Foliar Fertilizer Application

Preliminary review

VFRC Report 2013/2

Wim Voogt, Chris Blok, Barbara Eveleens, Leo Marcelis and Prem Bindraban

Foliar Fertilizer Application

Preliminary review

Wim Voogt[1], Chris Blok[1], Barbara Eveleens[1], Leo Marcelis[1] and Prem Bindraban[2]

[1] Wageningen UR Greenhouse Horticulture, Bleiswijk, THE NETHERLANDS
Email: glastuinbouw@wur.nl

[2]Executive Director, Virtual Fertilizer Research Center, Washington, D.C. 20005, USA
Email: pbindraban@vfrc.org

VFRC Report 2013/02

Washington, D.C., USA

Executive Director
Virtual Fertilizer Research Center
1313 H Street NW
11th Floor
Washington, D.C. 20005
USA
E-mail: contact@vfrc.org

Additional information on VFRC can be accessed through http://www.vfrc.org.

Citation
Voogt, W., C. Blok, B. Eveleens, L. Marcelis and P. S. Bindraban. 2013.
Foliar fertilizer application. VFRC Report 2013/2. Virtual Fertilizer Research Center, Washington, D.C. 43 pp.; 9 tables; 2 figs.; 98 ref.

Virtual Fertilizer Research Center

Contents

List of acronyms and abbreviations v
1 Introduction 1
2 Aim 1
2.1 Approach 1
3 Results 2
3.1 Quick scan of scientific data 2
3.2 Assessment of literature 5
3.2.1 General 5
3.3 Mechanisms and physiological aspects 6
3.3.1 When to apply foliar fertilization 6
3.3.2 How to apply foliar fertilization 6
3.4 Crops 8
3.5 Common practice of foliar application 10
3.5.1 General 10
3.5.2 Crops 10
3.5.3 Comparing Literature and Common Practice 12
4 Discussion 13
5 Conclusions 24
6 Acknowledgements 26
7 References 27
Appendix I. Literature database results 33
Appendix II. List of contacts consulted for the common practice of foliar application 34
Appendix III. Summary of information from consultants 35

Table 1. Results of literature research foliar spray + nutrient* in ANY FIELD (top row) 3
Table 2. Literature search in Web of Science using terms foliar + fertiliz* in ANY FIELD 3
Table 3. A combination of two searches in databases. 1. foliar spray + nutrient* in ANY FIELD from the 3 databases, Scopus, Web of Science and CAB-Abstracts from 2010 – 2013. 4
Table 4. Interactions between crop phenology and the environment can determine the usefulness of foliar fertilization through the following processes 6
Table 5. Reasons for foliar application of macro elements (N, K, P, Ca, Mg, S) with corresponding literature reference 14
Table 6. Reasons for foliar application of micro elements (Fe, Mn, Zn, Co, Si) with corresponding literature reference 15

Table 7. Recovery of elements (N, Zn, Fe, B, Zn) after foliar application in various crops with literature reference 16
Table 8. Concentrations for foliar application of elements (N, Zn, B, N, P, K) in various crops with literature reference 17
Table 9. Framework of the reported interaction effect of Fe foliar applications, related to physical chemical factors and plant characteristics, specified per crop 22

Figure 1. The number of publications per year from the data base 5
Figure 2. Accumulation of Ca, using 45Ca to visualize, in leaves of Coreandrum sativum exposed to different transpiration, showing that xylem imported Ca in the leaf accumulates in the center 20

List of acronyms and abbreviations

B	boron
Ca	calcium
$Ca(NO_3)_2$	calcium nitrate
$CaCl_2$	calcium chloride
Cl	chloride
Cu	copper
DTPA	diethylene triamine penta acetic acid
EDDHA	ethylene diamine-N,N'-bis(2-hydroxyphenylacetic acid)
EDTA	ethylene diamine trichloro acetic acid
Fe	iron
H_2PO_4	phosphate
IDHA	N-(1,2-dicarboxyethyl)-D,L-aspartic acid
IFDC	International Fertilizer Development Center
K	potassium
K_2SO_4	potassium sulfate
KH_2PO_4	Monopotassium phosphate
KNO_3	potassium nitrate
LAI	Leaf Area Index
Mg	magnesium
$MgSO_4$	magnesium sulfate
Mn	manganese
$MnSO_4$	manganese sulfate
Mo	molybdenum
N	nitrogen
Na	sodium
Na_2MoO_4	Sodium molybdate
NH_4	ammonium nitrogen
Ni	nickel
NO_3	nitrate
NUE	Nutrient Use Efficiency
P	phosphorus
PPP	Plant Protection Products
RH	Relative Humidity
S	sulfur
SO_4	sulfate
VFRC	Virtual Fertilizer Research Center
WUE	Water Use Efficiency
Zn	zinc
$ZnSO_4$	zinc sulfate

