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Fertilizing for High Yield and Quality

Pome and Stone Fruits of the Temperate Zone

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Pome and Stone Fruits of the Temperate Zone

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1. Introduction

The history of fruit tree cultivation began some 5,000 years ago, the step from collecting fruits from forest trees to the cultivation of trees being initiated in the house gardens of the first emerging cities in Mesopotamia. Fruits were regarded as precious commodities, providing sweet, refreshing and storable food, and were - last but not least - a source of alcoholic beverages.

Fruits were highly prized by the ancient communities. The Egyptians were renowned for the sycamore fig or fig-mulberry (mulberry fig, *Ficus sycomorus*) so named because of the resemblance of the leaves to those of the mulberry. In ancient Greece, the very harsh laws introduced by the Greek aristocrat Drakon (621 B.C.) included the death penalty for fruit thieves. And even as late as the 18th century, the Prussian King Friedrich II (also known as “Der Alte Fritz”) committed fruit thieves to jail.

Hand in hand with man’s great appreciation of fruits over the ages there developed a knowledge and understanding of the botany of fruit trees and their cultivation that increased rapidly, especially during the Renaissance period. Indeed, many of the common techniques and methods in use today such as pruning, grafting, artificial pollination and irrigation were developed centuries ago. This huge pool of traditional knowledge still provides an important source of reference and information in the development of fruit production worldwide.

Today, in a global world market, the successful fruit farmer has to consider three major aspects in relation to cultivation:

- To produce as economically as possible
- To use environment-friendly and sustainable methods
- To deliver maximum quality to the market

In this context, optimizing mineral nutrition of fruit trees has to be regarded as one of the most important means of achieving these aims.

Over the past few decades, deciduous fruit production - as a branch of the food industry - has changed from traditional farming into a modern industry applying latest technologies and state-of-the-art knowledge. This implies that in the production of fruit of maximum yield and quality, not only have the biological resources of the tree to be taken into account, but also new techniques in orchard management including developments in mechanization. In relation to mineral nutrition, the thinking of fruit growers of today is far removed from the old ideas that a high input of fertilizers *per se* would result in the production of high yields of quality fruit. It is now commonly accepted that all natural resources such as water, soil and plants as well as chemical and physical inputs into the horticultural production chain should be used in the most efficient manner. Sweet cherry production in Northern Europe is one of the most interesting examples of this new thinking in fruit farming; high quality, healthy and tasty fruits can be produced even under the suboptimal environmental conditions of Norway, provided that appropriate plant material (new cultivars and rootstocks) and adapted cultivation methods (rain shelters) are used. This intensification of the production system does not *a priori* conflict with the objectives of so-called organic farming. On the contrary, fruit production based on a high level of knowledge and accuracy ("precision farming"), delivered with great care and responsibility is of definite benefit to the environment, in contrast to various so-called biological methods which are often applied without any scientific validity.

1.1. Important fruit tree species and areas of production

The terms "pome" fruit and "stone" fruit describe two major groups of deciduous tree species originating from the temperate zone of the northern hemisphere. Apple, pear, Asian pear and quince are the most abundant species of the pome fruit group; sweet and sour cherries, peaches, plums and apricots belong to the stone fruits. Due to their origin, both pome and stone fruit trees require a period of low winter temperatures to enable bud break and sprouting in spring ("chilling requirement").

The main temperate zone fruit production areas are located between 60° and 35°, latitude north as well as between 30° and 50°, latitude south. In relation to the globalization process, temperate fruits are also grown in mountainous areas of the tropics and subtropics, as for example in the Andean Cordilleras of South America or in the foothills of the Himalayas in India.

1.2. Economic importance

Apples and grapes are by far the leading deciduous fruit species cultivated on a worldwide scale. The list ranking the "Top Ten" in fruit production (Table 1.1) shows that apples and grapes are produced in similar amounts to table bananas or oranges. In Europe, apple represents about 50% of total fruit production (Table 1.2), Italy, France and Spain being the major fruit producing countries in the EU27.

China, the European Union, the USA and South American countries like Argentina and Chile are the main pome fruit producers on a worldwide scale. Though most of the apple crop is sold for fresh consumption, about 700,000 mt of apple juice concentrate are produced per year.

Table 1.1. "Top Ten" of worldwide fruit production in 2006 (deciduous fruits in italics).

Fruit species	Production (million mt yr^{-1})
Table Banana	70.67
Grapes	68.95
Oranges	64.80
Apples	*63.80*
Other Citrus	52.21
Mango	30.54
Pear	*19.54*
Peaches and Nectarines	*17.19*
Pineapple	18.26
Plums	*9.43*
World total:	526.50

Source: FAOSTAT, 2008.

Table 1.2. Total pome and stone fruit production in the EU27 and main producers (2006).

Fruit	Production (million mt yr^{-1})	Main producers
Apple	11.41	Poland, France, Italy, Germany
Peaches and Nectarines	4.37	Italy, Spain, Greece, France
Pears	2.77	Italy, Spain, Germany, France
Plums	1.58	Germany, France, Spain, Italy
Cherries (sweet and sour)	0.95	Poland, Germany, Spain, France
Apricots	0.76	Italy, France, Spain, Greece
Almonds	0.39	Spain, Italy, Greece, Portugal

Source: FAOSTAT, 2008.

China is by far the biggest apple producer, representing about 35% of the world's total. Over the past 15 years, world apple production has increased by 1.9% per annum (= 1 million mt), whereas exports of apples (representing only 15% of total production), have increased by more than 3.4% (= 190,000 mt). While plum production in most European countries has remained relatively constant, the increase in overseas countries over the past 10 years has been remarkable: China: +516%, Chile: +300%, South Africa: +237%, Argentina: +217% and Spain: +149% (Ellinger, 2007).

1.3. Fruit quality

What is understood by the term "fruit quality" varies greatly. Some of the many quality attributes are summarized in Table 1.3.

Table 1.3. Quality attributes of fruits.

EC requirements	Average consumer	Bio
Size (classification)	Size	Vitality attributes
Color (cultivar dependent)	Color	Absence of residues
Absence of skin defects	Taste	Preference for local cultivars
Ripeness	Appearance	Origin (bio-label)
	Origin (cultivar)	

The definition of quality is strictly dependent on the destination of the fruit after harvest, i.e. to the fresh market or the fruit processing industry. Different parameters are used to describe the desired quality: Table fruits must have an optimal appearance, whereas fruits for making juices should be rich in acids. Also for fresh fruit, consumer opinion, which can be quite divergent, plays an important role in the assessment of quality.While most consumers prefer fruits with an attractive appearance (e.g. big sized, well colored), others place greater emphasis on "internal values", such as taste or vitamin content. Within the European market, EU standards describe the minimal requirements for fresh fruits and define quality classes (Extra, Class I, Class II). Usually fruits are graded depending on their outer appearance, i.e. size, cultivar specific color and whether or not they are free from defects, blemishes and diseases. In so-called organic production, fruit quality is more related to the sum of factors, which represent the biological value of the entire fruit as a living organism. New concepts of fruit physiologists define the "inner quality" as "those characteristics which together result in a crop-specific product that is ripe, tasty and has satisfactory keeping quality", which includes terms like "vitality" and "integration" (Bloksma *et al.*, 2004).

1.4. Fruits as healthy food

There is general agreement that fruits are regarded as healthy food. However, there is much debate as to what are the valuable components that fruits provide. The old British saying: "An apple a day keeps the doctor away" has nowadays been changed into the marketing campaign of "five servings of fruits or vegetables every day". Fruits have long been regarded as a rich source of vitamins especially vitamins A and C. The content of vitamin A can vary considerably between fruits as evident from the findings that the total daily demand for this vitamin by the human adult can be satisfied by 250 g apricot but requires as much as 4 kg of apple fruit. A summary of vitamin A and C contents of pome and stone fruits in comparison with two "wild" fruit species (acerola and rose hip) is given in Table 1.4. The abundant quantity of pectin in apple fruit is believed to be beneficial in reducing both high cholesterol and high blood sugar.

Table 1.4. Vitamin A and C contents of pome and stone fruits in comparision to acerola and rosehip.

Fruit	Vitamin C mg 100 g^{-1}	Vitamin A μg 100 g^{-1}
Apple	5-20	45
Pear	4	20
Cherries	10-15	40
Plum	5	20
Peach	7	440
Apricot	5-10	400-1,000
Acerola (*Malphigia glabra*)	1,500	1,500-3,000
Rosehip (*Rosa* spp.)	1,250	500

Source: After Souci *et al.*, 2007.

Today, fruits are also more valued particularly for their health giving properties and in supplying a "low-fat" and "fiber rich" form of nutrition. Furthermore, some secondary compounds in fruits possibly play a role in the prevention of stress and other ailments. These compounds (antioxidants) are able to detoxify so-called free radicals in the human body, which are very harmful to biological membranes and may lead to cell death. One such group, the phenolic compounds, flavonoids play a major role in this respect. Apples are rich in quercetin, which has a very high antioxidative capacity[1] whereas blue and red fruits including plums and cherries are a rich source of anthocyanidins. Both blueberries and blackberries in particular possess a very high antioxidative capacity (Table 1.5).

Table 1.5. Antioxidative capacity of various fruits.

Fruit	Trolox μmol TE g^{-1}
Apple	5-10
Pear	5-10
Cherries	10-20
Plum	5-15
Peach	5-10
Apricot	5-10
Citrus	5-15
Blueberry	20-50
Blackberry	25-50

Source: After Wang *et al.*, 1996.

[1] Capacity to bind free oxygen radicals ($O^{\cdot}$) = Oxygen Radical Absorbance Capacity (ORAC), expressed in Trolox Equivalents (TE). The unit is μmol TE g^{-1}.

2. Botany and Physiology

2.1. Growth and structure of deciduous fruit trees

2.1.1. Plant Material

From the early days of fruit production, valuable cultivars have been grafted on compatible rootstocks. The major reason for this form of propagation has been simply to maintain the characteristics of the cultivar, which otherwise would have been lost, had the life cycle of the plant been allowed to continue via seed germination with subsequent cross-pollination. Suitable rootstocks have been selected using existing knowledge of their compatibility with grafting partners and the specific behavior of the rootstock in relation to soil properties. Currently, breeding new cultivars and rootstocks with improved characteristics is one of most important tasks in horticultural research.

In recent years, knowledge of the physiological background of scion-rootstock relationship has increased markedly although it is still not possible to predict the responses of both partners after grafting. It is known that the rootstock significantly influences a number of important processes in the tree such as fruiting behavior, frost tolerance or the uptake of mineral nutrients from the soil. On the other hand, there is an interaction between scion and rootstock affecting both partners which means, that the growth and metabolism of the whole tree is also regulated by the genetic constitution of the cultivar.

The choice of appropriate plant material by the farmer is a prerequisite for successful fruit production in a given environment. For example, the apple cultivar "Granny Smith", which requires a very long growing period, will never produce superior fruit in the north of Europe. Trees for modern high density plantations have to be grafted on dwarfing rootstocks and not on vigorous clones or on seedlings. The choice of a particular fruit cultivar is first and foremost the result of market demand. Furthermore, the farmer's decision must also be based on special characteristics of the cultivar. These characteristics depend on the presence of genes which provide resistance to diseases or pests, or allow tolerance to adverse growing conditions as for example drought and salinity. The length of the ripening period which is a very important criterion is also cultivar specific and genetically determined.

2.1.2. Rootstocks

The choice of a suitable rootstock for a high-performance tree is based on the following considerations:

- Compatibility with the scion (the fruit producing cultivar)
- Influence on growth characteristics of the entire tree (size)
- Promotion of early bearing
- Influence on fruit quality
- Pest and disease resistances
- Ability to tolerate adverse soil conditions
- Availability and price

These considerations are not equally weighted in the different areas of production of temperate fruits. When the orchard is in optimal conditions the grower is mainly concerned with the first four points. Under suboptimal site conditions, however, factors such as hardiness or disease resistance become more important.

With only few exceptions, rootstocks are mainly propagated by vegetative means. For intensive production systems based on high density plantations, rootstocks have been selected to induce a strong reduction in the growth of the tree. Apple cultivars grafted on the European standard rootstock M9 (*Malus paradisiaca*) reach only 20% of the height of trees grafted on a seedling rootstock. M9 and other "dwarfing" rootstock clones such as M27 or M26 are the common rootstocks for "high density" plantations with 2,500 or more trees per ha. These clone apple rootstocks are highly compatible with most of the present cultivars. Since viral diseases can be transferred through clone propagation, all rootstocks used in commercial orchards should be routinely tested and certified before use to ensure that they are free from known virus particles. As listed in Table 2.1, rootstocks for pears and for stone fruit trees are genetically more different from the grafting partner than are the apple rootstocks. As a consequence, problems of incompatibility are more pronounced in *Prunus* combinations than in apple. Pear varieties grafted on quince rootstocks (*Cydonia oblonga*) in order to reduce the great vigor of pear trees, are known to be incompatible with many of the present pear cultivars. The same is true for a great number of sweet cherry (*Prunus avium*) cultivars grafted on less vigorous *Prunus cerasus* or other *Prunus* rootstocks. In sweet cherry production, a great deal of effort been made in recent years to find suitable, growth-reducing rootstocks. For an economically reasonable production the tree's height should not exceed 4 m. However, as yet there is still no *Prunus* rootstock that simultaneously reduces tree height and favors fruit quality as does the M9 rootstock in apple production.

