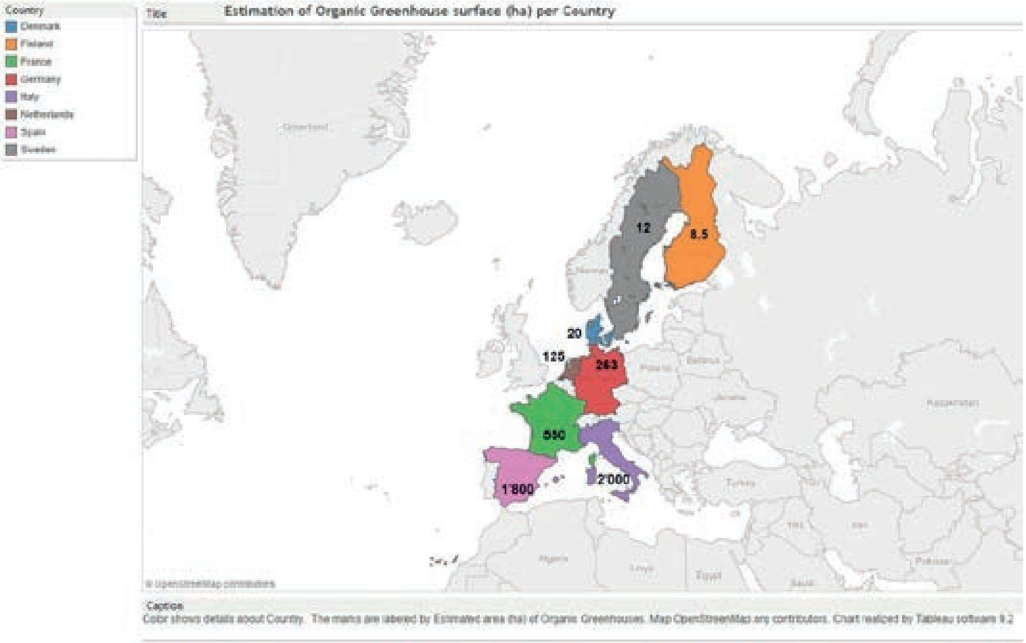

Figure 1 *Estimated organic greenhouse area (ha) in eight European countries.*

Although the economical and structural characteristics of greenhouses in Europe are extremely diverse with respect to the different and specific pedoclimatic conditions, the main cultivated crops are very similar. They belong to the Solanaceae botanical family e.g. tomato (Solanum lycopersicum L.), pepper (Capsicum annuum L.) and eggplant (Solanum melongena L.), to the Cucurbitaceae family e.g. melon (Cucumis melo L.), watermelon (Citrullus lanatus Thunb), zucchini (Cucurbita pepo L.), and cucumber (Cucumis sativus L.), and to the Asteraceae family e.g. leafy vegetables like lettuce (Lactuca sativa L.). Some crops also belong to the Fabaceae family e.g beans (Phaseolus spp.) and the Rosaceae family e.g. strawberry (Fragaria × ananassa Duch).

1.2 Protected cropping and organic farming principles

It is obvious that organic greenhouse production must comply with the existing regulations regarding organic production, Reg (EC) No 834/2007 (EC, 2007) and Reg. (EC) No 889/2008 (EC, 2008). However, no direct reference to greenhouse production was made in Reg (EEC) No 2092/91 (EEC, 1991a) or in its replacements Council Regulation (EC) No 834/2007 and Commission Regulation (EC) No 889/2008. The main articles, of the above mentioned regulations, describing organic farming principles, are reported as follows:

Article 5 of Reg (EC) No 834/2007 states that "...organic farming shall be based on the following specific principles:

a. Maintenance and enhancement of soil life and natural soil fertility, soil stability and soil biodiversity preventing and combating soil compaction and soil erosion, and the nourishing of plants primarily through the soil ecosystem;
b. The minimisation of the use of non-renewable sources and off-farm inputs;
c. The recycling of wastes and by-product of plant and animal origin as input in plant and livestock produce;
d. Taking into account of the local or regional ecological balance when taking production decisions;
e. The maintenance of plant health by preventative measures, such as the choice of appropriate species and varieties resistant to pests and diseases, appropriate crop rotations, mechanical and physical methods and the protection of natural enemies of pests....".

Article 12 (1) of Reg (EC) No 834/2007 states that"...the following rules shall apply to organic plant production:

a. Organic plant production shall use tillage and cultivation practices that maintain or increase soil organic matter, enhance soil stability and soil biodiversity, and prevent soil compaction and soil erosion;
b. The fertility and biological activity of the soil shall be maintained and increased by multiannual crop rotation including legumes and other green manure crops, and by the application of livestock manure or organic material, both preferably composted, from organic production;
c. The use of biodynamic preparation is allowed;
d. All plant production techniques used shall prevent or minimise any contribution to the contamination of the environment;
e. The prevention of damage caused by pests, diseases and weeds shall rely primarily on the protection by natural enemies, the choice of species and varieties, crop rotation, cultivation techniques and thermal processes...".

Since the principles and objectives of organic farming were originally formulated to cover open field systems of production, their implementation in intensive systems of production is difficult to fulfil (Voogt, 1999; Voogt *et al.* 2011; Zikeli *et al.* 2014).

This paper takes into account the considerations and recommendations of all the documents previously published concerning soil fertility management in organic greenhouse production. In particular, the booklet's main objectives are as follows:

- To briefly describe the main cropping systems including the main crops grown in organic greenhouses throughout Europe;
- To describe the main soil fertility management practices in organic greenhouse production;
- To identify different soil fertility management systems in organic greenhouses as they have been implemented in different geographical areas in Europe;
- To identify and compile the main knowledge gaps and research needed to improve the sustainability of agricultural practices for short and long term soil fertility management in organic greenhouses.

Picture 1 *Lamb's lettuce, a short cycle crop in organic greenhouses in less intensive Northern greenhouse cropping systems (Germany) (Photograph made by Sabine Zikeli).*

2 Soil fertility management

Soil fertility is the ability of a soil to sustain plant growth. It depends on closely linked physical, chemical and biological soil characteristics that determine soil functions such as soil water holding capacity and nutrient release. The origin of the soil defines many of its inherent properties (e.g. soil texture, pH, and depth) but agronomic techniques can have an effect on the more dynamic properties (e.g. soil organic matter content, soil mineral nitrogen, etc.).

Organic farming systems are required to maintain and enhance soil fertility (as reported above in Article 5 of 834/2007), to provide essential nutrients and water to plants. An active and diverse biotic community is part of the nutrient transfer and plays a central role in the interactions between soils, microorganisms (including pathogens) and plants. Organic producers seek to build or enhance soil fertility by using soil fertility management tools such as soil tillage practices, crop rotations, organic fertilisers and amendments, and agro-ecological service crops (ASCs [REF to par. 2.3]). These approaches are included in a package of tools and knowledge that should be used by organic farmers to both maintain soil fertility and avoid negative environmental impacts. However, achieving these goals in organic greenhouse production systems can be challenging and relevant issues have to be considered, such as:

- High investment costs;
- High organic matter turnover (Voogt, 2014);
- High nutrient demands with high risk of unbalanced fertilizations (Cuijpers *et al.* 2008, Voogt *et al.* 2011, Zikeli *et al.* 2014);
- High soil health problems due to low crop diversification (Miller, 2015);
- High salinity risk due to imbalanced element input-output relationships (Voogt *et al.* 2011);
- Short time to cultivate ASCs (Mihreteab *et al.* 2014);
- High irrigation water needs (Voogt, 1999;Voogt *et al.* 2016).

In Table 1, the main tools for soil fertility management are reported and their pros and cons are listed.

***Picture 2** Diversified main crops cultivation with biocontrol plants in greenhouse, a characteristic of less intensive Northern organic greenhouse cropping systems (Germany) (Photograph made by Sabine Zikeli).*

Table 1

Soil fertility management in OGH – technical tools.