1 Introduction

Nutrients are taken up by plant roots. Yet, several nutrients can also be taken up by leaves when deposited on the leaf surface or with foliar sprays (Marschner, 2012). Moreover, certain plants, like epiphytes such as Bromelia Tillandsia have no or hardly any roots and obtain nutrients mainly through their leaves (Benzing et al., 1976), like aquatic plants. For instance, foliar sprays are used when the soil or the plant conditions limit the availability of some nutrients. This is common practice for crops susceptible to Fe and Mn deficiency such as citrus in calcareous soils or crops grown in soil poor in delivering Zn (Marschner, 2012 ; Fernández et al., 2013). Nevertheless other nutrients, like K, N and P, can be absorbed through foliage as well. These nutrients can enter the plant within hours which could make foliar sprays a means for quick corrections for soil applied nutrients in case of any limitation in supply or uptake, or crop specific situations like the rapid supply of urea after the harvest and before leaf senescence in apple (Dong et al., 2005).

Research does not provide a clear picture of the effectiveness of foliar sprays, and this information must be studied to enable us to understand the mechanisms of foliar uptake. Conditions during application such as humidity, wind, rainfall and sunshine are known to affect uptake. Much of the research is restricted to the description of application methods and resulting uptake or yield response (Fernández et al., 2013). There is some elementary knowledge about the physiological mechanisms of nutrient uptake through leaves (or stems). Better understanding of these mechanisms would help identifying effective nutrient composition and chemical formula of foliar fertilizer, need for coating or chelation and maximum uptake potential through leaves (and stems) (Fernández and Brown, 2013).

Moreover, the basis for the recommendations and common practice of foliar spays is a mixture of scientific data, facts from demonstration trials but also from growers and farmers experiences, beliefs, myths and suggestions, which are sometimes influenced by commercially driven people. Differentiating “facts” from “fiction and perception” would help to create a clear picture for recommendations and use of foliar application strategies. If the improved factual understanding of current practises is then combined with the knowledge available on plant uptake and metabolic efficiency this will contribute to the improvement of fertilizer use efficiency.

2 Aim

The aim of this study is to present a quick view of the current worldwide science, practical experience and knowledge and gaps in knowledge about nutrient application through foliar sprays.

2.1 Approach

The scientific review on foliar application has been undertaken by a literature search in recent publications using Wageningen UR desktop library and searching through databases with agricultural literature, soil science and plant nutrition data. The search was a quick scan; in most cases only titles, keywords and abstracts have been assessed. Relevant data are listed in a database.

The common knowledge and practice of foliar nutrient application as well as recommendations have been obtained by interviewing crop and soil consultants and in some cases representatives from the agricultural supply chain. Fertilizer companies have not been consulted in this phase on purpose. In addition, specific crop

management handbooks or leaflets dealing with the topic have been consulted.
Within the scope of this study, we focused on the following crops and areas:

- Greenhouse crops (North west-Europe).
- Field crops (North west-Europe).
- Fruit crops (Netherlands and Belgium).
- Citrus (Mediterranean, USA).
- Tropical fruits (South America).
- Cereals, rice, wheat, maize (Europe, Asia).

A database was set up to enlist the results of the literature search and the data obtained from the interviews on common practice.

Within the short time frame of this assignment, we were not able to obtain sufficient information about common practice by consulting crop-advisors or consultants for the categories citrus, tropical fruits and cereals. Additional information for those crops is obtained from the internet.