Compared to non-grafted seedling trees, growth reduction is a common characteristic of any grafting combination. Though the nature of this phenomenon is still obscure, the reduction of the stem vessel area across the grafting junction is probably the major reason for the slower tree growth. Because these vessels act as transport systems for water, nutrients and assimilates, their cross sectional area limits liquid flow from the root to canopy (xylem) and *vice versa* (phloem): The smaller the area, the slower the rate of transport in both directions.

Table 2.1. Common rootstocks for deciduous fruit trees species in Europe.

Species	Rootstock
Apple (*Malus domestica*)	M9 (*Malus paradisiaca*) M27 M26
Pear (*Pyrus malus*)	Quince A, C (*Cydonia oblonga*) *Pyrus* rootstocks (new)
Plum (*Prunus domestica*)	Seedlings: ▪ Plum (*Prunus domestica*) ▪ Myrobalana (*Prunus cerasifera)* ▪ St. Julien Plum (*Prunus domestica ssp. insititia var. juliana)* Clonal: ▪ Myrobalana Alba (*Prunus cerasifera)* ▪ St. Julien A, Brompton, Pixy (*Prunus domestica ssp. insititia var. juliana*) ▪ Jaspi (*Prunus salicina* x *Prunus spinosa*) ▪ Ishtara (*Prunus salicina* x *Prunus cerasifera*) ▪ P 2038 (*Prunus besseyi*) ▪ Damil GM 61-1 (*Prunus dawyckensis*)
Sweet Cherry (*Prunus avium*)	Seedlings: ▪ Wild Cherry (*Prunus avium*) ▪ Mahaleb Cherry (*Prunus mahaleb)* Clonal: ▪ F 12/1*(Prunus avium)* ▪ Colt *(Prunus avium x Prunus preudocerasus)* ▪ St. Lucie I.N.R.A. 64 *(Prunus mahaleb)* ▪ Weiroot (*Prunus cerasus)* ▪ GiSelA 5 (*Prunus rerasus x Prunus canescens*)

Sweet Cherry (cont.) (*Prunus avium*)	▪ Inmil (Gembloux), different *Prunus* species ▪ Edabriz *(Prunus cerasus)* ▪ Maxma *(Prunus avium x Prunus mahaleb)*
Sour Cherry (*Prunus cerasus*)	Seedlings: ▪ Mahaleb Cherry (*Prunus mahaleb*) Clonal: ▪ Weiroot 11 (*Prunus cerasus*) ▪ European Dwarf Cherry (*Prunus fruticosa*) ▪ St. Lucie INRA 64 (*Prunus mahaleb*) ▪ F 12/1 (*Prunus avium*)
Peach/Nectarine (*Prunus persica*)	Seedlings: ▪ Peach (*Prunus persica*) ▪ Plum (*Prunus domestica*) ▪ Almond (*Prunus dulcis*) Clonal: ▪ Nemaguard, Infel Cadaman Avimag (*P. persica* x *P. davidiana*) ▪ GF 677, GF 557 (Peach/almond hybrids) ▪ Damas GF 1869, St. Julien 655/2 (plums, *Prunus domestica*) ▪ Brompton (*P. domestica* ssp. *insititia*) ▪ Sand Cherry (*P. pumila*)
Apricot (*Prunus armeniaca*)	Seedlings: ▪ Apricot, peach and plum seedlings ▪ St. Julien Plum (*Prunus domestica ssp. insititia var. juliana)* Clonal: ▪ Marianna (*Prunus cerasifera* x *Prunus munsoniana*) ▪ Myrobalana (*Prunus cerasifera*)

In addition to morphological aspects, a great number of physiological processes are affected by the grafting zone and may alter the metabolism in all parts of the tree. Studies of Treutter and Feucht (1988) indicate that in certain *Prunus avium/Prunus cerasus* combinations some chemical compounds are produced either in the vicinity of the graft junction or - far distant from this region - in the leaves. These compounds, mostly phenols, can be regarded as markers of incompatibility between scion and rootstock. The term incompatibility describes a latent disorder of the tree relating to genetic differences of the partners, which induce restricted growth, lower yield and last but not least, bring about the death of the tree.

It has been shown in numerous publications that uptake of nutrients and their distribution in the tree is significantly influenced by the type of rootstock (Betran *et al.*, 1997). As a general trend, self-rooted trees have higher nutrient concentrations in the leaves as compared to trees on rootstocks (Jadczuk *et al.*, 1997). At least to a certain extent, there seems to be a tendency for lower foliar nutrient contents in dwarfing and in non-compatible rootstock-scion combinations because of impaired upward transport of nutrients through the grafting junction (Ystaas and Froynes, 1998).

2.1.3. Function of Roots

For many fruit growers (and scientists too) the root systems represents nothing more than the tree's anchorage in the soil or the water and nutrient transport pipeline to the stem and canopy. However, research activities over the past few decades have established very clearly that the growing root is a very active site of complex metabolic processes and presents a huge interface for the exchange of chemical constituents from the tree to the soil and *vice versa* as well as a providing a site of high microbiological activity much greater than in the bulk soil.

The soil-root interface or rhizosphere of a tree is much greater in area than the leaf-atmosphere interface. While the latter is in the range of several m^2 per unit area of soil surface, (the so-called Leaf Area Index, LAI) usually 5 to 10, for apple trees, the estimated root surface is some magnitudes larger. From the studies of Ebert and Lenz (1991) it can be calculated that a 5-year-old apple tree has a root surface area of more than 250 m^2. The root surface area varies during the growing period because of the development of short-lived root hairs, which significantly increase the contact area of the growing root to its environment.

In comparison to leaves, the lifespan of active roots is much shorter. The fast turnover of roots requires a great deal of metabolic energy in the form of photosynthates from the leaf canopy for the growing process as well as for the synthesis of organic metabolites and uptake of mineral nutrients. The interrelationship between root and shoot growth during the season controls the development of the entire tree.

The root, this very active part of the tree, serves the following important functions:

- Anchorage of the tree in the soil

- Uptake and transport of water
- Uptake, release and transport of organic and inorganic constituents
- Synthesis, decomposition and storage of metabolites

These functions also moderate yield and fruit quality in relation to the activity of the root system. Root growth is favored in well aerated light soils which are easily penetrated. In high density plantations, it is very important to take the greatest of care of the relatively small root systems of the trees, which – under conditions of high fruit yield – are not very competitive with the fruits in terms of obtaining enough assimilates from the leaves for growth and metabolism. The root systems of dwarfed trees also encounter strong competition from the roots of weeds and grasses for uptake of water and nutrients. In this respect the soil should not be compacted and any competition with weeds should be avoided by weed control in the tree rows. The soil should be maintained so that moisture, aeration, and organic matter components are conducive to the growth of fruit tree roots.

2.1.4. Mycorrhizae

Under natural, non-disturbed soil conditions tree roots undergo a symbiotic association with fungal microorganisms, widely known as mycorrhizae. These fungi, living on or within the tree root, enhance nutrient absorption from the soil solution and profit – in return – from the photoassimilates provided by the host. Of the three main types of mycorrhizae, namely arbuscular (AM, forming internal hyphae into feeder roots and the surrounding soil), ectomycorrhizae (forming a sheath of fungus material on the surface of the root) and eriocoid mycorrhazae (mostly on *Ericaceae*), AM is the dominant type in fruit tree roots. In this symbiotic association, the exploration of the soil by the hyphae greatly extends the effective root surface - soil contact to enhance in particular both the acquisition of water and the relatively soil immobile plant nutrients such as P and some of the micronutrients (Zn, Cu). By this means trees are able to survive on marginal stands under adverse soil conditions. With increasing intensity of irrigation and fertilization, however, the occurrence of mycorrhizae is significantly reduced. The circumstances, under which a beneficial association between fungi and tree roots can be established, are difficult to predict. Variability of dominant fungal species as well as spatial patterns in an orchard are usually high. In a survey study in the USA it was reported that colonization of apple tree roots by *Glomus* and up to seven other species of Endogonaceae was negatively correlated with soil P and Zn levels (Miller *et al.*, 1985). It can be concluded that in intensive drip irrigation/fertigation systems tree roots are less mycorrizal as compared to extensive growing conditions (Atkinson and

White, 1980). Apple trees grow very well in containers filled with a sterile sand substrate, if they are properly supplied with nutrients (Luedders *et al.*, 1969). Under these artificial growing conditions, no mycorrhizae can be detected at all. In modern orchard systems it can be assumed that mycorrhizae are only of marginal importance for fruit trees. Under suboptimal cropping conditions or in bio-production systems with reduced fertilizer input, however, mycorrhizae probably play a greater role. The same is also true for the growth of young trees in nurseries and under certain stress conditions (drought, salinity, ion toxicity) where mycorrhizae obviously increase tree tolerance to environmental constraints.

2.1.5. Function of leaves

In the temperate zone leaves of fruit trees have a life span of about 7 to 8 months. The bifacial leaf has two different surfaces: The upper side, which is directed to the sunlight, and the lower side, containing a great number of apertures, the stomata. These pores allow the leaves to control the release of water vapor (transpiration) and the uptake of CO_2 (photosynthesis). The stomata are also believed to play a role in the uptake of nutrients applied as foliar sprays (Eichert *et al.*, 1998).

Leaves contain considerable amounts of nutrients. On a dry weight basis, the K leaf content is two-fold higher and the Ca leaf content nearly forty-fold higher than their respective contents in the fruits. Leaves are thus the strongest sink for nutrients within the entire tree.

Before leaf fall at the end of the season, some foliar nutrients such as N and P are retranslocated into storage organs (stems, roots and buds). Others like K and Ca remain in the abscised leaves to become available for uptake by tree roots after biological degradation in the soil during winter and spring (Table 2.2).

Table 2.2. Nutrient retranslocation from leaves to storage organs in apple trees.

Nutrient	Retranslocation rate (%)
N	>50
P	>50
K	<50
Ca	<5
Mg	<5

2.1.6. Flowering and fruit development

Flower induction occurs during the summer period of the year prior to blossom. Many factors are involved in this physiological process, i.e. plant hormones, the balance of nutrients, vegetative growing activity and environmental conditions such as sunlight. However, the process is not yet fully understood and seems to take place at the molecular level. Flower buds, initiated during July to September, continue developing throughout the autumn season and usually reach morphological competence before winter temperatures prevent any plant growth. In apple, pear and late plum varieties, the developing flower buds have to compete with the growing fruit, which is the strongest sink for assimilates in the tree. It has been found, that the fruit inhibits both initiation and development of flower buds via hormonal signals. As a consequence, a heavy fruit load reduces the number of flowers and thus minimizes fruit yield in the following year. This phenomenon is known as “alternate bearing”.

2.2. Physiology of yield and fruit quality

Fruit quality is defined in many different ways, depending on trade rules or customers preferences. According to the terms of trade in the EU, apple fruits in the “Extra” class have to fulfil the following recommendations: Cultivar-specific fruit size, coloration of fruit peel, be free from external injuries and at an optimal stage of ripening (total soluble solids or sugar content, firmness, starch decomposition). Besides “external” quality factors, which are of most relevant to the farmers’ price, consumers are now giving more and more attention to “internal” values of fruits including contents of vitamins, presence of radical scavengers, which suppress oxidative stress in the human body, or to less well defined attributes such as biological activity. Taste, which is the result of both sugar/acid ratio and the complex pattern of numerous volatile compounds, may also act as a quality factor.

All these attributes are to a certain extent genetically fixed and a cultivar characteristic. This means that, a “Cox’s Orange” apple can never be as big as a “Fuji” fruit, but, on the other hand, “Fuji” can never have the same delicious taste as that of a “Cox’s Orange”. However, horticultural practice including irrigation and fertilization also influence fruit quality. Balanced nutrient supply to trees is one of the most important prerequisites for optimal fruit growth and development. Nutrient deficiencies and imbalances impair the composition and appearance of the fruit and may reduce its internal or external quality.

The physiological development of the fruit is a complex interaction between different parts of the tree: Leaves, shoots, roots and fruits. All these organs are dependent on the supply of photoassimilates from mature leaves. Competition between vegetative growth and fruit development strongly determines fruit growth and the formation of valuable compounds within the fruit. It is well known that a specific leaf to fruit ratio is required for optimal yield and quality of apple fruits. For “Jonagold” (under growing conditions of Germany) this ratio is about 20 leaves per fruit. The optimal fruit load in plum varieties has been found to be 20 to 30 fruits per meter of fruiting branch (Drkenda and Bertschinger, 2006).

Fruit growth is initiated by the pollination of the ovum in the ovary of the flower. Non-pollinated flowers abscise a few days after full bloom. The number of flowers which become fruits (“fruit set”) varies from species to species, i.e. fruit set in cherries is about 25 to 50%, whereas in apple it is only 5 to 10%. The first fruit drop occurs a few days after blossom and is followed by later fruit fall periods, which are in June (“June fruit fall”) and shortly before fruit maturation in autumn. The intensity of the pre-mature fruit drop is strongly dependent on climatic factors and is more severe during dry and hot periods.