Technical tool	Description	Problems/challenges	Regulations
Tillage	• Normal or special tractor, • Chisel plough, disc plough, rotor implements, etc. • Small pedestrian controlled motorised cultivators	• Compaction by tillage tractor • Mechanical impact on soil structure • Decomposition of harvest residues, roots • Regulation of phyto-sanitary impact	
Crop rotations	Main crops: • *Solanaceae* (tomato, sweet pepper, eggplant), • *Cucurbitaceae* (cucumber, melon, watermelon), • *Asteraceae* (lettuce)	Low variation in main crops leads to: • high risk of soil borne diseases and pests, • little or no biodiversity • Incorporation of traditional cultivars	Basic rule for organic farming
Animal manures	• Manures from farm animals • Own, cooperative exchange or commercial product • Should be from organic farming (compulsory in some countries)	• Availability from organic farm; if not organic, diverse interpretation of the regulation prohibiting manures from factory farming ; • Manures should provide the base level of nutrients; • Manures have to maintain the humus level; • Risks of nutrient imbalances for plant feeding; • Hygienic risks from products	• Basic rule and list in annex I (EC, 2008) • Definition of husbandry systems (but not clear enough) • Dutch adaptations of regulation 889/2008 (SKAL, 2013) Discussed/planned: 50% of nutrients as base fertilization before starting the cultivation
Other organic fertilizer	• Animal: residues from slaughtering process incl. wool • Plant: oil/food processing residues, legumes, Microbial processing residues	• Unclear sources and processes • Possible residues of medicine and pesticides, heavy metals • Standards for products and production	List annex I (EC, 2008)
Composts	• Derived from plant, animal, mineral components • Farm made or trade compost	• Quality: fertilization effect, humus effect, possible residues of heavy metals. • Nutrients: amount, ratios, pH-effect and micro-nutrients • Hygienic status • Standards	Material Annex I, (EC, 2008) Composts

Technical tool	Description	Problems/challenges	Regulations
Agro-ecological service crops (ASC)	• Plant species introduced in the agro-system in order to provide or enhance its environmental functions; • Green manure or cover crops incorporated to soil to maintain soil organic matter and improve nutrients recycling; • Different plants in different region and with special aims; • Green manure brought in from outside the greenhouse (farm's own fields or other farms); • Silage, biogas digestates	• Non-use reasons: uneconomic, vegetation period too short; • Partially use reasons: regional vegetation condition, lack of alternatives for organic matter; • Nitrogen supply by own system, soil structure; • Soil diseases and pests management • Weed control	Basic rule for organic farming
Weed control	• Mechanical • Organic mulch material • Plastics covers • Solarisation and biosolarization	• Effect on organic matter mineralization • Irrigation • Organic mulch and fertilizer at the same time	Rules may be different over Europe
Irrigation system	• Drip irrigation • Whole area covering irrigation	• Interaction with fertilizer • Wide spread manure in contrast to fertilizer deposited on special spots • Mineralisation of fertilizer • Efficiency of fertilizer • Salinity	
Disease management	• Plant residues removed (as far as possible) • No recycling of plant compost • Grafting on resistant rootstock • Solarisation/biosolarization	• Manure and nutrient balance • Sulphur as disease control – impact on soil pH • Interaction with disease susceptibility	Basic rules, biodiversity, crop rotations

2.1 Regulatory framework and general consideration

The main criteria for soil fertility management in organic farming are set out in Reg (EC) No 834/2007 (EC, 2007). In order to comply with the organic method of production, farmers must implement a crop rotation to increase crop diversity and to manage soil borne diseases. To reach these objectives, the introduction of ASCs into the crop rotation can be helpful. Agro-ecological service crops are non-cash crop species, that, when introduced into a crop rotation provide environmental services or enhance existing environmental services of the agro-ecosystem (Thorup-Kristensen *et al.* 2003). Organic fertilizers and soil improvers should, as a general rule, be applied before the start of the growing season. Complementary fertilizers listed in annex I of the regulation, may be applied during plants growth to support crop production (EC, 2008). Unfortunately, the reduction of off-farm inputs, the recycling of nutrients within the farm, the low environmental impact and the decrease of the use of non renewable resources may not be easily achieved within the boundaries defined by the Regulation. One of the major issues, especially in intensified organic greenhouse production systems, is the huge turnover of nutrients and organic matter (Voogt 1999, Cuijpers *et al.* 2008, Voogt *et al.* 2011, Zikeli *et al.* 2014). Greenhouse holdings are specialised and are usually stand-alone enterprises. As a consequence, the possibilities for internal reallocation of nutrients by the use of farmyard amendments are limited or non-existent. Furthermore, high efficiencies are required for the greenhouse production system to be competitive in the market and to have an economic return on investments. This is also the reason why ASCs do not fit into highly intensified organic greenhouse production systems. Moreover, intercropping of legume crops in long term fruit vegetables like tomato will not be successful because of low residual light intensity under the crop canopy and because of potential competition with the cash crop. High levels of production mean that large amounts of plant nutrients are exported out of the greenhouse and have to be replaced. The EU regulation does not restrict the rate and quantities of allowed supplemental fertiliser inputs. The list of soil conditioners and fertilisers allowed is quite long. However, due to the composition of these inputs (contents and mutual nutrient ratios) their use can lead to strong nutrient imbalances. In addition, the input of animal manure is restricted to a maximum supplied level of 170 kg N/ha (EEC, 1991b). This limitation may lead growers to use high quantities of composts or supplemental fertilisers to meet the requirements of the cropping plan.

As described in more detail in the following pages, it is possible to assume that the higher the intensity of a cropping system (in terms of element flows), the stronger the risk of development of element imbalances in soils over time and therefore the stronger the need for management tools and consultancy to design balanced systems.

A common feature of some systems of production is the application of the so-called "substitution" approach (Darnhofer *et al.* 2010). In systems of production mainly based on input substitution, soil fertility is managed only with the use of off-farm fertilizers listed in Annex I of Reg (EC) No 889/2008. Nutritional needs or deficits are treated on a case by case basis by "substituting" off-farm synthetic inputs with off-farm organic inputs. Actually, this approach is often referred to as an imitation of conventional agriculture practice even though it is based on the application of products allowed by the ruling standards of organic farming (Contreras *et al.* 2014) and it is often referred to as a "conventionalized" organic farming system (Goldenberg, 2011). Of course, the level of "conventionalization" can differ from one system to the other over a wide range of possibilities.

An alternative approach, as stated above, may be to implement a crop rotation to increase crop diversity (by inclusion of ASC species) and to favour soil incorporation of amendments that are rich in organic matter. This strategy is more common in less intensive organic greenhouse production systems where the soil nutrient imbalances are less evident due to the lower level of yields obtained. Finally, there is a predisposition to introduce ASCs especially in greenhouses of the Mediterranean Countries.

Picture 3 *Decomposed mulch derived from silage (clover grass mixture) spread 2 weeks after tomato planting in early spring in a warm greenhouse in Bavaria (Germany) (Photograph made by Hans Jürgen Reents).*

2.2 Crop rotation

A crop rotation is the variation of plant species in time within the same cropping space. With its many possibilities, the design of a suitable crop rotation is an important strategy for organic farmers. Key elements of good rotations include the breaking of disease and pest cycles and the inclusion of soil fertility building crops. Different crops with different root systems will colonize different soil layers, thus improving soil structure and nutrient availability. They will also stimulate different types of microorganisms thus favouring soil biodiversity and resistance to soil-borne pathogens. In the rotation, farmers can decide to cultivate effective ASCs to maintain or increase soil organic matter content and nutrient availability for further crops. Wider use of crop rotations in greenhouses would be desirable even if it is more difficult to implement in protected than in arable production. This is mainly due to economic reasons. Since time span is an important feature of rotations, less positive effects, in particular in pest and disease prevention, can be expected with shorter rotations.

It is a widely accepted concept that the cultivation in greenhouses of annual legumes and green manure crops, which are explicitly mentioned in the EU Regulation, is not feasible.

However, in some cases, the cultivation of short term cover crops (or ASCs), and of commercial legumes in crop rotations may be suitable alternatives.