3 Results

3.1 Quick scan of scientific data

For the quick scan of scientific data we used the databases Scopus and Web of Science. Literature from 2002 onwards was selected using terms *foliar spray* + *nutrient*'. Additionally the data base Web of Science was used to search using terms *foliar* + *fertiliz*, yie*lding 1702 hits. This search was further specified to *foliar* + *fertiliz**+ various search terms such as *absorption, leaf surface, penetration, cuticle, stomata*, uptake* and *permeability* to gain more information on the functioning of foliar application. Additionally these terms also gave information on adjuvants, charge particles, environment.

CAB abstracts with the terms *foliar spray* + *nutrient** were also used, and all additional articles or books up to 2010 were included. Our database (ENDNOTE) list contains 944 entries. Summaries are presented in Tables 1 and 2.

Table 1. Results of literature research foliar spray + nutrient* in ANY FIELD (top row)

	SCOPUS	WEB of SCIENCE	CAB-Abstracts
foliar spray + nutrient*	302	319	448
ELEMENTS			
+ boron	39	42	56
+ iron	35	43	84
+ nitr*	81	92	222
+ calcium	38	57	52
CROPS			
+ citrus	21	24	18
+ rice	19	30	52
+ vegetables	9	13	18
+ tree			
OTHER TERMS			
+ crop protection	4		
+ growth regulators	6		

Further specified for specific nutrients (e.g., *foliar spray + nutrient* + boron*), crops or groups of crops (e.g., *foliar spray + nutrient* + citrus*)

There is a large body of publications from the last ten years. Crop yield depends to a large extent on nitrogen availability in the soil and this must be present in a form accessible for the plant. This explains the large number of publications on nitrogen.

Table 2. Literature search in Web of Science using terms foliar + fertiliz* in ANY FIELD

	WEB of SCIENCE
	ANY FIELD
Foliar + fertiliz*	1,702
MECHANISM	
+ absorption	66
+ leaf surface	44
+ penetration	25
+ cuticle	18
+ stomat*	48
+ uptake	195
+ permeability	8
+ aqueous+ stomat*	7
+ uptake efficiency#	17
CROPS	
+ rice	15
+ millet	0
+ maize OR corn	12
+ sorghum	2
+ oilseed OR canola	1

#more detail on uptake efficiency in the discussion

Further specified using different terms for mechanisms and physiology of foliar fertilization (*absorption, leaf surface, penetration, cuticle, stomat*, uptake, permeability)*. In the second half of the table is a short summary of a crop search within this data.

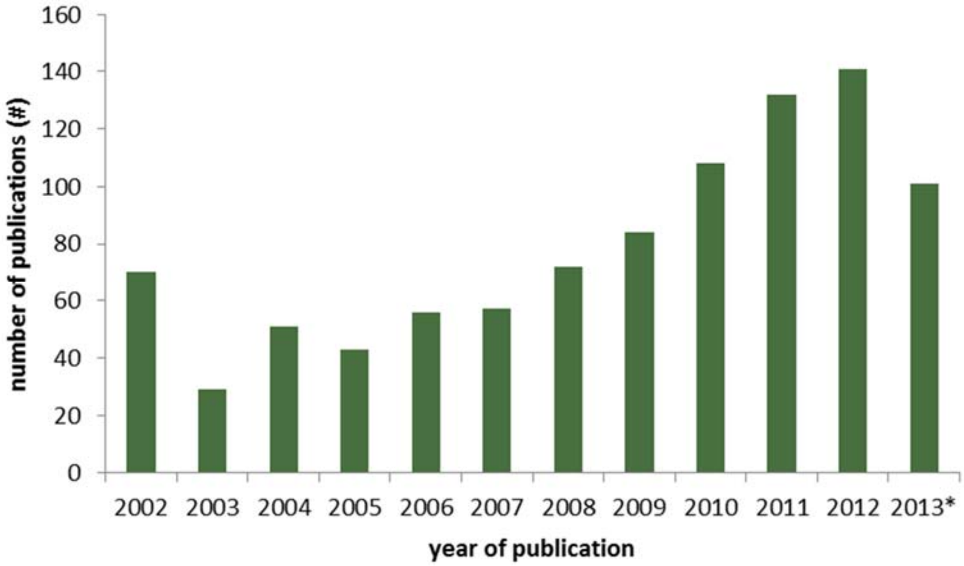
Nitrates, nitrogen and ammonium have been investigated considerably, as can be seen from the number of articles with these elements in the title. The micro elements iron, boron and zinc have also been used in many experiments, tests and trials and the importance of this will be dealt with later in this paper in the section on common practice in greenhouse crops and in the discussion. Appendix I presents a more detailed version of this table with regard to the crops.