Fruits undergo different developmental stages. A rapid increase of fruit volume after fruit set is usually followed by a period of slower growth. Towards the end of fruit ripening, fruit volume and weight increase again at a faster rate (Fig. 2.1). This sigmoid growth pattern can be explained as follows: The first stage is a period of rapid cell division with a fast increase in the total number of cells. The “lag” phase which follows is represented by internal structural changes such as the hardening of the stone (i.e. the fruit endocarp) in cherries, plums and peaches, or the ripening of embryos in pome fruits. At the next stage, a cell elongation phase associated with a rapid incorporation of water, fruits appear to grow faster. It has been shown recently, however, that fruit growth process occurs more or less continuously at the same rate when calculated as dry matter increment per day (Blanke, 1990; Fig. 2.1).

Fruit thinning

Deciduous fruit trees usually develop a great number of flowers in order to assure the formation of as many fruits as possible. In apple trees, 5 to 10% of the flowers are transformed into fruits (“fruit set”), whereas in cherry trees a fruit set of 25 to 50% is regarded “normal”. However, the natural fruit set is not always ideal for the formation of big sized, well stained and sweet fruits. Indeed the converse is true, the higher the number of fruit, the smaller the individual fruit and the lower the external and internal quality. Furthermore, too many fruits inhibit the initiation of flower buds and thus reduce fruit yield in the following season, the so-called alternate bearing effect. This may result in significant losses of income in apple, pear, plum and peach orchards.

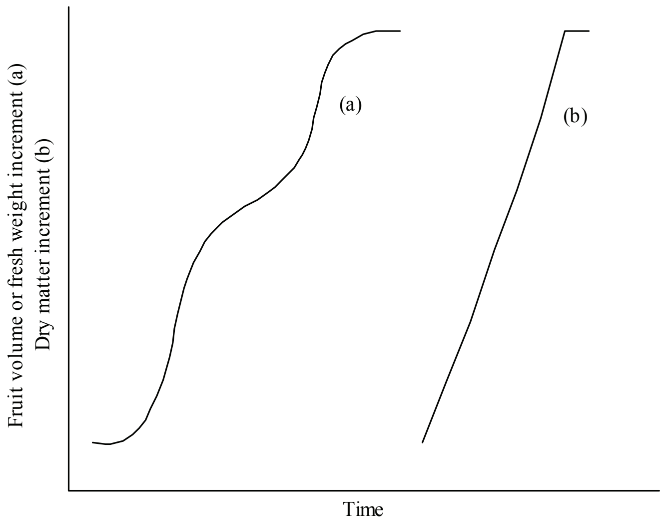

Fig 2.1. Schematic growth pattern of fruits on a volume or fresh weight basis (a) and on a differential dry matter increase basis (b). *Source*: After Blanke, 1990.

The method of regulating the number of fruits per tree is by thinning (or eliminating) surplus flowers or fruitlets before they mature. During thinning the number of fruits per tree is actively reduced in addition to the naturally occurring fruit drop periods, as for example the June fruit fall.

The optimal number of fruits per tree is a cultivar characteristic and a complex interaction of orchard conditions (number of trees per ha) and environmental factors. It is usually defined as number (or weight) of fruits per meter branch or per tree. As an example: To ensure an optimal yield in terms of quality, “Elstar” trees should have not more than 70 fruits per tree if the planting density is 3,000 trees per ha and the expected yield level is 30 mt per ha

Different methods are used to eliminate undesired flower buds, flowers and fruits:

- Mechanically: Rotating nylon wires or other similar tools remove buds prior to blossom.

- Hormones or hormone-like substances: Simulating or disturbing the natural action of plant hormones. Cytokinins (benzyladenine), gibberellic acids (GA_{4+7}) or ethylene-releasing substances (ethephon) are used depending on the regulations pertaining to particular countries. Side effects can include earlier or delayed ripening and quality losses such as russetting.
- Fertilizer solutions: Ammonium thiosulfate (ATS), applied as a foliar application at 2% has a burning effect on the salt sensitive flowers, as well as having a fertilizing side effect.
- Manually: Removal by hand of poorly developed, damaged fruits or of those, growing in shade at a later stage of fruit development.

2.3. Post harvest physiology

Fruits at the harvesting stage contain about 85% of water and 10 to 15% sugars (see Table 2.3). This is why a very intensive metabolism continues in the mature fruit after it has been detached from the tree. Depending on their pattern of respiration, fruit species are subdivided into climacteric fruits which show a sudden increase of respiration towards the end of the ripening period, and non-climacteric fruits in which respiration steadily declines during fruit maturation (Table 2.4). Apple, pears and some plum cultivars are typical climacteric fruits, whereas most of the stone fruits possess a non-climacteric ripening pattern. The climacteric peak of respiration (CO_2 production and O_2 consumption in the fruit tissue,) coincidences with a burst of ethylene (C_2H_4) release (Fig. 2.2), which is known to act as a strong ripening accelerating hormone.

Towards the end of fruit development, the ripening or maturation period is characterized by rapid biochemical changes of fruit constituents (transformation of starch into sugars) and a loss of structural integrity (softening), as indicated in Table 2.5. This is associated with a decline of acids, the formation of volatile aroma compounds and color changes in peel and pulp which indicate the ripening stage of the fruit.

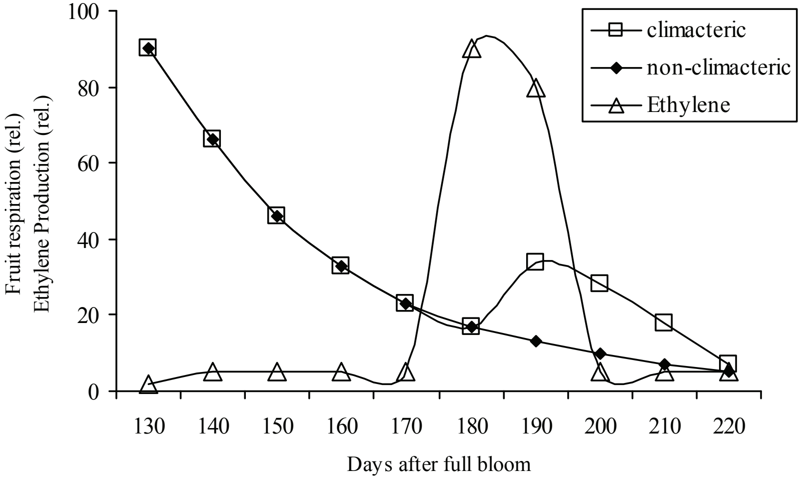

Fig. 2.2. Climacteric and non-climacteric respiration patterns and ethylene production in fruits.

Table 2.3. Composition of different fruits at harvest (% of fresh weight).

	Water	Sugars	Acids	Fiber	Minerals	Protein	Fat
Apple	85	12	0.7	2	0.15	0.3	0.4
Pear	84	12.5	0.3	2.5	0.15	0.5	0.3
Plum	85	10	1.0	1.7	0.3	0.6	0.2
Peach	87	9	0.7	2.3	0.25	0.8	0.1
Apricot	86	9	1.1	2.0	0.35	0.9	0.1
Sweet Cherry	83	14	0.6	1.5	0.25	0.9	0.3
Sour Cherry	84	11	1.4	1.0	0.15	0.9	0.4

Source: After Souci *et al.*, 2007.

Table 2.4. Climacteric and non-climacteric fruit species.

Climacteric	Non-climacteric
Apple	Cherries
Pear	Grape vine
Plums	Citrus
Peach	Olive
Apricot	
Persimmon	

Table 2.5. Changes in the composition and structure of ripening apple fruits.

Developmental stage	Process
Beginning of ripening	Transformation of starch into sugars
Ripening, early harvest for long-term storage	Softening of tissue due to destruction of middle lamellae
Ripening, main harvest (compromise between taste and storage ability)	Color changes (decomposition of chlorophyll, synthesis of carotenoids and anthocyanins)
Maturation, optimum consumption quality but low storage ability	Formation of volatile aroma compounds

To assure maximum quality, fruits should be harvested at the optimal stage of ripening. For processing or long-term storage, apples have to be harvested earlier as compared to fruits for immediate consumption. The right time for picking apples can be assessed using the so-called Streif-Index[1]. This cultivar-specific term implies fruit firmness, sugar content and starch degradation.

The role of rootstock on quality of pome fruits is still obscure (in contrast to citrus) (Castle, 1995). Some dwarfing apple rootstocks have a promoting effect on parameters such as fruit size or coloration, but obviously these effects vary greatly and depend on cultivar and site conditions.

[1] Streif-Index = Fruit firmness/sugar content X starch decomposition value

3. Mineral Nutrients

3.1. Nutrient sources and their availability in the soil

The distribution of plant mineral nutrients in natural soil is extremely heterogeneous. Nutrient concentrations and availabilities in the soil of a fruit orchard may thus vary both spatially and temporally which is of importance in their acquisition by tree roots.

Several different sources of nutrients for the fruit tree may be distinguished:

- Mineralization of organic matter (plant residues, microorganisms)
- Mineral fertilizers
- Organic fertilizers
- Release from parent rocks by weathering and release from fixed sites in clay minerals (e.g. K from Illite)
- Atmospheric deposition
- N-fixation by specialised microorganisms

For practical orchard management, fertilizer supply and the biochemical release or fixation of mineral nutrients are the most important factors influencing the nutrient balance in the soil.

The availability of nutrients to tree roots is a function of conditions in the soil and of its biological activity. In general, tree roots only absorb nutrients that are dissolved in the soil solution and present in ionic form. In their acquisition by tree roots, nutrients must be transported in the soil solution to the root surface. Two main processes are involved in this movement, mass flow and diffusion. Mass flow of nutrients to the root is brought about by the transpiration of the tree which during the uptake of water literally sucks the nutrients in the soil to the root surface. For most of the plant nutrients which are present in relatively high concentrations (NO_3^-, Ca^{2+}, Mg^{2+}) this is the means by which they are transported to the root surface prior to uptake. However, for K and particularly for P the ionic concentrations in soil solution are comparatively low so that the amounts transported by mass flow are not high enough to meet the nutrient requirements of the tree. These two nutrients move to the roots by the physical process of diffusion i.e. down a concentration gradient induced by the removal of these nutrients at the tree root surface during uptake. Factors which disturb this process therefore induce deficiency.

For both P and K, the release of bound forms from soil organic or inorganic particles into the soil solution in inorganic form thus to a large extent controls their availability to plant roots. Potassium (K) can be present in abundance in the soil occurring in various forms: As a structural element in soil minerals, associated with organic matter in exchangeable form, in a readily exchangeable or slowly exchangeable form in clay minerals and in ionic form in soil solution. By far the largest fraction, however, that present as a structural component of the soil minerals is virtually inaccessible to plants. On the other hand the clay minerals which constitute only a few percent of the total K in soils usually provide the major source of K by buffering the soil solution which provides the tree roots with K. During drought periods, K may become deficient due to 1) the enhanced fixation within the layers of clay minerals (e.g. illite) which is favored by dry conditions, and 2) by interruption of the diffusion pathways by which K is transported to tree roots during uptake.

Phosphorus occurs in soils in forms which vary considerably in availability to plants. Phosphate ions added to the soil in the form of soluble phosphate fertilizer rapidly undergo chemical and physical transformations so that the added phosphate is held in pools contrasting in availability and between which there is a reversible transfer of phosphate. The major feature of this system is that phosphate ions are only slowly released into the soil solution to become accessible for uptake by roots. Availability is particularly depressed in soils of low and high pH (see Fig 3.1). The relative immobility of phosphate in soils and its presence in very low concentration in the soil solution means that trees can very easily suffer from a deficiency of this nutrient.

A variety of soil conditions determines the availability of nutrients to tree roots, such as:

- Water content
- Soil type and structure
- Organic matter
- pH

Micronutrient availability in particular relates closely to soil pH. Most micronutrients are only poorly accessible to plant roots at high pH, but availability increases as the soil pH falls. As is also true for the macronutrients, total micronutrient concentrations provide little information concerning availability to plants. Fe deficiency for example occurs very frequently in dicotelydenous species growing on calcareous soils with a pH higher than 7, although the soil can be very rich in this element (Fig. 3.1).

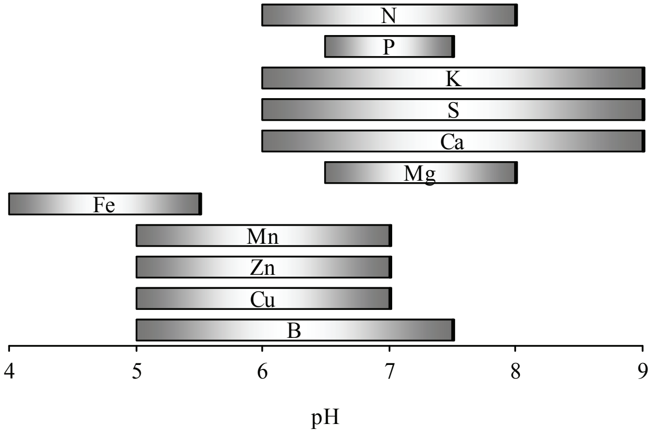

Fig. 3.1. Nutrient availability as a function of soil pH. (Bars represent pH ranges of nutrient availability to plant roots).