2.3 Agro-ecological service crops

Agro-ecological service crops (ASCs[1]) are not directly aimed to yield but they can help to sustain agricultural production through a wide range of mechanisms. They enhance soil fertility by improving soil structure, soil biological activity, soil organic matter content and nutrient availability and, if N-fixing, they supply nitrogen to the cropping system (Thorup-Kristensen *et al.* 2003). They can also help to improve crop rotation effects if they belong to different botanical families to the cash crops (for example Poaceae are not cultivated in vegetable production systems), thus breaking pest and disease cycles if the cover crops are not alternate hosts. They can also contribute to the management of some soil borne pathogens by the production of toxic compounds and other inoculum reducing processes.

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[1] Various terms have been used to identify crops with multiple agro-environmental functions (i.e. catch crops, cover crops, complementary crops, green manure etc). The new terminolgy of *Agroecological service crops* has been introduced to overcome the lack of a comprehensive term to include all crops used in agro-ecosystems to provide or enhance their environmental functions, irrespective of their position in the crop rotation and/or indipendently of the method (green manure vs flattened crop) that can be applied to terminate them (Canali *et al.* 2015).

For example, plant species belonging to the Brassicaceae family produce sulphur compounds (Michel, 2008) and sorghum incorporation releases hydrogen cyanide (Widmer and Abawi, 2002). ASCs also contribute to better weed management through space competition (Ciaccia *et al.* 2015). Finally, ASCs increase the complexity of the system, plant diversification and general biodiversity.

Picture 4 *Tagetes erecta as agroecological service providing crop, to promote nematodes protection in organic greenhouse with cluster tomato cv. Guanche (Almeria, Andalusia, Spain) (Photograph made by Maria Del Carmen Garcia).*

The use of ASCs is highly recommended in organic farming, however in greenhouse environments this practice has to face a lot of constraints. The possibility of green manuring also depends on the farm structure. Bigger farms can sometimes afford to have no cash crops during a few weeks in parts of their greenhouses while there is usually no time or space for green manuring on small intensively managed and diversified farms.
In open field production, ASCs are sown in the late summer-autumn to be incorporated during the winter before the beginning of the main crop cultivation. This timing depends on the best period for production of the main crop. In autumn, the ASC will benefit from the off-season rain, so that no water supply is required.

In greenhouse production, the main restrictions limiting the use of ASCs are the reduction of the production period and the cost of water. Identification of the most feasible season for cover crop cultivation should take this into account and minimize these constraints. Depending on the geographical localization and the cropping system, ASCs could be cultivated in greenhouses in autumn/winter after a long summer crop such as a Solanaceae. In this case, the cover crop has to be cultivated for at least 2 months to reach a sufficient level of biomass and will take the place of a cash crop.

Under different conditions, in the Mediterranean area or after shorter summer crops such as Cucurbitaceae, ASCs can be grown during summer and they do not usually take the place of a cash crop. In this case, 5 to 7 weeks under greenhouse conditions can be sufficient to generate good biomass production. The summer period might be the most feasible for this purpose because vegetable production from open field units can decrease the market price of these commodities. Moreover, the shorter period of cover crop cultivation in greenhouses during summer allows the greenhouses to produce for the market for ten months per year during the off-season. Finally, the species to be cultivated should also be selected according to their water requirements which must be low. In Table 2, the main ASC species cultivated in greenhouses and their ecological functions are reported.
In the medium to long term, the benefits of ASC cultivation in terms of nutrient turnover, soil borne disease prevention, beneficial insect attraction, soil physical properties improvement and biodiversity increase are able to balance and prevail over the increased costs and reduced income that may be faced in the short term.

Picture 5. *Cultivation of ASCs mixture (pearl millet, buckweath, egyptian bean, radish) (Italy) (Photograph made by Fabio La Notte).*

Table 2

Main ASCs species – growing season, botanical families, and ecological functions.

Botanical family	Autumn species	Summer Species (mainly in Mediterranean area)	Ecological function
Poaceae	*Secale cereale* *Avena sativa* *Triticum spp.* *Hordeum vulgare* *Lolium multiflorum*	*Sorghum spp.* *Pennisetum glaucum* *Setaria italica*	• Fast growth • Weed suppression • Soil structure improvement • Soil organic matter building • Break in the vegetable species sequence • Suppressive effects (Sorghum spp.) • Beneficial to insects • Banker plants for biological control
Fabaceae	*Vicia spp.* *Trifolium spp.* *Pisum arvense*	*Vigna sinensis* *Dolichos lablab* *Crotalaria spp.*	• Break in the vegetable species sequence • N fixation • Nutrient recycling
Brassicaceae	*Sinapsis alba* *Eruca sativa* *Raphanus spp.* *Brassica napus*	*Brassica juncea* *Eruca sativa* *Sinapsis alba* (short cycles)	• Fast growth • Weed suppression • Soil structure improvement • Suppressive effects on soil-borne pathogens • Nutrients recycling
Polygonaceae and Hydrophyllaceae	*Phacelia tanacetifolia*	*Fagopyrum esculentum*	• Weed suppression • Break in the vegetable species sequence • Insect attractiont

Picture 6 *Agroecological service providing crops flattened by roller crimper in Mediterranean organic greenhouse (Italy) (Photograph made by Fabio La Notte).*

2.4 Fertilizer requirements of greenhouse crops and the implications of their use

Greenhouse crops have a high productivity level and require large amounts of nutrients. A close linear relationship has often been found between the yield of crops and the uptake of nutrients (Sonneveld and Voogt, 2009). The annual uptake calculated from available data for a high yielding organic tomato crop in the Netherlands (yielding up to 50 kg m^{-2}) can be as high as 1,250 kg nitrogen (N) per ha (Cuijpers *et al.* 2008). These quantities are several times greater than the uptake of any open field vegetable or arable crop. A further factor, besides the absolute quantities of minerals absorbed by greenhouse crops, is that the nutrient uptake ratios will also differ from those in field crops (Sonneveld and Voogt, 2009).

High nutrient outputs need high inputs to be applied to the soil to ensure soil productivity, a balanced nutrient supply and long term soil fertility. In organic farming, only N can be recovered, by cropping legumes as ASCs, and in any case, only small amounts inside the greenhouse. For all other nutrients, only external inputs (from outside the greenhouse) can replace the nutrients exported in the sold products. The use of soil amendments and mineral fertilizers is regulated in organic farming by the Reg (EC) No 889/2008 (annex I) (EC, 2008). There are several amendments and fertilizers available for use in organic farming (see chapter 2.5.2).

However, almost all the nutrient sources are multi-element sources, meaning that they contain a range of several plant nutrients which do not comply with the nutrient demand of the harvested crops (Voogt 1999, Voogt *et al.* 2011, Zikeli *et al.* 2014). A high input of these fertilizers leads to an increased risk of significant nutrient imbalances in the soil. Indeed, the few available reports calculating input-output ratios in organic greenhouses indicate large nutrient imbalances and the budget sheets show large surpluses of Phosphorus (P), Sulfur (S) and Sodium (Na), as well as Calcium (Ca) and Magnesium (Mg), and strong deficits of Potassium (K) (Voogt, 1999; Cuijpers *et al.* 2008; Voogt *et al.* 2011; Zikeli *et al.* 2014). Several surveys indicate very high P levels in soil used for organic vegetable production both in open field (von Fragstein *et al.* 2004; Zikeli *et al.* 2014) and greenhouse conditions (Voogt, 1999; von Fragstein *et al.* 2004; Voogt *et al.* 2011; Zikeli *et al.* 2014). Several publications (Boyle and Lindsay, 1986; Norvell *et al.* 1987; Pérez-Novo *et al.* 2009) indicate that high soil P levels can negatively affect the bioavailability of Manganese (Mn), Copper (Cu) and Zinc (Zn) among other negative effects like eutrophication.