Table 3. A combination of two searches in databases. 1. foliar spray + nutrient* in ANY FIELD from the 3 databases, Scopus, Web of Science and CAB-Abstracts from 2010 – 2013.

	ANY FIELD	TITLE	KEYWORD
Foliar spray + nutrient*	313		
Foliar + fertiliz*	626		
ELEMENTS			
+ boron, B, Borax		56	32
+ iron, Fe		50	47
+ nitr* incl ammon*, NO_3, NH_4,N		200	187
+ zinc, Zn		85	59
+ calcium, Ca		36	39
+ potassium, K		49	47
+ phosph*, P, *H_2PO_4		48	69
+ silic*, Si		14	13
+ magnesium, Mg		11	12
+ sulf*, S, SO_4		3	4
+ mangan*, Mn		24	22
+ molybd*, Mo		5	3
+ copper, Cu		12	11
+ uptake efficiency		0	4
CROPS			
Field vegetables (excl. cereals)		66	36
Fruit crops (excl. citrus)		69	35
+ Citrus		35	21
Tropical Fruits		19	9
Cereals		254	240

The data list in literature database (ENDNOTE) is a combination of two searches in databases. 1. foliar spray + nutrient* in ANY FIELD from the 3 databases, Scopus, Web of Science and CAB-Abstracts from 2010 – 2013. This last data base showed overlap for the 'scientific journals' (Table 1) and 2. foliar + fertiliz* + the terms in Table 2 (absorption, leaf surface, penetration, cuticle, stomata*, uptake, permeability) from Web of Science 2002 – 2013. This database includes 185 books and book sections. The search of each of the terms in the left column has been carried out for TITLE and KEYWORD.

In figure 1 the number of publications per year in the data base of 944 entries, with *foliar spray* + *nutrient** in ANY FIELD and *foliar* + *fertiliz** combined with search terms (*absorption, leaf surface, penetration, cuticle, somat*, uptake, permeability*). It is clear that the number of publications increased rapidly during the past few years.



* 2013 is not complete.

Figure 1. The number of publications per year from the data base

3.2 Assessment of literature

3.2.1 General

A selection of the publications from the literature search is reviewed. The recently published book *Foliar Fertilization* (Fernández et al.. 2013) gives a broad overview of the scientific literature on foliar nutrient application, and the miniature review on application efficiency in Frontiers in Plant Science (Fernández and Brown, 2013) also describes the complexity of factors that influence the effect of foliar fertilisation.

Broadly speaking, foliar application of fertilizers, both macro and micro elements, is very popular and effective with tree crops and in particular for nut bearing trees (Pecan, Pistachio, Macadamia, Walnut etc.). This holds true for production areas as diverse as India, Australia and the southern states of the USA (Huet, 2006, Keshavarz, 2011). For Brazil and tropical South America, an agricultural journalist stated that foliar application in combination with pesticide application is the most common way to apply fertilizers, and the number of advertisements in trade press journals like “Plasticultura” confirms this (Matthias, 2013).

The foliar application of fertilizers, both macro and micro elements, is also popular and common for fruits like citrus, *Prunus* and apple (Sanchez et al., 2006, Yuri et al., 2006). The application of macro and micro elements is effective for extensive orchards and soils which hinder normal uptake (e.g., tropical Brazil). For high production crops on more normal soils, the uptake of macro elements is not always effective, whereas the use of micro elements seems to have value (Fernández et al., 2013).

The production volume is an important indicator of the extent to which macro elements can be applied successfully on the crops. A high production volume means many nutrients are removed from the field, thus, the volume of fertilizer application has to be equally high up to the point where foliar application can no longer supply all macro elements as fast as required.