Orchard practices influencing nutrient availability

Fruit trees are long-lived plants, which are productive for several decades. With the exception of the year of planting young trees, orchard soils are not disturbed by ploughing or tillage as is occurs on arable land. In fruit orchards, all soil-related activities are focused on the control of the herbaceous flora growing between the tree rows. In general, there are three options for cultivating soil orchards:

- Keeping the soil bare without any grass/herbs vegetation or other coverage.
- Covering the soil with either living vegetation or with natural or artificial materials.
- Mixed systems of a) spatial variation of bare and covered areas or b) temporarily covered areas.

In practice, the choice of the appropriate system is more or less a question of water availability in the particular region. In dry climatic zones, the soil has to be kept free from any vegetation other than fruit trees in order to eliminate the competition for water and nutrients. In more humid zones, only young trees have to be carefully protected from herbal vegetation.

It is well accepted that under undisturbed grass/herbs vegetation, soils develop optimal structure, aeration and organic matter content. On the other hand, the strong competition of herbs with the tree roots for water and nutrient resources is not negligible. Tree roots are very sensitive to the biological status of the soil surface so that fine root distribution between different soil layers can vary. This was reported as long as forty years ago by Weller (1968) who found that when the soil was covered with an organic mulching material, most of the actively growing apple roots were in the very upper soil layer. In contrast, under grass vegetation, the fine roots were found at greater depths where there was less competition with the grass roots.

The most commonly used system today in fruit orchards in regions with sufficient rainfall is illustrated in Plate 3.1 (see Appendix). While the strips between the tree rows are permanently covered by grass/herbs vegetation, the soil in the tree rows is kept open at least during spring and summer to ensure adequate development of the trees.

Annual plants are much more effective than trees in absorbing nutrients, including those which have been applied as fertilizers. Many studies have shown that the mineralized N content (N_{min}) in 0 to 30 cm soil layers under grass or organic mulching materials is up to 20 times lower than in bare soil. In summer, the N_{min} value under vegetation or organic mulching is in the range of 20 to 30 kg ha^{-1} N, whereas in bare soil it can be 100 to 200 kg ha^{-1} N. Thus the covering of soils is a very important factor in the calculation of nutrient rates of application, especially for N. On the other hand, grass and herbs prevent nutrient depletion by translocation into deeper soil layers.

3.2. Function in the tree

There are numerous publications on the function of mineral nutrients in fruit trees, which deal mainly with growth and physiological aspects. Today, mineral nutrition has to be considered more in relation to aspects of fruit quality rather than to yield. Fruits are regarded as healthy food and thus fertilization of fruit trees is not only a means of increasing productivity of the plant, but also of promoting the formation of valuable components within the fruit.

Nitrogen (N) is the driving force for vegetative and generative development of the tree. Besides its promoting effects on shoot growth, N is absolutely necessary for flower bud formation, fruit set and fruit development. N-deficient trees do not produce a sufficient number of fruits and the individual fruits are small and poorly developed. Low quality fruits can also be the result of excess N, resulting in a great number of small fruits per tree, and in delayed fruit ripening. The influence of N on fruit properties, which are related to human health, is ambiguous. On the one hand N promotes the development of the ripening fruit, but, on the other hand, the formation of some vitamins, color pigments (carotenoids and anthocyanins) and aroma compounds can be suppressed by excess of N and the optimum sugar-acid ratio can be impaired. N is known to favor the production of N-containing compounds, which may cause off-flavours in stored fruits. Fruit firmness and shelf life may be reduced as a consequence of excess N supply (Bramlage *et al.*, 1980). Results of experiments carried out with “Gala” apple trees indicate that raising N supply reduces fruit quality, primarily fruit firmness (Neilsen *et al.*, 2000). Excessive N may also lead to nutrient imbalances within the fruit such as the Ca deficiency symptom in apple known as “bitter-pit”. Nitrate as an N source has been shown to be more effective than NH_4 or urea in maintaining a physiologically adequate level of Ca in fruits (Motosugi *et al.*, 1995). N-fertilization usually leads to a rapid uptake of N. Shortly after application, a strong increase of glutamine in the xylem occurs and the relative importance of arginine as a N-carrier drops sharply (Tromp and Ovaa, 1985). This is an indication of nitrate assimilation in the roots unlike many other plants in which the leaves act as the primary site of nitrate reduction.

The function of phosphorus (P) is mostly related to flowering and fruiting as well as to the energy metabolism of the tree. P promotes yield by increasing the number of flowers, fruit set and fruit size. P level seems to be the regulator of meristematic activity. A beneficial effect of P on fruit quality parameters such as fruit firmness and skin color has also been shown. Fruits from P-deficient trees contain fewer but larger cells (Taylor and Goubran, 1975). Fruits high in P are better able to tolerate pre- and post harvest diseases. The formation of vital plant P-containing compounds such as phospholipids, nucleic acids and adenosine-tri-phosphate (ATP) can be impaired when soil P availability is poor.

In terms of requirement, potassium (K) is the second most important nutrient for fruit trees. Being very mobile within the plant, K is not directly involved in the structural growth of the tree but it plays a major role in a number of physiological processes. These involve water relations of the tree, raising frost tolerance and lowering the susceptibility of plants to attack by pests and diseases as well as a wide range of biochemical processes in the developing fruit. K participates in numerous enzymatic reactions and is an important factor in the development of fruit color, TSS and vitamin C content. Recent studies have pointed out the strong correlation between leaf K and red color pigmentation of apple fruits (Daugaard and Grauslund, 1999). K is the key nutrient in osmoregulation and the maintenance of cell turgor and therefore closely related to firmness and crispness of the fruit. Fruits rich in K are more resistant to sunscald. However, too much K in relation to Ca can induce fruit disorders and the K/Ca ratio (mg K or Ca per 100 g fruit fresh weight) in apple fruit should not exceed 30 at harvest.

In contrast to K, calcium (Ca) is the typical structural nutrient element in the tree and the fruit. Calcium transport into fruits is always critical because it largely depends on the water influx driven by transpiration which is very low in fruits. By contrast, Ca is virtually sucked away from fruits by competing transpiring leaves in which it accumulates in very high amounts. Since Ca is usually almost absent in the phloem, this source provides only minute quantities for the fruit. Calcium deficiency-related disorders of fruits are thus common. Calcium forms bonds in the middle lamellae and the micro-fibrils of the fruit tissue, and is therefore crucial for fruit firmness. However, a specific K/Ca ratio and a minimum content of 5 mg Ca 100 g^{-1} FW are important for the maintenance of the fruit's structural integrity. Ca has also an important function in maintenance of cell membrane integrity: Ca deficiency causes membrane leakage and favors the onset of diseases. The appearance of physiological disorders such as bitter pit, internal breakdown and fungal fruit rot is negatively correlated to the internal Ca content of the fruit. For pear fruit, the critical Ca level is regarded higher than in apple (>10 mg Ca 100 g^{-1} FW).

The role of magnesium (Mg) for growth and development of fruit trees is often underestimated and limited to its function as the central atom of the chlorophyll molecule. However, more than 60% of Mg is located elsewhere in the cell and is involved in numerous metabolic reactions. In terms of fruit quality, Mg improves fruit size and color, increases sugar content and promotes the formation of aroma compounds and acidity. Fruit premature drop was found to be higher in Mg-deficient trees (Platon and Soare, 2002).

In the past, sulphur (S) has not been regarded as an important element in fruit tree nutrition. Today, however, there is a greater awareness of the importance of S following the significantly lowered industrial output into the atmosphere and the consequent continuing fall in S contents in soils. Sulfur is essential for protein synthesis and for the formation of aromatic compounds in the fruit. S-containing substances can either enhance the plant's tolerance to diseases or act as repellents to pests. The tripeptide glutathione plays a key role in the formation of substances which are involved in stress alleviation of both biotic and abiotic stresses (i.e. heat and cold stress).

The significance of micronutrients in fruit quality has not been evaluated in detail. However, most of the physiological processes depend on the action of iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and boron (B), which are involved in numerous enzymatic reactions. Micronutrient deficiencies appear mainly on soils with a high pH, where their availability is very low. Deficient trees develop characteristic leaf symptoms.

Iron is an abundant element in soils, mostly present in its oxidized form Fe^{3+} but to be available to the roots of most plant species including fruit trees it has to be chemically reduced to Fe^{2+}. The role of Fe in the formation of fruit quality compounds is not clear. However, the element is closely linked to CO_2-assimilation in the leaf with 80% of total Fe in plants being located in the chloroplasts. In addition to that, Fe is an activator of many biochemical processes such as regulation of oxidation/reduction pathways. The mobility of Fe in the tree is very low, as is also true of Zn, therefore young leaves and shoots show typical deficiency symptoms.

Manganese is also involved in CO_2-assimilation and respiratory pathways. The element plays a crucial role in N-assimilation and Mg uptake. Excess Mn can increase the problem of russetting in some sensitive apple cultivars. However, this effect is very much dependent on local weather conditions. Over a very narrow concentration range, Mn favors the formation of green color pigments in fruits (Deckers *et al.*, 1997).

The Cu concentration in apple leaves is usually less than 10% of the foliar Fe or Mn concentration. However this element is of crucial importance for growth related processes such as in meristematic tissues as well as in xylem development. The ban of Cu from modern pesticides has led to deficiency problems especially on soils with very high organic matter contents.

Zinc is one of the most deficient micronutrients in soils worldwide (FAO, 2004), Zn deficiency being present in many calcareous or alkaline soils. The element has been found to be essential for fruit set of trees. It has a strong influence on elongation growth. Zn-deficient trees have very short internodes resulting in rosette-like, stunted shoots known as “little leaf”. This appears to relate to the requirement of Zn for the synthesis of the growth hormone indole acetic acid (IAA).

Many studies have indicated beneficial effects of B on fruit set and yield which is in accord with physiological evidence of a high requirement of B during the reproductive phase of growth (see Mengel and Kirkby, 2001). B inhibits post harvest disorders and increases both uptake and deficiency of Ca. B deficiency in pear trees results in malformed fruits, which contain a lot of stone cells. Recent studies have pointed out the role of B in alleviating water deficiency stress in plants (Goldbach *et al.*, 2007) and in enhancing frost resistance of fruit trees. B deficiency impairs Ca transport in trees and may lead to Ca deficiency in fruits. B is the microelement which is most strongly connected to fruit quality. In apple, B deficiency can induce cracking and russetting, premature ripening, internal corking and increased fruit drop. Boron mobility within plants varies considerably between species. In most it is immobile like Ca accumulating in older leaves. In apple trees, however, it is quite mobile so that leaf analysis of the tree in contrast to other plant species can provide a good indication of B status (see Mengel and Kirkby, 2001).

In a study on the influence of mineral nutrients on apple fruit quality, Fallahi and Simons (1996) reported that quality parameters were more often correlated with leaf and fruit N, K, Ca, and Mn concentrations than with other elements. Leaf and fruit N, Ca and Mn for example were negatively correlated with fruit color, whereas fruit K was positively correlated with fruit weight, color, and soluble solids.

3.3. Requirement and uptake

The nutrient requirement of a fruit tree is determined by the tissue nutrient content, which is necessary for optimal growth, development and yield. Therefore, requirement is closely related to the defined optimum range of nutrient concentration in leaves and fruits, as presented in Table 3.1 and Fig. 3.2. However, nutrient uptake by the tree is quite variable because it is dependent on specific site conditions during the growing season and the developmental stage of the tree. As a consequence, uptake of nutrients from the soil may vary considerably from year to year and from orchard to orchard.

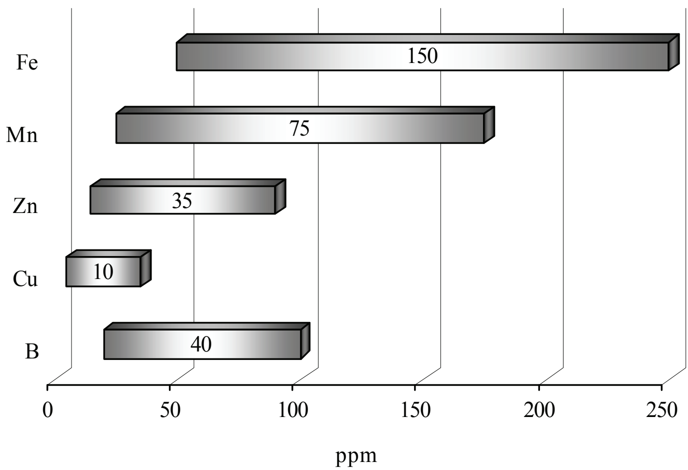

Fig. 3.2. Micronutrient concentrations in deciduous fruit tree leaves.