Organic amendments do not only provide a range of nutrients, but also contribute to the build-up and maintenance of organic matter (Möller & Schultheiß, 2014) and compounds affecting soil alkalinity and therefore soil pH (Sluijsmans 1970; Harmsen *et al.* 1990; Yan *et al.* 1996; Eghball, 1999; Whalen *et al.* 2000; Möller & Schultheiß, 2015). For soil pH, the available literature reports contradictory effects of organic management. Under Central European growing conditions, the pH of greenhouse soil mostly increases (Voogt, personal communications; Zikeli *et al.* 2014). A survey carried out under Mediterranean conditions in Almeria indicates the opposite, i.e. organic management decreases soil pH (Del Moral *et al.* 2012). Most of the available organic amendments decrease soil acidity due to the imbalance of cations and anions, which is compensated for by bicarbonates and/or organic acids to maintain the equilibrium between positively and negatively charged ions. Soil acidity is increased by organic amendments with high sulphur content and low cation concentration (e.g. keratins) or by the application of elemental sulphur (e.g. as part of a pest or disease control strategy). High pH values in soils can strongly reduce plant bioavailability of most micronutrients (with the exception of Molybdenum), negatively affecting crop uptake and potentially inducing micro-nutrient shortage (Marschner, 1996). It is well known that nutrient surpluses in the soil have only minor effects on the overall nutrient uptake but the mutual ratios in the external solution of the ions can affect the uptake of a specific ion (Sonneveld and Voogt, 2009). No data is available, however, about the influence of soil nutrient imbalances on micro-nutrient availability under organic growing conditions.

Fertilization influences not only crop performance and crop yields, but also crop quality (taste, firmness, storage performance) in fruit vegetables like tomatoes and fruits like strawberries (Segura *et al.* 2009; Sonneveld and Voogt, 2009). Few data are available about the influence of the growing conditions (region, growing system) and the fertility management strategy on the quality attributes of organic greenhouse crops (Ceglie *et al.* 2015). A survey by Oliveira *et al.* (2013) suggests that tomatoes from organic farming systems grown under conditions of stress show higher concentrations of sugars and secondary metabolites such as vitamin C and phenolic compounds that contribute to the nutritional quality of organic production. This has been also confirmed for organic strawberries produced in greenhouse conditions (Ceglie *et al.* 2014). The variation in the types and quantities of secondary metabolites at harvest may therefore affect the initial quality and the antioxidant effect during the storage period, and it may determine diverse postharvest performances of the products. Despite the relevance of the issue, few comparison studies have focused on postharvest investigations.

Fertilizers and soil conditioners allowed in organic farming are listed in Annex I of the Reg (EC) No 889/2008 (EC, 2008). They can, however, vary considerably in terms of the origin of their raw materials, composition, nutrient content, and rate of nutrient release. For these reasons, a systematic grouping is proposed as a useful tool to better understand how, when and at which application rate they can be used. They have been divided into three main groups that are described in the following paragraphs:

- Organic amendments (base fertilizers): animal manure, compost and digestate;
- Organic fertilizers or complementary organic fertilizers;
- Complementary mineral fertilizers.

2.4.1 Organic amendments: animal manure, compost and digestate

The term “organic amendments” (or “base organic fertilizers”) refers to bulky fertilizers applied often in large amounts and mostly as base dressings before crop sowing or planting. They have low nutrient concentrations with respect to their fresh weight. Their use is therefore only economically sustainable within a short transport distance. The main role of organic amendments is to supply the soil with all the basic nutrients and organic matter to improve soil fertility and soil structure.

Organic amendments used in organic farming include different types of animal manures, along with composts and digestates from vegetable and animal household waste. Generally speaking, the term ‘compost’ refers to a heterogeneous material obtained by partial degradation of mixtures of organic waste materials of different origins through an exothermic process carried out by aerobic microorganisms. As a consequence, compost has heterogeneous characteristics that vary widely in terms of physical, chemical, biochemical and microbiological properties according to: the quality and relative quantity of the raw materials that have been utilized to formulate the composting mixture; the technological approach for the process management; and the age (maturity level) of the compost. Extended composting processes and storage are often associated with high losses of N (leaching and volatilization) and, to a lesser extent, of K (leaching). This can lead to a relative enrichment of P in the final product that in turn leads to an imbalanced nutrient supply in relation to the vegetables needs.

Anaerobic digestion is an alternative treatment method of farm residues as well as of many off-farm wastes. As the wastes are in a closed system, only minor gaseous nutrient losses (mainly N and S) take place and the original nutrient spectrum of the feedstock is only slightly altered.

Digestion leads to mineralization of organic nitrogen compounds, leading to a product with a higher NH_4^+-N content and a lower C/N ratio. The resulting nutrient spectrum is more closely matched with plant needs (Montemurro *et al.* 2013; Möller & Schultheiß, 2014) and the fertilizer value for greenhouse crops is relatively high (Trinchera *et al.* 2012, 2013; Sigurnjak *et al.* 2016).

Picture 7 *Row application of green compost in a Dutch greenhouse as pre plant dressing for a tomato crop (The Netherlands) (Photograph made by Wim Voogt).*

2.4.2 Organic fertilizers or complementary organic (N) fertilizers

The terms "organic fertilizers" or "complementary organic fertilizers" refer to inputs with relatively high nutrient concentrations (measured as percentage of fresh matter) and comparatively low C/N ratios which are generally used to improve N supply to high N demanding crops. For their nutritional role, they are applied just before crop establishment, as well as top dressings during the growing period of the crops. The role of the complementary organic fertilizers is to adjust N supply to meet crop N demand and to correct nutrient imbalances derived from the base organic amendments used.

Allowed products or by-products of animal origin (e.g. blood meal, hoof and horn meal, bone meal, feathers, etc.) are explicitly named in Annex I of Reg (EC) No 889/2008 (EC, 2008) and in its amendment reported in Reg. (EC) No 354/2014 (EC, 2014) while other fertilizer materials are referred to in more general terms.

Products and by-products of plant origin (e.g. oilseed cake meal, cocoa husks, malt culms) along with seaweeds and seaweed products are also allowed for use as fertilizers, among others.
The nutrient spectrum of complementary organic fertilizers varies over a very wide range. There is a group of fertilizers with a high percentage of N (keratins, fermentation residues), some of them very low in P and sometimes with a balanced N/P ratio. A second group are fertilizers rich in P with an unbalanced N/P/K ratio in relation to the needs of vegetables (e.g. bone meal, poultry litter and bovine manure). A third group are plant-source fertilizers (like pulse grains and lucerne pellets) with a more or less balanced N/P ratio and varying K contents. A fourth group are N fertilizers rich in K and S, with varying N/P ratios, as well as K/S ratios (e.g. residues of sugar beet and potato processing). In Table 3, the names and main characteristics of organic products and materials in Annex I of Reg. (EC) 889/2008 and in Reg (EC) 354/2014, amending and correcting Reg. (EC) 889/2008, are listed.

Table 3

Specific suitability of fertilisers and soil conditioners for use in arable and greenhouse organic farming systems (adapted from Möller & Schultheiß, 2014). (Names of products and materials are those reported in Annex I of Reg. (EC) 889/2008 and in Reg (EC) 354/2014 amending and correcting Reg. (EC) 889/2008).