3.3 Mechanisms and physiological aspects

3.3.1 When to apply foliar fertilization

Marschner (2012) indicates that the use of foliar sprays potentially offers advantages like direct application, fast response and no losses. Unfortunately, the 10 criteria mentioned to reach the potential are almost never met. General reasons for failure are poor spraying equipment, improper spray formulation, poor timing, adverse climatic conditions and imbalanced dosing. Fernández et al., (2013) state foliar application should be considered when:

1. Soil conditions limit availability of soil applied nutrients (for example calcium and phosphate fixation in soils of high pH).
2. High loss rates in soil occur (for example rainy season on coarse quartz sandy soil).
3. Delivery to the right organ is impeded (for example calcium and boron to fruit tips).
4. Plant uptake is severely hindered (for example severe root loss after flooding)

They give some idea of when crop stage or condition is advantageous for foliar application (Table 4).

Table 4. Interactions between crop phenology and the environment can determine the usefulness of foliar fertilization through the following processes

Environment	Crop phenology
A limitation in soil nutrient uptake capacity occurs as a consequence of the environment or plant senescence that limits nutrient uptake by roots.	During early spring when many deciduous species flower and set fruit and soil temperatures or moisture regimes are unfavourable for soil nutrient uptake.
	As a consequence of plant senescence limiting roots activity.
Periods of peak crop growth induces a nutrient demand that exceeds nutrient supply even in a well-fertilized soil.	Nutrient demand for rapid fruit growth or grain fill can exceed uptake capacity even in adequately fertilized soils.
	Competition between roots and shoots during periods of high shoot demand can reduce carbohydrate allocation to roots and restrict root growth and metabolism and hence reduce nutrient acquisition.
Plant architecture and organ development create local nutrient demand that exceeds capacity for within-plant nutrient delivery.	Limitations in transport of phloem-immobile elements to fleshy organs with inadequate vascular connectivity or low transpiration e.g., B or Ca deficiencies in fruits and fleshy organs and B, Cu, Fe, Zn deficiencies in reproductive structures.
	Nutrient depletion due to rapid withdrawal of mobile nutrients in leaves adjacent to large rapidly growing reproductive organs.

3.3.2 How to apply foliar fertilization

Fernández et al. (2013) observe: The commercial significance of foliar sprays of plant protection products, herbicides, fertilizers, or plant growth regulators for agricultural production, has resulted in many cuticular permeability trials over the past 60 years (Riederer 2006; Fernández and Eichert 2009; Schlegel, Schonherr et al., 2006). Such studies enabled the development of a “dissolution– diffusion model” for the cuticular penetration of apolar, lipophilic compounds (Riederer 2006). In contrast, the mechanisms of penetration of hydrophilic, polar solutes through the cuticle are currently not fully understood (Fernández and Eichert 2009).

Fernández et al. (2013) discussed various aspects of spray effectiveness by giving long lists of individual factors of influence on the effectiveness of foliar application and examples for each factor. It is, however, still difficult to combine all these factors in a complete prediction of effectiveness. An incomplete summary yields:

1. Physico-chemical formulation: spray formulation such as concentration, molecular size, solubility, electric charge, pH, surface tension, retention, spreading, and point of deliquescence.
2. Environment during application: relative humidity, temperature, and light.
3. Plant surface: leaf shape, cuticle composition, surface wax architecture, leaf hairs, leaf surface architecture, phenological stage, the presence of abiotic stresses.

The following section gives a summary of the factors affecting foliar application. In the discussion these points will be used to illustrate the case of iron in combination with different crops.

Physico-chemical formulation:

Concentration: The higher the concentration, the faster total uptake will be. However threshold levels for damage should be observed, and the fertilizer should be readily soluble at the concentration chosen to prevent damage to the leaf.

Molecular size: Generally speaking the smaller the molecule the easier the uptake by the leaf.

Solubility: The fertilizer should be readily soluble and contain no residues which are left on the leaf surface. This also applies for the water used for the sprays, which can contribute to covering the leaf with a dust layer which reduces assimilation efficiency.

Electric charge: Uncharged molecules and anions can penetrate the leaf surface much more readily than positively charged molecules like the fertilizer cations. Most fertilizer salts have to enter the leaf through the stomata, i.e. from the bottom side of the leaf.

pH: Theoretically a pH above pH 3 should be advantageous, but experimental data are not conclusive.

Surface tension (adjuvant): A lower surface tension of the liquid to be sprayed will decrease the droplet size and increase the effectiveness of spraying. Tensides (also called surfactants, soaps, wetting agents or detergents) are routinely added to spray formulations for plant protection products (PPP).