Table 3.1. Ranges of macronutrient concentrations in leaves of pome and stone fruit

	N	P	K	Ca	Mg
	------------------------------ *% of DM* ------------------------------				
Apple					
Min	2.00	0.12	1.00	0.70	0.20
Max	2.80	0.30	2.20	2.20	0.45
Opt	**2.40**	**0.21**	**1.50**	**1.50**	**0.32**
Pear					
Min	1.80	0.10	1.20	0.80	0.20
Max	2.80	0.30	2.00	3.00	0.60
Opt	**2.26**	**0.18**	**1.50**	**1.80**	**0.33**
Peach					
Min	2.20	0.12	1.25	1.40	0.25
Max	3.80	0.30	3.00	2.80	1.00
Opt	**3.20**	**0.21**	**2.10**	**2.10**	**0.54**
Plum					
Min	1.80	0.14	1.50	1.20	0.20
Max	3.20	0.35	3.50	3.00	0.80
Opt	**2.75**	**0.21**	**2.26**	**2.18**	**0.50**
Apricot					
Min	1.80	0.11	2.00	1.10	0.25
Max	3.20	0.35	3.50	2.50	0.80
Opt	**2.50**	**0.20**	**2.70**	**2.00**	**0.50**
Sweet cherry					
Min	2.20	0.14	1.40	1.20	0.20
Max	3.20	0.30	3.00	2.70	0.80
Opt	**2.70**	**0.22**	**1.90**	**1.90**	**0.50**
Sour cherry					
Min	1.80	0.13	1.30	1.30	0.25
Max	3.20	0.35	2.10	2.60	0.77
Opt	**2.60**	**0.24**	**1.70**	**1.90**	**0.40**

Note: S content in leaves is comparable to Mg; usually it is in the range of 0.2 to 0.4% of DM.

Source: Nagy and Holb, 2006.

A study in Poland based on the determination of mass increments of tree organs and their mineral contents has provided the following annual mineral nutrient uptake data for sour cherry trees (Table 3.2).

Table 3.2. Nutrient uptake of sour cherry trees per year (at a yield of 20 mt ha^{-1}).

Nutrient	kg/ha
N	117.6
P	5.8
K	62.5
Ca	80.2
Mg	12.1
Fe	1.699
Mn	0.575
Cu	0.068
Zn	0.188

Source: After Baghdadi *et al.*, 1998.

It will be shown later, that the uptake of nutrients by fruit trees is much higher than that removed in the export of nutrients by the fruit at harvest. The reason for this is the requirement for mineral nutrients by the vegetative parts of the trees, i.e. leaves, shoots, frame and roots.

In the following section an attempt is made to present the contents of macronutrients (N, P, K, Ca and Mg) in different parts of an apple tree. The concentrations given in the accompanying tables have been calculated from the literature and from lysimeter experiments carried out over the past 25 years in Berlin (Ohme and Luedders, 1983; Schembecker and Luedders, 1989; Dinkelberg and Luedders, 1990; Schreiner and Luedders, 1992). These lysimeter experiments have provided very precise analytical data of nutrient concentrations in tree parts from trees grown under different nutritional regimes. There is a considerable variation of nutrient concentration between different apple cultivars and between the various growing conditions. However, the data provide quantitative estimations of nutrient distribution in apple orchards (Fig. 3.3 and Fig. 3.4).

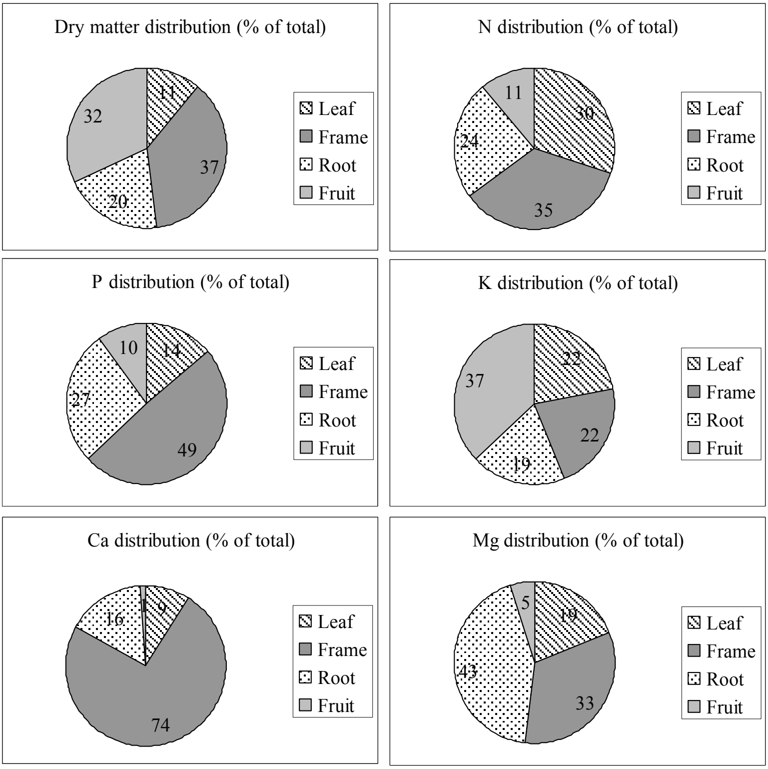

Fig. 3.3. Dry matter and nutrient element distribution in a 3-years-old "Golden Delicious" tree. *Source*: After Ohme and Luedders, 1983; Schembecker and Luedders, 1989; Dinkelber and Luedders, 1990; Schreiner and Luedders, 1992.

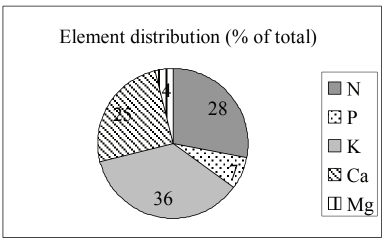

Fig. 3.4. Distribution of nutrients in a 3-years-old "Golden Delicious" tree. *Source*: After Schreiner and Luedders, 1992.

Besides plant internal and environmental factors, foliar nutrient contents also depend on orchard management practice. In apple trees for example it was found that with increasing number of trees per ha, N, Ca and Mg contents decreased, whereas K increased (Barrera-Guerra and Slowik, 1980; Table 3.3).

Table 3.3. Foliar macronutrient concentrations in apple trees as influenced by planting density.

Nutrient	Plant density		
	Low	High	Change
	------------ *% of DM* ------------		
N	2.50	2.37	-5.2%
K	1.57	1.80	+14.6%
Ca	1.25	1.21	-3.2%
Mg	0.341	0.288	-15.5%

Source: Barrera-Guerra and Slowik, 1980.

Calcium contents in apple trees vary significantly in relation to growing conditions. Calcium is low in trees growing on replanted land, after intensive N-supply, and a heavy crop load. In summer-pruned trees the Ca content of fruits is higher as compared to those pruned in winter and in fruits growing in the full sunlight.

As indicated in Fig. 3.5, foliar concentrations of specific macronutrients vary during the growing period. The Ca content for example is usually higher in the fall as compared to early summer, whereas N concentrations drop towards the end of the season. Although P concentration in leaves seems to be quite constant during the year, root P content may increase two-fold from spring to the end of the growing season, indicating an enhanced uptake by the tree. During spring and early summer, P is retranslocated from the storage organs to the new leaves and expanding fruits. In contrast to that, an intensive absorption of P from the soil takes place during the second half of the year (Yan'an and Fan Hongzu, 2007).

The concentration of specific micronutrients in leaves may vary considerably as evident in Fig. 3.2 which shows the foliar ranges in deciduous fruit trees. Within these ranges growth and yield of fruit trees are usually satisfactory but the lower end of the range leaf deficiency symptoms appear whereas too high micronutrient concentrations may result in toxicity symptoms. Micronutrient concentrations in plant tissues, however, are not always directly related to the appearance of deficiency symptoms. This is particularly the case for Fe chlorosis in fruit trees in which the chlorotic leaves can be high in Fe but of low physiological availability in the plant (Mengel 1994; Fernandez and Ebert, 2003). In the temperate climate zone, toxicity symptoms rarely appear because extremely adverse soil conditions such as sodicity or very low pH are more related to subtropical and tropical soils.

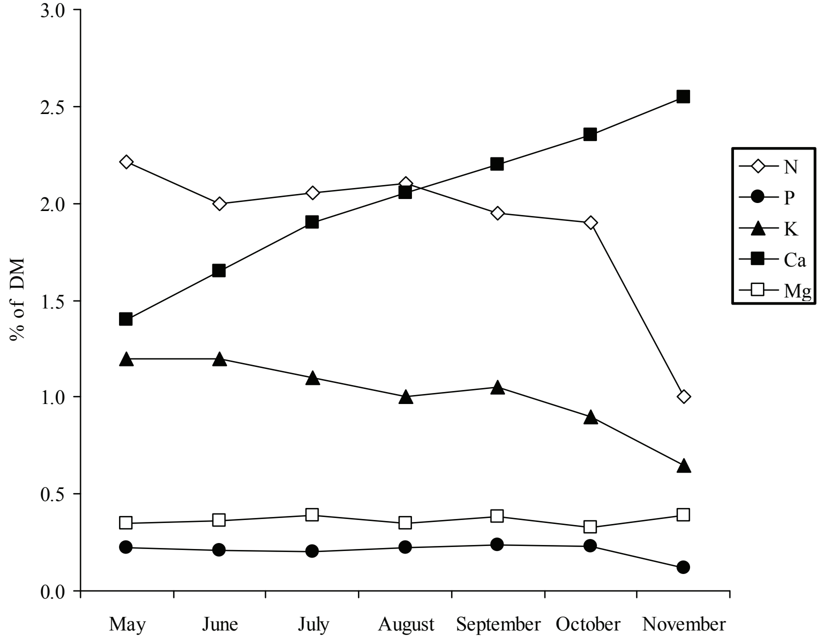

Fig. 3.5. Seasonal variation of mineral nurtient concentration fruit tree leaves. *Source*: After Witte, 1994.

3.4. Deficiency symptoms

Both absence and excess of a nutrient element are mirrored by characteristic symptoms of the leaf. Therefore, the occurrence of visible deficiency symptoms can be used as a simple indication of nutrient imbalances in the orchard. The leaf deficiency symptoms as described in Table 3.4 are indicative of progressive and severe deficiency which should be avoided by a suitable fertilization practice. Color photographs of foliar nutrient deficiency symptoms in fruit trees are presented in Plates 3.2-3.10 (see Appendix).

Table 3.4. Mineral deficiency symptoms in fruit trees.

N	Leaves are light-green to yellow (chlorosis), sometimes with red margins. Early leaf drop, retarded growth of the tree. Small and firm fruits.
P	Small, but dark-green leaves, sometimes with red margins, growth of the tree is retarded, resembling a “shade plant”. Delayed bud burst. Poor flowering and fruiting.
K	Older leaves with chlorotic margins, later turning necrotic, beginning from the leaf tip. Leaves sometimes curled. Weak branches, poor quality of fruits, shorter post-harvest life.
Ca	Leaf symptoms are very rare in most orchards. Young leaves turn chlorotic, midrips lighter in color, leaf drop, dieback of branches. Physiological disorders of fruits (bitter pit).
Mg	Mature leaves become chlorotic, starting from areas in the region of the midrib (interveinal chlorosis), then progressing later from the centre to the leaf margins. Leaves are sometimes curled.
S	Similar to N-deficiency, chlorotic, pale-green leaves. In contrast to N-deficiency, young leaves are more affected.
Fe	Young leaves become yellow, but their veins remain green. Leaves may loose all pigments and turn white, later necrotic.
Mn	Similar to Fe-deficiency, but veins have a green seam, chlorotic interveinal areas turn pale-green to yellow, sometimes necrotic spots.
Cu	Young leaves turn yellow or pale, necrotic leaf tips and margins. Dieback of young shoots, small sized fruits. Often associated with Zn deficiency.
Zn	Similar to Fe-deficiency, leaves are small; twigs are stunted and rosette-like. Poor flowering and fruiting.
B	Leaf chlorosis or yellow spots, smaller leaves with a hard leaf texture. Stems and leaves distorted. Malformed fruits with stone cells (often in pear fruits).

3.5. Removal by harvest (fruits)

The removal of nutrients by fruits is usually much lower as compared to nutrient exports by field crops (e.g. cereals, tuber crops), because the nutrient element concentration in fruits is relatively low. For example, 10 mt ha^{-1} apple fruit contain only 20 kg N, whereas 10 mt ha^{-1} of wheat represent 100 kg N. Nitrogen recommendations for fruit trees are higher than the amount present in the fruit because N and other nutrients are also incorporated into leaves, stem and roots. It has also to be taken into account that minerals stored in leaves and roots are not exported from the orchard but are mineralized in the soil to become available to the tree during the following years. On the other hand, however, some nutrients are lost from the system in pruned branches that are usually collected and removed from the orchard.

Potassium is by far the most abundant nutrient element in fruits and is exported from the orchards with the harvested fruit in considerable amounts (Table 3.5). Assuming a K content of 0.8% (based on fruit dry matter), one ton of fresh fruits remove about 1.2 kg K.

The removal of micronutrient elements by fruit is in the range a few grams to several kilograms per hectare.

Table 3.5. Nutrient content of apple fruits and calculated removal of nutrients by fruits.