Fertilisers and soil conditioners	Characteristics and specific suitability
Products and by-products of animal origin	
Keratins (horn & hooves, feather, wool, hair meal)	• High N and sometimes S contents, and low in P and K • Due to rapid N mineralization and low P contents, are well suited for use as specific top dressing and corrective N fertilization in intensive vegetable systems
Meat meal	• High contents of N; • Due to rapid N mineralization, well suited for use as specific top dressing and corrective N fertilization in intensive vegetable systems
Bone meal	• High content in P in an apatitic crystal structure not plant bio-available under neutral and alkaline soil conditions • Rather unfavourable nutrient spectrum • High P contents combined with low plant P availability in neutral and alkaline soils, therefore less suited as complementary fertilizer to composts and even digestates
Hydrolysed proteins	• Fertilizers with varying N concentrations • Rapid N release
Products and by-products of plant origin	
Residues of sugar beet processing (molasses)	• High K and S, medium N and low P contents • Rapid N mineralization • High Na contents relevant when used in greenhouses (salinity, product quality)
Liquid potato protein	• High N, K and S contents • rapid N mineralization • balanced P contents in relation to N and K, high S contents
Pulse crops seeds	• medium N and P contents combined with low K contents • medium N mineralization
Alfalfa and clover foliage (fresh, silage, dry)	• almost balanced nutrient spectrum (NPKS) combined with low Na contents • well suited for fertilization of vegetable crops • digestion improves N availability • composting determines N and K losses • mulching as well as composting could result in strong NH_4^+-N emissions
Residues of maize starch industry	• medium N and P contents combined with low K and high S contents • rather unfavourable nutrient spectrum • N mineralization slower than expected by the C/N ratio à N mineralization inhibiting factors
Mushroom culture wastes	• low N and K contents combined with high P and S contents • low N mineralization
Composted poultry manure	• moderate N content combined with high P content and low K content • moderate N mineralization • rather unfavourable nutrient spectrum
Dehydrated Poultry manure	• high N content combined with high P and Na contents and low K content • high N mineralization in the year of application • high NH_4^+ à high risk for NH_3 volatilization and risk of crop damage • rather unfavourable nutrient spectrum

Fertilisers and soil conditioners	Characteristics and specific suitability
Composted or fermented household waste	• low N and K contents in relationship to the P contents, high ash contents and à rather unfavourable nutrient spectrum • use in intensive vegetable cropping systems limited by the P inputs
Composted or fermented mixture of vegetable matter	• low N and K contents in relationship to the P contents, high ash contents • rather unfavourable nutrient spectrum • use in intensive vegetable cropping systems limited by the P inputs
Biogas Digestate containing animal by-products co-digested with material of plant or animal origin	• nutrient contents and nutrient spectrum depend on feedstock used • often relatively low K contents compared with the K requirements mainly of fruit vegetables like tomatoes • high immediate plant N availability, not suited for application in great amounts as base dressing before seeding/planting (salinity, short term N oversupply, physiological disorders) • field application should be rated according to salt contents (electrical conductivity), and suitability for use in greenhouses depends on NaCl contents

2.4.3 Complementary mineral fertilizers

Potassium (K) is the nutrient with the highest offtake in vegetable crops. As base fertilizers are relatively low in K compared to other nutrients like P, K supplementation is an important measure to achieve balanced fertilization systems.

The mineral fertilizers reported in Annex I of the Reg (EC) No 889/2008 all originate from mined minerals. These include soft ground rock phosphates, basic slag, for basic soils ($pH > 7.5$) aluminium-calcium phosphates, crude potassium salt or kainit, potassium sulphate (possibly containing magnesium salt), magnesium sulphate. Trace elements (inorganic micronutrients) are permitted as well, but are not necessarily derived from mining or organic sources. Most phosphorus fertilizers are allowed if the Cadmium (Cd) contents are ≤ 39.3 mg kg^{-1} P (or 90 mg kg^{-1} P_2O_5). There are also some organic sources of potassium e.g. residues of sugar beet and potato processing, as mentioned above.

All of the above mentioned fertilizers of mineral origin are rich in S. Many organic N fertilizers are also rich in S (e.g. residues of sugar beet and potato processing, keratins, etc.). As a consequence, the S budgets of organic greenhouses are strongly positive.

3 Main characteristics of protected cropping systems in Europe

Organic protected production systems in Europe are extremely differentiated. The four main categories which represent an actual picture of the European framework with their main cultivated species, the rotation schemes and characteristics of soil fertility management are described in the following paragraphs and in Table 4 and Table 5.

3.1 Mediterranean less intensive systems

In the Mediterranean climate, greenhouse systems are mainly used for production of vegetables during the winter season, and to anticipate and to extend the production season. They are based on unheated plastic tunnels or greenhouses where CO_2 enrichment and artificial lighting are not used. The greenhouses structures are usually made of galvanized iron and covered with PVC (polyvinyl chloride) EVA (Ethylene vinyl acetate) or LDPE (low density polyethylene) plastic sheets. The average height of the greenhouses has been rising over the years, standing today at up to 4 m. Unlike glass, plastic films are characterized by low cost and require a lighter and cheaper support frame. The area of a single unit ranges from 200 to 600 m^2, and they can be joined in poly-tunnels. In regions where vegetable production is more specialised (Sicily and Campania in Italy, Almeria in Spain) farms can have from 2000 m^2 up to 10-20 ha of greenhouses under organic management. Organic farmers usually produce crops in both open field and protected conditions on the same farm.

3.1.1 Main crops and crop rotation

The less intensive cropping systems in the Mediterranean areas rely on a crop rotation, which is usually shorter in comparison to open field systems. However, it still represents a relevant tool for the prevention of soil health diseases. For the same reason, green manure species (belonging to Fabaceae, Brassicacee and Poaceae botanical families) are quite commonly cultivated for short periods of time, often during the summer period, in order to provide different ecological services to the system. In this way, the cultivation of the same crop on the same field is interrupted.

3.1.2 Soil fertility management

Generally, Mediterranean soils are characterized by a low level of soil organic matter. The more frequently used organic amendments include animal manures in some areas, and different kind of composts in other areas where animal manures are rarely available. Nevertheless, both compost and manure utilization is often limited by the cost and availability of quality products. Usually, the amount utilized ranges from 1 to 30-50 t ha^{-1} $year^{-1}$. Complementary organic and mineral fertilizers are needed to provide the remaining nutrient requirements of the plants. Types and doses of complementary fertilizers to be utilized are extremely difficult to set, a priori. A simplified input-output nutrient balance should be a common requirement for sustainable soil fertility management but such calculations are not often prepared by the farmers or advisory services. Organic greenhouse farmers are used to deciding the fertilization plan for any single crop of the rotation using a short term perspective. The input-output nutrient budget is more often used by farmers and their advisors who are aiming to implement a long term fertility management strategy.

Picture 8 *Winter green manure mixture (Rye + Fava bean + Berseem clover) (France) (Photograph made by Hélène Vedie).*

3.2 Mediterranean intensive systems

The uses of intensive greenhouse systems are similar to the less intensive systems in that they are mainly used for production of vegetables during the winter season, and to anticipate and extend the production season. Intensive greenhouse systems of production in the Mediterranean climate environment are situated mainly in Spain, basically in Murcia and Andalusia (Almeria and to a lesser extent in Granada coast) and in some areas of Italy, like Ragusa province in Sicily and the Salerno province in Campania. They are characterized by off-season production of high value crops like tomatoes and sweet peppers, cucumber, eggplant, water melon and melon, zucchini, and also beans to a lesser extent. They are based on unheated plastic tunnels or greenhouses. Carbon dioxide enrichment and artificial lighting are not used. To reduce light irradiation during summer period (especially in Spain), farmers put a whitewash of calcium carbonate on the outer part of the plastic covers as a method to lower the temperature (Céspedes *et al.* 2009). Farm sizes are comparable to the less intensive system; they can have from 2000 m^2 up to 10-20 ha of greenhouses under organic management. Organic farmers in this system are more specialized than in the less intensive systems.

The level of productivity is lower compared to the high intensive systems in Northern Countries. Short and long cycle tomatoes produce between 6 and 12 kg m^{-2} respectively, while sweet peppers yield around 5-7 kg m^{-2}, exceptionally reaching 11 kg m^{-2} (Lacasa *et al.* 2006; Pellicer *et al.* 2008). After removal of crop residues in the late spring, the soil is fertilized (usually 170 kg N ha^{-1} as animal manures - a mixture of goat and sheep manure), and solarized or biosolarized for a period of approx. 4-8 weeks.

3.2.1 Main crops and crop rotation

Crop rotation is quite common in the intensive systems in the Mediterranean areas but cultivated crops are restricted to species belonging to the Solanaceae, Cucurbitaceae and Asteraceae botanical families as reported above. The EU regulations on organic farming are interpreted in different ways in the different countries and by different certifying bodies. In Italy, organic tomatoes can only be cultivated for two consecutive cycles. The second tomato crop must then be followed by the cultivation of two cycles of different species of which one must be a legume or a green manure crop (Mipaaf Decree, 2009). In Spain, a common crop rotation starts in the summer period (June to August) and consists of two cycles: one cycle of Solanaceae species (mainly pepper or tomato) grown until January-February, followed by a short cycle crop of 4-6 months, usually Cucurbitaceae (cucumber, melon, watermelon, zucchini) until May-June. Beans are usually intercropped or in rotation. Sometimes the beans are harvested, while in other cases the beans are incorporated as green manure. Brassica species may be grown for about a month and incorporated as green manure before solarization.