Nutrient	% of DM	% of FW	Removal per mt fresh fruit (kg)
N	0.35	0.05	0.5
P	0.06	0.01	0.1
K	0.8	0.12	1.2
Ca	0.04	0.006	0.06
Mg	0.03	0.005	0.05

Table 3.6 presents a general estimation of nutrient removal by apple trees in relation to different yield levels. Nutrient uptake of young fruit trees (first and second year after planting) was assessed in detail by Dierend (2006). He found that pome and stone fruit trees took up 8/19 kg N ha^{-1} during the first/second year after planting, 2/3 kg P, 6/9 kg K, 1/3 kg Mg and 9/26 kg Ca.

Table 3.6. Macronutrient removal by apple trees at different yield levels.

Nutrient	yield level (mt ha^{-1})			
	20	40	60	80
	---------------------------	*kg*	---------------------------	
N	12	24	36	48
P	2	4	6	8
K	40	80	120	160
Ca	1.2	2.4	3.6	4.8
Mg	1	2	3	4

Source: After Dierend, 2006.

3.6. Stress alleviation

Stress is defined as a deviation from normal living conditions which affects growth and metabolism. Stress can be either of abiotic (heat, cold, drought) or of biotic in origin (pests and diseases).

The role of plant nutrition in relation to stress alleviation is a matter of balanced fertilization. Both nutrient deficiency and excess can induce stress conditions for the tree. Adequately fertilized trees have a greater resistance to any kind of stress. Nutrients have distinct functions in the physiological stress response of trees, because they are involved in the formation of certain substances which alleviate stress (i.e. oxidative stress) or directly repulse invading organisms.

3.6.1. Heat, cold, pest and diseases

Imbalanced fertilization, i.e. excess of N, can lead to a lowering in frost tolerance during winter because of the retarded maturation of wood and buds, which are softer, contain more water and are thus also more vulnerable. Susceptibility to pests and diseases may be increased by the same means, or in the case of plant diseases, by the effect of excess N inhibiting the production of defense responses to pathogens (Huber, 1980).

There is evidence for the significance of K in stress alleviation. First of all drought and frost tolerance can be improved by additional K supply. Fruit trees with optimal foliar K contents are better able to withstand periods of water shortage, because K maintains cell turgor. Potassium is involved in frost tolerance by depressing the freezing point of the cell sap.

However, many post-harvest fruit disorders are related to a lack of Ca or to an imbalanced K/Ca ratio, especially when the fruits are kept under suboptimal storage conditions (Osterloh *et al.*, 1996).

Magnesium is beneficial in increasing resistance to Al-toxicity in a number of plant species growing in water culture (Keltjens and Tan, 1993). The same has been found in woody species such as tea, and is probably also true for fruit trees growing in field conditions.

Sulphur plays a significant role in defense strategies of plants against insect attacks or diseases. After fungal attack plants produce so-called “phytoalexins”, which have a repellent or toxic effect on invading microorganisms; they may also induce autolytic die-off of the affected leaf tissue in order to prevent the invader to progress into other leaf areas. The induction of phytoalexins is promoted by S-containing compounds, so-called S-Induced-Tolerance SIR (Bloem *et al.*, 2007).

Micronutrients activate many plant enzymes. In relation to stress alleviation Mn, Cu and Zn are directly involved in the defense strategy of plants against all kinds of oxidative stress. Oxygen radicals which occur in all living organisms are very reactive and are known to destroy cell membranes and enzyme systems. These micronutrients, in the form of specific enzymes, superoxide dismutases (SODS), act as “radical scavengers”, which are able to eliminate oxygen radicals before they damage the tissue. The interaction of nutrients and plants diseases has been summarized by Datnoff *et al.* (2007). However, knowledge of their nutritional effects in fruit trees on pests and diseases is still marginal.

Latest research results indicate that B plays a major role in water stress (drought) regulation in plants (Goldbach *et al.*, 2001).

3.6.2. Salinity

Soil salinity is a rising problem in many areas of Mediterranean countries as well as of the subtropics and tropics. It is often associated with drip irrigation systems. Sodium chloride (NaCl) is the dominant salt involved in the problem.

Compared to other crop species, fruit trees are very salt sensitive. For example, sugar beets tolerate 300 mM NaCl in the soil solution, but apple trees die when irrigated with water containing only 10% of this concentration. Fruit trees readily develop chlorotic and necrotic leaf margins when exposed to salts. Typical symptoms are shown mostly in older leaves whereas young leaves remain green (see Appendix, Plate 3.11). The presence of competitive ions such as K^+ or Ca^{2+} for Na^+ and SO_4^{2-} or NO_3^- for Cl^- are able to alleviate the toxic action of the salts. Container experiments with apple trees have shown that increasing NO_3 supply reduced foliar Cl content and consequently moderated Cl-induced damage (El-Siddig and Lüdders, 1995).

4. Management of Nutrient Supply

4.1. Soil tests

Fertilization of fruit trees should always be based on the content and availability of nutrients in the orchard soil. Knowledge about the nutrient reserves can prevent the producer from under- or over-estimation of the tree's demand and should always be related to other influencing factors such as climatic conditions, physiological tree parameters and the expected yield level. To assess the nutrient levels in the soil, representative soil samples have to be analysed using expensive laboratory equipment. Thus, the farmer himself often does the sampling, but chemical analysis is carried out in specialized laboratories.

Standardised analytical procedures have been developed for the assessment of macro- and micronutrients. The results quantify the pool of nutrients in the soil which is available for plant roots. For both K and P, the available fraction is much lower than the respective total contents of the nutrient elements in the soil.

To assess the levels of available plant nutrients in the soil, a standard classification scheme is useful, indicating ranges of nutrient concentrations relating to soil type (i.e sandy, clay, calcareous soils etc.).

N_{min}-method

This method allows the mineralized fraction of the soil to be assessed, thereby indicating the current amount of N which is available for the tree. Usually, shortly before flowering, soil samples are taken from depths of 0 to 30 and from 30 to 60 cm within the tree row. N_{min} values which include extracted nitrate and some ammonium N can vary markedly due to specific site conditions and microclimatic factors. However, this method provides valuable data in estimating the appropriate N application. The requirement of fruit trees for vegetative growth and fruit yield has to take into account both the current status of available N and the potentially available N from the soil reserves, in order to obtain maximum quality fruit and to avoid N-losses by nitrate leaching into the ground water or by denitrification.

Available P, K, Ca and Mg are analysed from mixed soil samples using different extraction methods (e.g. water, $CaCl_2$, electro-ultrafiltration [EUF]), which simulate the activity of the tree root in nutrient removal from the soil. A standard soil analysis thus comprises P, K, Ca and Mg as well as micronutrients organic matter, pH and soil type. For a meaningful interpretation of the soil data classification schemes are used which are regional as well as crop specific and dependent on soil type. In Germany for example orchard soils are divided into 5 classes according to their available nutrient contents (Table 4.1). Similar schemes are used elsewhere throughout the world where horticultural tree crops are grown. It has to be borne in mind, however, that such schemes can only provide a qualitative "rule of thumb" guide to fertilizer recommendation as is evident from a lack of quantitative data in the "Fertilizer recommendation" column in Table 4.1. This is because other factors than soil nutrient availability determine the nutrient requirements of the tree (see section 4.3).

Table 4.1. Classification of soil according to available nutrient contents and fertilization recommendation using the VDLUFA[(1)] scheme.

Soil class	Nutrient content	P_2O_5	K_2O[(2)]	Fertilization recommendation
		---- mg 100 g^{-1} dry soil ----		
A	Very low	<3.5	<8	Very high
B	Low	3.5-7.4	8-16	Higher than C
C	Optimum	7.4-14	16-24	Equal to that removed by fruits
D	High	14-20	24-32	Less than C
E	Very high	>20	>32	None

[(1)]Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten

[(2)]For loamy soils

Source: After Kerschberger *et al.*, 1997.

4.2. Plant analysis

Soil nutrient analysis does not always provide sufficient information about nutrient availability to trees. Therefore additional plant analysis is recommended in order to assess the uptake of nutrients from the soil.

4.2.1. Leaves

Standard methods for the determination of foliar N have been described by several authors (Aichner and Stimpfl, 2001; Deckers *et al.*, 2001). It is common practice to collect leaf samples for so-called “late analysis” in July/August. At this time, the N concentration in apple leaves is very stable as the leaves have reached their final size and maximum photosynthetic activity. Usually four leaves from the middle position of one-year-old long shoots are sampled from 20 representative trees per orchard.

The main disadvantage of this late analysis is that there is no time left to take corrective measures during the same crop year. However, this standard method is a useful tool for the assessment of the following year’s N application and to prevent the tree from becoming N-deficient.

In addition to late foliar N analysis, early sampling of leaves shortly after blossom or buds collected in March may give useful estimations of the N reserves in spring. It must be remembered, however, that in the spring season leaf N content fluctuates much more than in late summer.

A quick analysis for N as provided by the optical estimation of leaf chlorophyll content using a portable meter is a promising tool to improve N-assessment in the orchard (Tagliavini *et al.*, 1995; see Appendix, Plate 4.1).

4.2.2. Fruits

Analysis, especially of Ca, can be useful to assess the fruit’s suitability for long-term storage. For “late” analysis, fruit samples should be taken two to three weeks prior to harvest. Similarly to leaf analysis, late sampling does not enable the farmer to carry out necessary corrections before harvest. Earlier sampling of fruits, i.e. in June or July, however, can provide valuable information about the potential Ca requirement of the developing fruit. It should not be forgotten that correlations between leaf and fruit nutrient element contents are usually very low.

4.3. Recommendations

The optimal amount of nutrient or fertilizer to be applied to a particular fruit tree species is highly variable and related to an array of plant- and site-specific factors as well as to soil and plant analysis. Recommendations for fertilizing pome or stone fruit trees are dependent on:

- Tree species and cultivar
- Fruit load and expected yield
- Planting system and soil management

- Soil conditions and nutrient status
- Regional climatic conditions

For example peach trees require twice as much nitrogen as sweet cherry trees because of difference in flowering behavior. Flowers develop on long shoots in peach but on short shoots in cherry; since nitrogen stimulates shoot growth, it is therefore beneficial to peach but not to cherry. Significant variation in N-demand also occurs between cultivars because of differences in levels of fruit yield. Low yielding "Cox's Orange" apple trees for example require less N than "Gloster" or other heavy bearers.

Large high density plantations in their first year of establishment, because of their higher nutrient demand per unit area in comparison to smaller low density orchards, require greater care in the maintenance of adequate nutrient supply. Trees in high-density orchards are also more susceptible to nutrient deficiencies including micronutrient deficiencies because their small and shallow root systems do not allow the exploitation of nutrient reserves in deeper soil layers.

Light sandy soil which contains low cation levels of K and Mg are also prone to leaching and nutrient concentrations can fall rapidly to very low levels. As a consequence, K and Mg deficiency are particularly found on light soils with a low buffer capacity.

Efficient fertilizer management always accounts for the existing nutrient reserves in the soil. The fertilizer rate for a particular nutrient is a function of the nutrient concentration in the soil solution measured by chemical soil analysis.

The regional climate controls factors such as precipitation and course of the temperature, which govern the mineralization process of nutrients, primarily that of N. The availability of N is significantly dependent on soil temperature and humidity. In a warm and humid period, N release from the organic matter in the soil can exceed the tree's actual requirement leading to undesirable stimulation of vegetative growth.

4.4. Application

4.4.1. Types of fertilizers

A huge variety of fertilizers is in use for the nutrition of fruit trees (Table 4.2). According to the crop management system and site conditions, solid (granular or crystalline) or liquid fertilizers are applied as straight (a single type of nutrient) or as complex NPK products. Today, the use of micronutrient fertilizers is very common in fruit production.

According to origin, nutrient sources can be classified as:

- Mineral fertilizers
- Organic fertilizers (composts and farmyard manure, residues from processing of organic materials)
- Soil amendments and products with low nutrient contents (e.g. lime, rock flour)

N can be applied as NO_3, NH_4 or other forms like amides in urea. Nitrate is immediately available to plant roots, however due to its high mobility in the soil it is also subject to leaching after rainfall or irrigation. Under anaerobic soil conditions it can also be lost to the atmosphere by denitrification in the form of oxides of N. NH_4 –N can be taken up directly by tree roots but it is also converted in the soil into NO_3, by nitrification. The mobility of NH_4 in the soil is low, so that it is not readily leached. However, N-losses via gaseous NH_3 (ammonia) emissions are possible particularly in high pH soils. Urea-N applied to the soil has to be converted into NO_3 or NH_4 before it becomes available to the tree. Thus NO_3 fertilizers are fast-acting, while NH_4 or amides are slower.

Table 4.2. Properties of mineral fertilizers used in fruit production.

Main nutrient	Fertilizer	Chemical composition	Nutrient content $N\text{-}P_2O_5\text{-}K_2O$ (%)	Properties
N	Urea	$(NH_2)_2CO$	46-0-0	Acidic
	Calcium nitrate	$Ca(NO_3)_2$	16-0-0 19% Ca	Basic
	Calcium ammonium nitrate (CAN)	NH_4NO_3 + $CaCO_3$	(21-27)-0-0 10% Ca	Basic
	Ammonium nitrate (AN)	NH_4NO_3	34	Acidic Quick acting
	Ammonium sulfate (AS)	$(NH_4)_2SO_4$	21-0-0 24% S	Acidifying
	Urea ammonium nitrate solution (UAN)	$(NH_2)_2CO$ + NH_4NO_3	(28-32)-0-0	Slightly acidifying effect in the soil

P	Monoammonium-Phosphate (MAP)	$NH_4H_2PO_4$	11-50-0	Acidic
	Diammonium-Phosphate (DAP)	$(NH_4)_2HPO_4$	18-46-0	Acidic
	Phosphoric acid	H_3PO_4	0-61-0	Acidic Quick acting
	Single Super-phosphate (SSP)	$Ca(H_2PO_4)_2 \cdot H_2O \cdot CaSO_4 \cdot 2H_2O$	0-(18-20)-0 20% Ca	Neutral Quick acting
	Triple Super-phosphate (TSP)	$Ca(H_2PO_4)_2$	0-(44-52)-0 14% Ca	Neutral
K	Muriate of Potash (MOP)	KCl	0-0-60	Neutral
	Sulfate of Potash (SOP)	K_2SO_4	0-0-(50-52) 18% S	Neutral No Cl
	Nitrate of Potash (NOP)	KNO_3	13-0-44	Basic Quick reacting
	Monopotassium Phosphate (MKP)	KH_2PO_4	0-52-34	Acidic
Ca	Gypsum	$CaSO_4 \cdot 2H_2O$	18% S	Not soluble
	Lime	$CaCO_3$ $Ca(OH)_2$	50-65% Ca	Hardly soluble Slow acting
Mg	Epsom salt	$MgSO_4 \cdot 7H_2O$	16% MgO, 13% S	Water soluble
	Kieserite	$MgSO_4 \cdot H_2O$	25% MgO, 20% S	Water soluble
	Dolomitic limestone	$MgCO_3$ $CaCO_3$	5-20% MgO 14-32% Ca	Slow acting
S	Elemental sulphur	S	100% S	Strongly acidifying
	Sulfate types of other nutritional elements	$(NH_4)_2SO_4$ K_2SO_4 $MgSO_4$	24% S 18% S 13-20% S	Acidifying ($(NH_4)_2SO_4$)

4.4.2. Timing and rates

The timing and rates of application of nutrients in modern orchard systems are important prerequisites for high yielding and quality of fruit trees. Deciduous fruit trees undergo a long rest period during winter followed by a rapid development of new leaves, flowers and shoots in spring. The tree's demand for water during the growing period is a function of leaf area, fruit load and environmental conditions with saturation deficit as the dominant factor.

In spring, flowers and leaves develop with virtually no nutrient supply from the roots, this spring flush being more or less completely dependent on nutrients stored in buds and wood. Dependence on this storage for early growth and development in trees explains the importance of an adequate supply of nutrients before the winter rest. For N nutrition there is a fine balance between supplying either too much or too little N. Supplying N at the end of the growing season results in prolonged shoot growth and a lowering in frost hardiness. On the other hand, some researchers and extensionists recommend late N application to fruit trees until October (in the Northern Hemisphere) in order to replenish the tree's N reserves. These workers argue that a high level of N reserves in the tree favors the development of flowers and shoots following the next year's bud break. Certainly at the beginning of the growing period, the tree is solely dependent on its internal carbohydrate and mineral reserves because at this stage the leaves are only developing and not yet fully photosynthetically active and the roots are unable to absorb enough water and nutrients.

Bearing in mind that N is a strong promoter of vegetative growth, this nutrient should be available for the tree throughout the entire growing season. However, N favors shoot growth but inhibits flower induction in summer, which leads to alternate bearing. Small split applications of N are therefore more favorable to fruit trees than only a single application per year. Slow release N-sources such as organic manure or coated mineral fertilizers are a suitable alternative to fast acting N-fertilizers based on NO_3.

In comparison with N and K, P is required by the tree in relatively small amounts. Like Ca, but to a lesser extent, P accumulates in the frame wood of the tree mainly as phytate, showing its importance for structural processes. Under normal soil conditions, a single application per year (or over even longer periods) is sufficient for fruit trees.

The function of K is strongly related to the water status of the tree. Besides that, K is the dominant nutrient in the fruit. The relatively high mobility of K in sandy soils requires the need to ensure a continuous supply to the tree throughout the season on these soils. In clay soils, a single application during winter is sufficient. However, split doses during the growing period have been shown to be more effective. The same is true for Mg, being very mobile in light soils and easily leached from the root zone.

Potassium is antagonistic to Ca, competing for binding sites of the clay minerals in the soil as well as in the apoplast of the tree root and in cellular membranes. Towards the end of the season, the K/Ca ratio has to be maintained at an optimum range in relation to fruit quality (i.e. firmness, freedom from bitter pit).

Micronutrients (for example B) have to be applied early enough to the soil to reach the target organs (flower buds) or applied with foliar sprays. Micronutrient supply should be based on the appearance of deficiency symptoms and on foliar analysis. In the past, trace elements like Cu and Mn were supplied inadvertently in sufficient amounts via fungicides or mineral NPK-fertilizers. Today, however, pesticides are more or less free from metal ions and based on organic substances and most of the current fertilizers have very low trace element contents (except those, which are "pure" by nature of their production from natural salt sources).

Fruits and vegetative parts of the tree compete for Ca provided by the root system. Therefore, summer pruning can improve the Ca content in fruits, preventing them from post-harvest disorders (Tomala, 1997).

In conclusion, timing of nutrient supply is dependent on the developmental stage of the tree as well as on orchard factors such as soil type, water availability and microclimate. In this context, fertigation has an advantage over spreading of solid fertilizers, because nutrients can be applied in very small amounts and exactly at the time they are needed. Foliar sprays are by far the fastest method of nutrient application in order to correct deficiencies. Both methods are discussed in the following sections of this chapter.

4.4.3. Fertigation

Modern fertigation systems enable the farmer to tailor nutrient supply to trees to their varying nutrient demand throughout the season. This is of great importance for N supply, but as well as that also for P, K, Ca and Mg which can easily be supplied via the irrigation system. Fertilizers used for drip irrigation systems must be highly soluble in water, since residues in the solution may block the pipes and emitters.

The term "fertigation" is a composite word derived from "fertilization" and "irrigation" and means the application of fertilizers through irrigation water

(Hagin and Lowengart-Aycicegi, 1999). In fruit production, fertigation usually refers to drip or microsprinkler irrigation of trees including an injection system for liquid fertilizers. However, *strictu sensu* any type of irrigation combined with nutrient application can be regarded as “fertigation”.

Modern high density plantations with small-sized trees with shallow root systems have needed to be equipped with suitable irrigation systems. The installation of an injector for nutrient stock solutions into the irrigation water stream is a relatively small financial investment, but it may be highly efficient. Drip irrigation systems provide 2 to 10 L ha^{-1} discharge rate per dripper, while microsprinklers are in the range of 15 to 150 L ha^{-1} per emitter. Nutrient requirements of fruit trees in high density plantation are measured in terms of g per tree per year. For N, the amount applied during the growing period is in the range of 10 to 20 g $tree^{-1}$ yr^{-1}. An estimation of the various nutrient doses for apple trees is given in Table 4.3.

Low nutrient doses given in several split applications over the season, usually starting from blossom until early fruit growth, have been proved to be more effective than a single application alone. Following a recommendation of Scholz and Helm (2001), N should be applied to apple trees in doses of 12 to 15 g $tree^{-1}$ in the year of planting, then 15 to 17 g $tree^{-1}$ in the second year, and a maximum of 50 kg ha^{-1} from the third year on.

One of the main disadvantages of modern fertigation systems is that they can not be used for the prevention of frost damage. High-pressure overhead sprinklers provided a very effective tool for keeping the frost-sensitive flowers alive during periods of spring frost. In modern orchards, however, overhead sprinklers are no longer used because of their excessive water discharge rate (25 to 30 m^3 h^{-1} ha^{-1}) and the relatively high input required for their maintenance.

Table 4.3. Nutrient application rates for mature apple trees via fertigation.

Nutrient	Rate (g $tree^{-1}$ yr^{-1})
N	20-40
P	10-20
K	30-50
Ca	Usually sufficient amounts dissolved in the irrigation water
Mg	10-20
S	10-20

The use of complete fertilizer solutions is the most convenient way of applying nutrients via the fertigation system. However, multi-nutrient solutions or solid mixtures are much more expensive than the purchase of single salt components and to mix one's own cocktail on the farm. This cheaper option requires more technical input from the farmer, who has to consider - amongst other things - the miscibility of the different salt types. Some salts show strong chemical interactions, so they may precipitate and block the irrigation lines, which can lead to time and cost intensive repair work.

The application of fertilizers through the irrigation system enables the grower to optimize timing and dosage of nutrient supply. By that, nutrient losses due to leaching, fixation or gaseous losses (N) can be minimized. Today, tailored fertigation schemes for deciduous fruit species are provided by extension services, which take into account specific orchard conditions such as tree age, developmental stage, fruit load, soil moisture and microclimate.

Different physical principles are in use for the controlled addition of fertilizers into the irrigation water flow: a) Simple hydraulic systems based on the Venturi effect or the water flow, and b) more precise (electronic) injector pumps with the final nutrient concentration in the irrigation pipes being checked using EC sensors (Electrical Conductivity).

4.4.4. Foliar Fertilization

Nutrient ions present in the soil solution and taken up by roots are the main source of mineral nutrients for fruit trees. Despite this, when treated with nutrient containing solutions, leaves, shoots and even flowers are also able directly to absorb significant amounts of mineral nutrients. Under certain circumstances, foliar supply of mineral nutrients can be a useful and even preferential means fertilizing trees.

Foliar fertilization as an additional supply of plant nutrients to that obtained via the soil should be considered under the following conditions:

- Adverse soil conditions (drought, salinity, sodicity)
- Lack of macronutrients or micronutrient by immobilization in the soil
- A need for rapid correction of temporary insufficiencies
- Positive side effects (thinning for fruit set with N-salts) or co-application of pesticides

Comparing the anatomical differences of roots and leaves, it is obvious that leaves are designed for gaseous exchange with the atmosphere whereas in the roots the liquid phase plays a more dominant role in relation to the soil solution. In contrast to the outer surface of the root, the leaf surface is covered with a cuticle which prevents water loss from the tissue. The uptake of CO_2 and the simultaneous transpiration of water occur mainly through specialised pores on the leaf epidermis, the so-called stomata. These pores also play a significant role in the absorption of liquids and dissolved solids into the leaf. The uptake mechanism of nutrients through the leaf cuticle is still less understood than the uptake by roots. However, recent research indicates that the nutrient uptake through the lower leaf side - the predominant site of the stomata is - is higher than nutrient absorption via the upper side (Eichert and Burkhardt, 2001).

On the leaf surface, hairs and wax crystals form a micro relief, on which water or other solutions form individual droplets rather than a continuous water film (Barthlott and Neinhuis, 1997). This kind of a non-wettable leaf is typical of most fruit tree species. The size of the droplets and their contact area with the leaf surface depends on the structure of the cuticle, as well as on the physical properties of the solution. The addition of surfactants or wetting agents lowers the surface tension of a solution so that it forms a thin film on a leaf (see Appendix, Plates 4.2). The uptake of mineral nutrients in the form of ions or uncharged molecules from such a layer is much more efficient than from individual drops, because of the larger contact area between the solution and the leaf surface.

Surfactants are ionic or non-ionic organic molecules. Due to their chemical characteristics, they may influence the absorption of mineral nutrients into the leaf tissue by the formation of complex species. Mineral nutrients in ionic form (e.g. K^+), organic complexes (e.g. Fe-EDTA) or molecules (e.g. urea) applied with spray solutions have to traverse several layers of the leaf surface before entering the cell to become physiologically active. After passing through the water-repellent wax layer, the water-soaked cell wall and the ion selective cell membranes, the nutrient ions enter the living cytoplasm and are then regarded as "absorbed" (Fernandez and Ebert, 2003; Fig. 4.1).

The effectiveness of this uptake process depends on a variety of factors:

- The concentration gradient from the solution to the leaf structures
- The physical nature of the applied ion and the composition of the spray solution
- The leaf structure
- Environmental factors (temperature, light and humidity)

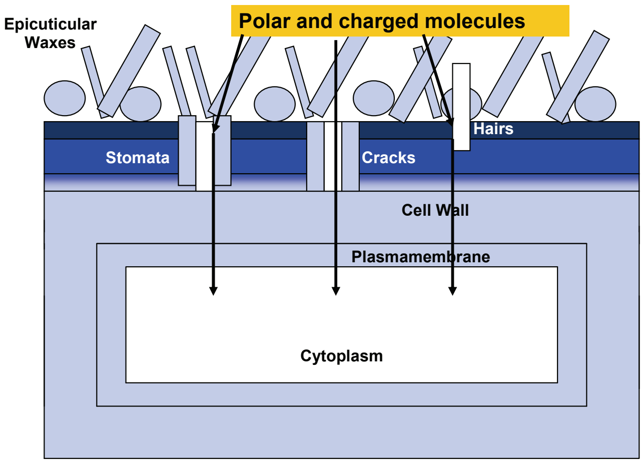

Fig. 4.1. The passage of polar elements from a spray solution into the leaf cell. *Source*: After Fernandez and Ebert, 2003.