3.2.2 Soil fertility management

Within the Mediterranean area, a more in-depth analysis of soil fertility management is available for the Almeria region (Spain) due to the peculiarity of the system of production and the huge area cultivated under protected conditions. Analysis of 160 soil samples from the West of the province of Almeria showed low organic matter content (around 1 %), low cation exchange capacity (8.6 meq/100g) and high pH (8.3) (Gil *et al.* 2003). In Almeria, greenhouses (both conventionally and organically managed) cover an area of around 30,000 ha characterised by a wide range of soil characteristics and management systems. In Nijar area (Eastern zone), soils are natural while native soils in El Ejido (Western zone) are very poor for agricultural purposes. For this reason, an agronomic technique of soil preparation has been developed in the area to cover the native soil.

The sandy mulch technique involves the placement of a uniform 10-12cm layer of silica sand over an area of ploughed land that has been terraced, evenly levelled, destoned, tilled and manured. Manure is usually placed in a layer between soil and sand (Serrano, 1990). In greenhouses, the overall management has affected the characteristics of the soil by reducing the pH, the bulk density and the water retention capacity. As a consequence, this management system has improved infiltration. However, total organic carbon, total nitrogen and cation exchange capacity have increased in organic systems compared to conventionally managed systems (Del Moral *et al.* 2012). As a general rule, where animal manure is available it is used in the amount allowed by current regulation (170 kg N ha^{-1} yr^{-1}). Compost is only applied alongside the irrigation lines and vermicompost is applied to the localized area where plants will grow. The quality and composition of manure is a limiting factor. Where sheep manure is used in bags, it is passed through a heat treatment. The usual dose is 1.0-1.5 t ha^{-1} year^{-1}. Complementary organic and mineral fertilizers are needed to provide the remaining plant nutrient requirements. Farmers use either a simplified input-output nutrient balance for fertilization management, or technical advice. Water and supplemental nutrients (in particular, amino acids from algae, residues of sugar beet processing, humic acids and potassium sulphate) are supplied during the growing season by fertigation, according to crop demands. A significant number of organic farmers incorporate crop residues into the soil. All greenhouse vegetable species have a significant concentration of nutrients in crop residues, constituting in most cases 50 % of the total plant uptake of N, P and K (Contreras *et al.* 2014).

Picture 9 *Row application of vermicompost in Mediterranean organic greenhouse (Almeria, Andalusia, Spain) (Photograph made by Maria Del Carmen Garcia).*

3.3 Northern and Central European high intensive Systems

In North, Northwest and central Europe (e.g., Austria, The Netherlands, Belgium, Germany, Scandinavia, UK), greenhouse systems are mainly used for production of vegetables during an extended summer season, both early and late, and sometimes for the production of winter leafy vegetables. The cropping systems and degree of intensification differ widely between countries, regions and growers, due to the more extreme climatic conditions and sometimes also for historical reasons, and are driven by market and economic conditions. Intensive systems will be found only on specialised farms, with greenhouse production as the unique activity. Generally speaking, greenhouse structures in use for organic production are mainly glass-houses including plexi-glasses. They were initially meant to protect the crops from the harsh climate and to extend the growing season. Under the current economic conditions, (including market competition), greenhouses are equipped with a lot of technology to increase yield and enable long season and even year-round cultivation. Therefore, the majority of greenhouses are heated, either by natural gas or alternative fuels and in the last decade combined heat and power (CHP) has become a popular energy source. Movable screens are used for energy saving. Additional CO_2 is supplied in virtually all greenhouses in the Netherlands and Belgium and in the other countries to a certain extent. Assimilation lighting is not used in OGH.

Climate and the other facilities are controlled on a fully automatic basis. Commonly, the enterprises have a size of several ha, some are over 10 ha. The productivity is high with typical yields of over 50 kg m^{-2} of tomatoes, 25 kg m^{-2} of sweet peppers and 60 kg m^{-2} of cucumbers. In the Netherlands and Belgium, irrigation water is usually rainwater, which is collected in water basins of 1500 – 2000 m^3 ha^{-1}. Other water sources are surface water and ground water.

3.3.1 Main crops and crop rotation

Tomatoes and peppers are the main production crops, followed by cucumber and to a lesser extent, eggplants. In the winter period, lettuces and other leafy vegetables are sometimes included in the crop sequence. All the fruit-vegetable crops are long term crops, with a growth cycle of 8 - 10 months. Planting usually takes place in January and the crops last until November. Crop rotation is rather narrow and consists usually of tomato, followed by sweet-pepper or by cucumber in consecutive years. Green manure or cover crops are not applied in these systems because of less suitable growing conditions during the winter break. Until recent, steam sterilisation was used in the Netherlands once in 2 – 5 years, but this has now been ruled out by the certifying body. Instead, biofumigation, or the method of “soil resetting” by anaerobic disinfestation is used (Streminska *et al.* 2014). Grafting onto disease and nematode tolerant or resistant rootstocks is commonly used for these crops.

3.3.2 Soil fertility management

The soil types present in these greenhouses vary considerably between regions. The organic matter content is relatively high and percentages of 5–7% are quite common due to the yearly amendments of composts, crop residuals and some manures. A general picture of the fertilisation strategy is hard to produce as the intensity varies considerably. Usually the soil is prepared pre-planting with organic amendments as base dressing using either composted animal manure or composts, green manure is rarely used (Cuijpers *et al.* 2008). The major source of organic matter is compost, usually ‘green waste compost’. Some growers prepare their own compost from materials that include the crop residues. Alternatively, the crops residues are incorporated into the soil. Top dressings in the form of rapid mineralising fertilisers are applied throughout the growing season, using a variety of complementary fertilisers. Fertigation with liquid organic fertiliser dissolved in water and mixed with magnesium sulphate or potassium sulphate is occasionally used. The dosage rates may be automatically controlled by establishing a certain electrical conductivity level (EC). Quantification of the fertilisers to be supplied is based on the estimated crop demand and a recovery rate based on standards and on growers experience.

To facilitate this process, calculation tools have been developed and are available for free for growers (De Visser *et al.* 2006; Voogt, 2010). Commonly, soil and plant analyses are taken throughout the growing season to monitor the availability of nutrients and to adjust top dressing applications. In these intensive systems, the total yearly turnover of nutrients is high and also entails risks of over-fertilisation and imbalances in the nutrient supply (Voogt, 1999; Cuijpers *et al.* 2008; Voogt, 2010; Voogt *et al.* 2011). In particular, over-supply of P is a serious threat.

Picture 10 *Sweet pepper crop in a modern, heated greenhouse, characteristic of an intensive Northern greenhouse cropping system (The Netherlands) (Photograph made by Wim Voogt).*

3.4 Northern and Central European less intensive Systems

Less intensive greenhouse production systems in North, Northwest and Central European countries are used to extend the production season, and for the production of winter leafy vegetables. This type of system can be found on specialised farms, but is more common on farms with field vegetables, where the greenhouses cover only a minor area. In general, greenhouses in these systems are only heated to keep them frost free or to establish the main crops in the early season. In plastic tunnel or glass greenhouses, fruit vegetables are usually cultivated in the spring/summer season and leafy vegetables during autumn, winter and early spring. Energy saving techniques are being introduced but artificial lighting and CO_2 enrichment are not commonly in use. The productivity is intermediate reaching 7 – 25 kg m^{-2} of tomatoes, 2-7 kg m^{-2} of sweet peppers and 5-25 kg m^{-2} of cucumbers.

3.4.1 Main crops and crop rotation

The most important crops in the less intensive cropping systems are tomatoes and cucumbers, and to a lower extent sweet peppers and eggplants as well as a broad variety of leafy vegetables. The setup of the crop rotation differs greatly between countries and farms. According to the survey carried out by Zikeli *et al.* (2014) in Germany approx. 10% of the greenhouses have a simple rotation of fruit vegetables with kohlrabi as a pre-crop. About half of the greenhouses and polytunnels have a more diversified crop rotation, with different salad crops grown before and after the fruit vegetables. The remainder of the greenhouses (40%) have very diverse rotations with many different crops grown in early, mid and late season.

3.4.2 Soil fertility management

Fertility management in these less intensive systems involves a great variety of organic amendments (including solid and liquid animal manures, bio-waste composts from urban areas, etc.) and commercial/complementary organic fertilizers. Green manuring is not common. Fertilization management is often carried out based on standard fertilization schemes without the use of Decision Support Systems. Farmers follow different fertilization strategies. Some use a base dressing approach primarily based on solid manures/composts and to a lesser extent liquid animal manure with only minor inputs of complementary organic fertilizers (Zikeli *et al.* 2014). Others, in Germany, utilize mostly complementary organic fertilizers like keratins and vinasse (residue of sugar beet processing), and a much lower level of base fertilizers. The results of the input-output nutrient budgets indicate that the average total N supply is much higher than the N removals by the crops, on average a little less than double the crop demand. For P, the results are also problematic as the total supplies are almost double the estimated crop removals (Zikeli *et al.* 2014).

Picture 11 *Tomato cv Mecano grafted on Maxifort, Borlänge (Sweden) (Photograph made by Elisabeth Ögren).*

Table 4

Technical features and productivity levels of the main greenhouse cropping systems in Europe.

	Northern high intensive	Northern less intensive	Mediterranean less intensive	Mediterranean intensive
Building	Permanent greenhouses	Semi-permanent or permanent greenhouses. Use of polyethylene (PE) plastic cover	Permanent greenhouses. Use of tricoat (PE+EVA+PE), low density polyethylene (LDPE) and glass	Permanent greenhouses Majority covering materials tricoat plastic (PE+EVA+PE), three years of duration
Heating	Intensive full heating system, moderate temperature year around	No heating, heating for frost protection (5°C) or keeping about 10°C, additional heating for earliness or humidity control	No heating, in the areas where it may frost in the winter the crop rotation is planned to avoid any crop damages.	No heating
Ventilation	Controlled	Controlled or natural	Natural	Natural, with zenith and side windows, manual or automatic
CO_2 enrichment	Generally used with regional exceptions	No, or together with heating	No	No
Cropping period	Growth year -round of fruit vegetables, crops with high temperature requirements	Mostly seasonal crops. Great variation, in winter time cold resistant leafy vegetables (e.g. lamb salad, endive, cauliflower), summer fruit vegetables berries (soft fruits).	Mostly seasonal crops. But short term and/or off-season crops are quite usual in the southern parts of the Mediterranean area, leafy vegetable during winter.	One cycle: Jul.-Aug. to Feb.-May Two cycles: Autumn cycle (the principal): Jul.-Aug. to Jan.-Feb Spring cycle: Jan.-Feb to May-Jun
Productivity level potential per year [kg m^{-2})	Tomatoes: > 40, Sweet pepper: > 20, Cucumber: > 60	Tomatoes: 7-25 Cucumbers: 5-25 Sweet pepper:2-7	Strawberry 4-6, Tomatoes: 10-15, Cucumber: 5 – 6, Lettuce: 2-3, Zucchini:3-5	Tomato short cycle: 6-8, Tomato long cycle: 10 – 12, Sweet pepper: 5-7 , Cucumber: 7-8, Zucchini: 4-6, Melon: 4 – 4.5
Main region	Mainly in Netherlands, Belgium, Scandinavian countries and few in Germany	Central & Northern, Northwest Europe	Southern Europe, Mediterranean Countries (EU and non EU)	Southern regions of Spain and Italy
Crop breaks	biofumigation (some)	Winter leafy crop, green manure (seldom)	Green manure, dead mulch, biofumigation, solarization and biosolarization	Green manure, Solarization, biosolarization

Table 5

Main characteristics of the soil fertility management in typical greenhouse cropping systems in Europe.

	Northern high intensive	Northern less intensive	Mediterranean less intensive	Mediterranean intensive
Base dressing	Composts or/and solid animal manures (sometimes applied as top dressing to the former crop)	Composts or/and solid animal manures	Composts or/and solid animal manures	Animal manures or blending of animal manures according to the maximum allowed rate of 170 kg N ha^{-1}.
Complementary fertilizers	Yes	Yes	Yes • legume crops and green manure	Yes • legume crops and green manure
Mulching	Plastic mulch	• Plastic mulch • Dead mulch	• Plastic mulch • Straw mulch • Dead mulch	• Plastic mulch • Sandy-mulch
Decision making (DSS) (fertilizer type)	• Nutrient dynamic balance (N, P, K) • SOM focused approach Fertilizers price less important	• Nutrient balance (N) • SOM focused approach • Price and fertilizer availability are important	• Nutrient balance (N) • SOM focused approach • Price and fertilizer availability • Scarce availability of high quality compost	• Nutrient balance • Technical advice
Top dressing	• Common for N and K, never for other nutrient • Based on N up to 75% of the inputs (50-90%)	• Leafy vegetables: no top dressings • Fruit vegetables • complementary fertilizers up to 50-60% of N input	• Relatively common for N and K, never for P and S • complementary fertilizers are used but to a lower extent (30-40% of N input)	Common for N, K and S; occasionally for P
Decision making (DSS) (quantity)	• Based on DSS (e.g. biokas) • Based on schedules and/or soil analyses, stop in August for soil nutrient depletion	Less sophisticated approaches like schematic nutrient application protocols	According to phenological phases	According to phenological phases
Fertigation	• Fertigation in the first four weeks of cropping to the propagation-pots, usually liquid pig slurry • Growing cycle: widely used for Mg and K application	Sometimes to fruit vegetables	Mainly for N , K and Ca, when used	Mainly for N, K and Ca
Micronutrients	Occasionally	No	According to the needs in chelate form	According to the needs in chelate form

4 Soil fertility management criteria: constraints and bottlenecks

4.1 Nutrient balances

The main bottlenecks to reaching a really good balanced nutrient management strategy are:

1. Lack of data regarding the nutritional requirements of organically managed crops;
2. Uncertainty or lack of knowledge of nutrient release, in particular of N, from fertilizers used;
3. Fertilizers with unbalanced N/P/K ratios.

An unbalanced supply of nutrients compared to crop demand leads to an excess of some nutrients and sometimes to a deficit of others (e.g. K). According to the EGTOP report on Greenhouse Production (2013), "Soil fertility and an active soil ecosystem are the basis for plant nutrition in organic systems. The types of fertilizer, the application method, dosage and timing are normally chosen by the farmers to match the availability of the nutrients with the plants' needs." This general statement is widely accepted, but more in depth considerations are needed to put this into practice. Another general statement with a wide consensus is that, whatever the intensification level of the production system, soil fertility management criteria for organic vegetable production in protected conditions must consider at least the following basic aspects in order to maintain and increase the public trust in organic food:

- Optimal use of on-farm means and agronomical methods for soil fertility management, aiming at a maximum of self-reliance of the greenhouse cropping system;
- High long term sustainability (e.g. by avoiding negative effects on soil fertility through depletion of soil organic matter, salinization, negative impacts on soil pH, etc.);
- High nutrient efficiency including efficient circulation and recycling of nutrients;
- Low emissions including low inputs of non-renewable resources (e.g. energy, mined fertilizers);
- Implementation of the precautionary principle, aiming to reduce any potential long-term effects on soil contamination and environmental pollution, and
- Guarantee of the economic sustainability of the system of production adopted by farmers.

Implementing these basic aspects may lead to technical constrains and potential yield reduction. They should be used as *stimuli* to look for alternative agricultural practices that can be adapted to greenhouse conditions while at the same time fulfilling organic principles and their main objectives.