It has been known for more than 150 years that foliar sprays can increase leaf nutrient concentrations to alleviate nutrient deficiency symptoms. Although significant amounts of the macronutrient elements (N, P, K, Ca and Mg) can be supplied to fruit trees via the leaf, foliar sprays are mainly used for supplying micronutrient elements such as Fe, Cu, Zn, Mn or B. Some fertilizers used as foliar sprays are listed in Table 4.4.

Spray solutions containing micronutrients in ionic form should not be concentrated higher than 0.5%, because this may result in toxic ion effects. If the salt index of a substance is low, such as in SOP or MKP, foliar sprays can be applied up to a concentration of 5% without causing leaf burn.

Foliar Ca-containing sprays have been shown to be very effective in preventing apple fruits from bitter-pit symptoms. Boron sprays also increase the Ca translocation into the growing fruit.

Foliar B-sprays effectively increase both flower cluster and the B-content of apple trees when applied at the flowering stage, regardless of the form in which B is applied (boric acid or Na-polyborate). Effects in increasing the leaf and fruit B content correspond to the rate of B applied (Peryea, 2005). Physiological effects of foliar B application on fruit characteristics can only be expected, however, when B availability in the soil is low. In this case, B applications are recommended in order to maintain adequate B status of the entire tree.

Table 4.4. Foliar fertilization in pome fruit trees at different developmental stages.

Stage	Compound	Main Effect
Swelling of buds	KNO_3	Improvement of frost hardiness
Green to red buds	Urea Zn B	Improvement of flower and leaf quality
Fruit set	Urea KNO_3 Mg Mn Zn	Extension of fertile flower period; enhancement of pollen tube growth; fruit set; leaf and fruit quality
Early fruit growth (June)	Urea Mg Zn B	Fruit set; leaf and fruit quality
End of June	K Ca	Improvement of fruit colour and size
July to September	$Ca(NO_3)_2$ Mn B	Prevention of bitter pit and tissue browning
July (cherries)	Urea Zn B	Improvement of fruit set for the next year
Post harvest	Urea MAP Zn B	Maintenance of leaf quality
Leaf drop (apples)	Urea (25 kg)	Promotion of leaf abscission to prevent from scab and canker

Applying foliar Ca sprays to apple trees resulted in higher fruit yield and a greater number of large fruits. Additionally there was less russetting, and less bitter pit in the fruits which showed improved fruit firmness and a higher sugar content. Mg-containing foliar sprays reduced physiological leaf fall (Bremer *et al.*, 1986).

Nitrogen is usually applied in the form of urea, $Ca(NO_3)_2$ or as KNO_3 in amounts varying from 1.5 to 5 kg N ha^{-1}. Only at leaf drop in autumn, can apple trees be supplied with higher amounts of N such as 25 kg KNO_3 ha^{-1} in order to accelerate leaf abscission and to establish an adequate N-reserve for the following year's growth. This late N-application also has a beneficial effect in the prevention of diseases like scab and canker. Urea is absorbed faster by leaves than ammonium or nitrate, because it is an uncharged molecule. If at all, P is sprayed as MAP or MKP. Potassium supplied as KNO_3, K_2SO_4 or KH_2PO_4 plays an important role in relation to fruit quality factors such as fruit size and coloration. Because of its low salt index (42.6), K_2SO_4 can be concentrated up to 5% without causing leaf burn. KH_2PO_4 (monopotassium phosphate, MKP 0-52-34) provides both high amounts of P and K, is highly water soluble and has a very low salt index of 8.4. Using K in foliar fertilization results in competition with Ca and Mg. Ca sprays [$CaCl_2$ or $Ca(NO_3)_2$] are essential for the keeping quality of pome fruits. Since post harvest treatments of fruits are not permitted in the EC countries, pre harvest application of Ca has become a routine measure to prevent fruits from bitter pit and browning. Mg can be applied as Epsom salt or other salts such as magnesium nitrate ($Mg(NO_3)_2$). Mg sprays are very effective in inducing fast re-greening of chlorotic leaves suffering from Mg deficiency.

Assessment of optimal fertilizer use in order to reach maximum yield and quality and avoidance of harmful nutrient accumulation in soil and ground water can be improved using computer programmes (Alt and Rimmel, 1997).

Foliar ready-to-use products from specialised fertilizer companies provide safe application and high effectivity. Multi-element sprays are able to increase the nutrient concentration in peach leaves (Gezerel and Dönmez, 1986) and in other fruit species.

5. Bio-Production

Although bio production is always a matter of public discussion, its share of the total fruit production worldwide is rather small. In North America, Japan and Europe, the promotion of organic production has often featured on the political agenda. Today, we see a rising demand for organic fruit products, mainly from wealthy, urban consumers. Besides the higher price for organic fruit as compared to “conventional” fruits, the unclear and misleading meaning of the prefix “bio” is one of the major obstacles restricting development of this segment of the market. In addition to that, the rules regulating organic production vary from country to country and also between different producer organizations. The followers of bio-dynamic production based on Rudolf Steiner’s anthroposophic guidelines use different methods and inputs from those farmers who favor a more moderate “bio-organic” line.

The principle of fertilization in organic farming is the maintenance of natural soil fertility rather than the sole replacement of nutrients, which have been exported with the harvested fruit. The soil-root system itself is regarded as an “organism”, describing a structure consisting of soil particles, chemical compounds, moisture and living organisms such as small animals, lower plants and microorganisms (e.g. fungi, bacteria), all of which interact with the environment in a very complicated and fragile way. Therefore, the physical and biological properties of the soil are most important for the success of organic farming, and include:

- Slow releasing nutrient sources
- A stable clay-humus complex
- A soil structure allowing free drainage
- High microbial activity

This implies the supply of organic matter *via* compost or other natural materials, the promotion of naturally occurring “helpers” such as N_2-fixing microorganisms, mycorrhizal fungi and earthworms as well as the renunciation of fast-acting mineral fertilizers. There are also very many “organic” remedies on the market, which supposedly increase soil fertility or vitality of trees such as the addition of extracts from algae or horn meal. However, close scientific investigation of the possible influence of most of these preparations has failed to show any beneficial effect.

Manure and other farm residues are the main source of mineral nutrients in organic production (Table 5.1). Soluble mineral fertilizers are not permitted with the exceptions of non-chloridic K salts such as K-sulfate, Mg-sulfate (or the double sulfate salt of these two nutrient cations), rock phosphates and naturally occurring Ca or Ca/Mg salts (Ca/Mg-carbonates). In contrast to other certifying institutions IFOAM (International Federation of Organic Agriculture Movements) permits KCl as a source for K in organic production. N supply is only allowed in the form of residues from animals (e.g. hoof and horn meal) and from plants (e.g. from processing procedures). Permission to use fertilizers and fertilizer-like substances is regulated by the particular organization with which the producer is associated. The use of these fertilizers is regulated by a control body. In Germany for instance, a list of permitted fertilizers is provided by FiBL (Forschungsinstitut für biologischen Landbau), the so-called list of "Organic Farming Inputs" (Table 5.2).

Table 5.1. Nutrient content of different farmyard manures.

	N	P_2O_5	K_2O	CaO	MgO
Cattle manure (kg mt^{-1})	5	3.5	7	-	1.5
Dry chicken manure (kg mt^{-1})	28	26	18	43	6
Cattle slurry (kg m^{-3})	4	2	5.5	-	0.8
Pig slurry (kg m^{-3})	5.1	33	3.3	-	1

Source: Quade, 1993.

In organic production, knowledge of the nutritional status of the soil and the tree is indispensable for assessing fertilizer requirements. Soil analysis is mandatory for the use of organic as well as mineral fertilizers. For European fruit farms, the EC regulation 2092/91 presents a list of mineral fertilizers which are allowed for use in organic production. During the first years of the changeover from conventional to organic farming, trees benefit from the existing nutrient reserves in the soil. However, with time these soil nutrient reserves gradually begin to deplete, as has been shown in numerous field studies. The lower yields obtained in organic production (as compared to conventional farming) and the relatively low export of nutrients by fruits may extend this time span but eventually low nutrient concentrations in the soil become the growth-limiting factor.

To increase nutrient availability from slow-releasing organic fertilizers, the biological activity of the soil has to be kept at a high level. This is achieved by ensuring optimal soil structure and the supply of energy for microbial metabolism in the form of organic carbohydrates (e.g. compost).

Lists of organic and inorganic materials which are allowed or suitable for organic farming are provided by the organizations responsible for formulating regulations (e.g. IFOAM, European Community).

Table 5.2. Some N, P, K, Ca and Mg fertilizers used in bio production.

Main fertilizer compound	Origin	Range of nutrient content
N	Animal residues: Feathers, hair, horn, meat meal Plant residues: Coarse castor, coarse repeseed, molasses	5-14% N
	Example: Hoof/horn meal from cattle (12% N)	
P	Raw phosphate, soft rock phosphate, phosphatic limestone, marine algae	12-29% P_2O_5
	Example: Soft rock phosphate (26-29% P_2O_5)	
K	Kainite, SOP, KCl	10-60% K_2O
	Example: SOP (50% K_2O)	
Ca	$CaSO_4$, $CaCO_3$, Mg-lime, Ca-carbonate, limestone	16-53% CaO
	Example: Calcium carbonate (45-53% CaO)	
Mg	Kieserite, $MgSO_4$, Ca-Mg-carbonate	6-27% MgO
	Example: Kieserite (26% MgO)	

Source: After FiBL, 2006.

Assessing the optimum time to supply N in organic farming is not easy. To fulfil the high demand of trees for N during spring organic N-reserves of the soil have to be mineralized to inorganic N before uptake by the tree roots. This process is dependent on soil microorganisms whose activity in turn depends on soil temperature and moisture and is thus to a large extent factors outside the control of the farmer. Moreover, there is a competition for uptake of N between the tree and grass or herbs which has to be maximized in favor of the tree. This to some extent can be achieved by mulching the herbal vegetation prior to fruit tree blossom.

Fertilization of fruit trees in relation to fruit quality is a matter of discussion. In general, both fruit yield and fruit size are lower in organic production than in integrated production. For example fruit size of “bio” apples is smaller and additionally most quality attributes are far from optimum. In contrast to common belief, nutrient contents of organic apple fruits are much the same as in conventionally produced fruits. This means that nutrient uptake and transport do not differ greatly between trees subjected to conventional or organic production. There are however some differences between the two systems but these are dependent on the type of rootstock and the intensity of irrigation and fertigation.

For instance, the more vigorous rootstocks used in organic fruit farming develop strongly-growing roots which are thus able exploit nutrients from deeper soil layers as compared to dwarfing rootstocks.

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7. Appendix: Plates

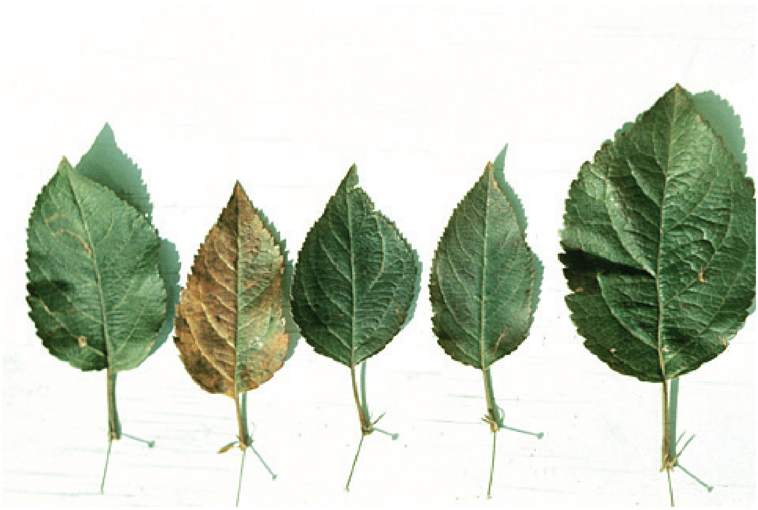
(Plates numbered according to the related chapter.)

Plate 3.1. Sweet cherry trees in a single row system in Central Germany.


(a)


(b)

Plates 3.2. Nitrogen deficiency symptoms in apple (a) and apricot leaves (b).



Plates 3.3. Phosphorus deficiency symptoms in apple leaves.

(a)

(b)

Plates 3.4. Potassium deficiency symptoms in apple (a) and sweet cherry leaves (b).

(a)

(b)

Plates 3.5. Magnesium deficiency symptoms in apple (a) and plum leaves (b).

Plate 3.6. Boron deficiency symptoms in apple leaves.

(a)

(b)

Plates 3.7. Iron deficiency symptoms in apple (a) and peach leaves (b).

(a)

(b)

Plates 3.8. Manganese deficiency symptoms in apple (a) and sweet cherry leaves (b).

Plate 3.9. Calcium deficiency symptoms in apple fruits ("bitter pit").

(a)

(b)

Plates 3.10. Boron deficiency symptoms in cherry (a) and peach fruits (b).

Plate 3.11. Salt damage symptoms in apple leaves and shoots.

Plate 4.1. A hand-held SPAD meter for rapid assessment of foliar N status.

(a)

(b)

Plates 4.2. Solution sprayed on a leaf surface (blueberry) with (a) and without (b) addition of a surfactant.