To achieve the long term sustainability of a cropping system, nutrient inputs should be more or less balanced with nutrient demands within a particular timeframe as both long term individual nutrient deficits and surpluses can have negative side effects affecting crop growth (yield) and quality. However, the nutrient spectrum of almost all fertilizers available for use in organic farming rarely matches the required nutrient spectrum for optimum crop growth. For example, vegetative plant organs like leaves and fruits usually have higher contents of N and K, and relatively lower contents of P than composts or solid farmyard manures, which will lead to P surpluses and K depletion. The combination of compost with leguminous (green manure) crops could improve the N/P ratio to a level that is more adapted to plant needs. However, if not adequately corrected with allowed mineral fertilizer, the K depletion problem would be maintained or even increased. Another kind of nutrient imbalance could arise from the nutrient release pattern of fertilizers. This could lead to temporary nutrient shortage, for instance, in the case of solid animal manure and compost, or nutrient oversupply if these amendments are applied in huge quantities (Voogt, 1999; Zikeli 2014). The use of liquid manures (animal slurries, digestates) could lead to temporary nutrient oversupply when applied in huge quantities before planting. The challenge is to design cropping and fertilization systems, which are balanced in terms of nutrient inputs and outputs, as well as in the nutrient release patterns over the growing season. This will mean that standard fertilization procedure should be replaced by strategic approaches of fertility management including an assessment of potential long term effects of the chosen fertilization management scheme. Certainly, when organic fertilizers and amendments are used and when green manure crops are grown, the rate of nutrient mineralization from the organic material incorporated in the soil represents a “black box” in any fertilization strategy. The quantity of mineral N provided to plants over time and how this matches with crop needs in different phenological phases is not easy to quantify for a farmer. So-called “N synchronization” is probably one of the main constraints in the implementation of any soil fertility management schedule.

An asynchronous pattern of availability and demand of N will cause NO_3 accumulation in the soil solution, which enhances the risk of N losses either by denitrification or through nitrate leaching in the case of over-irrigation, which cannot always be avoided (Voogt *et al.* 2016).

4.2 Decision support system

Current guidelines on nutrient management for organic farmers are fairly general. Organic farmers rely on the suggestions of advisors, intuition and observation, advice from vendors and their own experience to make decisions about the quantity and types of soil amendments to apply. The use of any decision support systems (DSS) is not common by farmers. As a result, there is tremendous variability in both the quantities of nutrients applied and the resulting soil fertility status on organically managed farms. Soil tests and simple budgeting tools can help producers maintain balance to achieve success. A more specialized DSS has to be developed, however, in order to match soil supply to plant demand, and this should take account of the variable mineralization conditions across a wide range of humus and organic fertilizers.

4.3 Water management

Another constraint in organic greenhouse is related to water management. The intensity of greenhouse production requires intensive irrigation that in combination with poor water quality regime has resulted, for some growers in Mediterranean Countries, in problems with the soil structure such as sodicity and physical crusts. This can lead to bad drainage which in turn causes bad aeration and increased problems with soil borne pathogens. High level of salinity can also be a problem in more intensively cultivated greenhouses. As reported by Voogt (2011), the input of residual salts (Na, Cl and SO_4) from organic fertilisers is high in relation to the uptake capacity of the crop under the conditions of ‘no-leach irrigation strategies’ (as required by regulations or just as a sustainable goal) even where the water sources used are of perfect quality. In this case, the only way to reduce the problem of soil salinity is over-irrigation combined with a drainage system. This requires careful consideration of when to apply soil flushing to minimise the risk of nutrient losses (Voogt *et al.* 2016).

Picture 12 *Summer green manure mixture (sorghum + cowpea) (France) (Photograph made by Hélène Vedie).*

5 Knowledge gaps and Research needs

As a conclusion of the analysis carried out on soil fertility management of organic greenhouse production, some knowledge gaps and relative research needs can be identified. The following list, summarizing the more urgent topics, cannot be considered exhaustive.

5.1 Assessment of the real state of the art

There are only very few data available on the state of the art of vegetable production in organic greenhouses. Most information is based on personal observations by scientists and practitioners. There is a lack of reliable data on the level of productivity, the crop rotations, the use of inputs like fertilizers, soil test data, quantity and quality of the soil organic matter, etc. Therefore, there is a strong need for a concerted assessment of the state of the art as a base for the evaluation of the current practices based on a common methodology for generating comparable data for the different regions of Europe.

5.2 Diversification of cropping systems, appropriate species and genotypes for ASC

The inclusion in the rotation of ASC species for soil fertility building purposes can give, on the basis of the total content of nutrients, a rough indication of their contribution to long term soil fertility, but the evaluation of their effectiveness in the short term is still very inaccurate. Available scientific literature provides only a rough estimate of ASC rates of mineralization once they are incorporated. Research activities aiming at a more precise quantification of the mineralization rates of single species or mixtures of agro-ecological service crops should be encouraged.

5.3 Nutrient imbalances and managing nutrient imbalances

Greenhouse crops have a very high overall nutrient demand, as their productivity is much higher than open field cultivation. There are strong indications that traditional approaches of fertility management in organic greenhouses can lead to huge nutrient input-output imbalances including the risk of the accumulation of some nutrients like P and many nutrients affecting soil salinity (S, Ca, Mg, and Na). The design of more balanced systems is very challenging as is the compilation of balanced mixtures of different kinds of fertilizer sources.

5.4 Assessment of N mineralization and fertilizer N release

Greenhouse crops have a very high N demand and their tolerance to temporary nutrient shortages is very low. Furthermore, the mineralization rate of compost and other organic amendments including green manure crops applied to soil is also substantially unknown. So, a more precise estimation of mineralization rate of different N sources would reduce the risk of excessive mineral nitrogen availability and/or excessive total nitrogen load. Moreover, in the Mediterranean area, filling this knowledge gap would be especially important for the prediction of the increase or depletion of soil organic matter content.

5.5 Assessment of the fertility management on GHG emissions

For open field cultivation, there is a huge number of publications available indicating that any N oversupply could increase the emission of GHG. N_2O emissions can also be influenced by the application technique as well as the soil water content. There are no data available that address the influence of soil fertility management on GHG emissions in organic greenhouses, and how these emissions influence the greenhouse N budgets.

5.6 Assessment of the influence of soil fertility management on quality parameters of organic greenhouse crops

A high product quality level is one of the main aims of organic farming. There are only few data available on the quality of organically produced greenhouse crops (e.g. Oliveira *et al.* 2013; Ceglie *et al.* 2015) and there is no systematic evaluation of the differences in quality parameters for different regions of Europe and their main driving factors (e.g. soil conditions, climatic conditions, chosen cultivars, fertility management).

***Picture 13** Tomato cv Maranello grafted on Beaufort, Väddö (Sweden). Straw in the aisles and grassland clippings in the rows (Photograph made by Elisabeth Ögren).*

6 Conclusions

The review of the available literature and the expertise of the involved scientists showed that the characteristics and fertility management of organic greenhouses in Europe is differentiated strongly both within the Regions and across Europe as a whole. In this European context, the implementation of a unique “standard” of soil fertility management is not realistic and, given the economic and pedo-climatic differences, not even desirable. Nevertheless, scientists, technicians and farmers agree on the need to respect the principles of organic farming by considering some basic aspects of soil fertility management, in order to maintain and increase the public trust in organic food. Self-reliance of greenhouse cropping systems, long-term perspectives, efficient recycling of nutrients, low emissions and low input of non-renewable resources represent some of the more common challenges to be tackled all over Europe. Furthermore, despite the great pedo-climatic differences, there are several common challenges across Europe with respect to soil fertility management. They include:
- The improvement of the data set addressing the state of the art;
- Nutrient supply and nutrient input-output relationships;
- Better synchronization of N mineralization and plant N needs;
- The improvement of crop rotations and better integration of green manure crops in the cropping sequence;
- Salinity management;
- Soil emissions;
- The development and implementation of DSS.

There are also some challenges that vary according to area, for example:
- Maintenance of an acceptable level of soil organic matter under Mediterranean systems vs. a deliberate increase of soil organic matter contents often measured under Northern conditions;
- Strong increase of soil P status under Northern systems vs. a risk of P shortage in some Mediterranean systems.

To overcome all these challenges there is a strong need for further development of science based systematic approaches compatible with the basic principles and aims of organic farming.

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