Retention (adjuvant): Once on the plant, the nutrient or PPP should stick to the plant. For PPPs, special products can increase retention.

Spreading (adjuvant): Compounds to help droplets spread out over the leaf when touching the leaf surface and to cover as much of the surface as possible. This is the same mechanism as discussed under surface tension. The lower the surface tension the better the leaf is covered but with a thinner water layer. The optimum is a somewhat lower surface tension which results in the largest possible mass of water adhering to the plant.

Penetration (adjuvant): Compounds in sprays which help molecules pass into the leaf. Usually these materials weaken the lipid cell barriers and are similar to the materials discussed under surface tension.

Point of deliquescence: This is the air humidity at which the nutrient dissolves in water vapour attracted from the air. By doing so the nutrient can be taken in by the leaf much easier than solid salt. The lower the deliquescence, the better.

Humectants (adjuvant): Compounds in sprays which lower the point of deliquescence, examples are carboxy-methyl cellulose as well as $CaCl_2$.

Environment during application:

Relative humidity: The higher the humidity, the longer nutrients can be adsorbed and the more effective foliar application is. Obviously rain is averse as it washes off all nutrients.

Temperature: For a proper leaf uptake, a leaf temperature between 15-25ºC is acceptable. Higher temperatures will reduce the period in which the pant can take in the nutrients.

Light: The light level should be moderate to prevent leaf scorching by the salts sprayed on the leaf as well as to allow the plant time to take in the nutrients. Moderate light levels are beneficial as they create xylem and phloem transport.

Plant surface:

Leaf shape: Governs how much of the spray is intercepted and how easy is it to reach the underside of the leaf.

Cuticle composition: Determines how easily the outer cells can be reached through the outer layer.

Surface wax architecture: As with the cuticle; thickness and type affects how easily molecules can pass this layer.

Leaf hairs: To some extent these facilitate catching droplets of spray but when denser they can also prevent the spray from reaching the surface.

Leaf surface architecture: Governs how easily droplets can spread out over the surface without obstruction.

Phenological stage: Older leaves take in nutrients more difficultly than young ones.

Abiotic stresses: Stressed leaves will not take in so much nutrients and transport may be poor because of stress.

3.4 Crops

The information below is based on the literature search about foliar application. The next section is a compilation of information attained from consultants. The information in these two sections is subsequently reflected upon.

Greenhouse crops

Foliar application is not commonly used in greenhouse crops. Soilless grown crops from systems like hydroponics or water culture are even less likely to be treated with foliar application, since nutrient supply and availability can be controlled and easily corrected if needed (Sonneveld and Voogt, 2009). The main reason for foliar fertilizer application in greenhouses is to cure Fe and Mn induced chlorosis in soil grown greenhouse crops, due to soil pH or rooting problems (Sonneveld and Voogt, 2009). Ca disorders like blossom end rot in tomato and sweet pepper are an important problem in greenhouse crops, and some authors showed positive effects of Ca spray against blossom end rot in tomato and sweet pepper or tip-burn in lettuce crops (Wada et al., 1996; Marcelis and Ho, 1999; Corrivaeu et al., 2012). Fe-chelates and $MnSO_4$ are the most common fertilizers applied via the leaves, commonly at concentrations of 5 g L^{-1}. For Ca usually $CaCl_2$ is used or $Ca(NO_3)_2$, (Smilde and Roorda, 1968) at rates of 5 – 10 g L^{-1}.

Field vegetables

For potato and broccoli we found the application of nitrogen (urea and nitrate) to be the most popular use of foliar application (Yildrim et al., 2007; Kannan, 2010) and it was used to immediately alleviate a perceived deficiency in the crop. Several authors mention that the application of nitrogen increases the uptake of trace elements like iron (Aciksoz et al., 2011), i.e. an indirect effect, but it is interesting to note no author claims a direct yield advantage of nitrogen application, e.g.Afifi et al., 2011.

Fruit tree crops (excluding citrus)

Tropical red soils are usually leached and contain high levels of iron oxide. Problems mentioned are pH related and or related to elements binding to iron oxides and clay. Most tropical nut bearing trees are sprayed routinely with micro elements. Fe, Zn and boron are mentioned a lot, but Mn, Cu and even Ni are also applied (Fernández et al., 2013). The period mainly used for corrections is from bud break to pollination and onto flower setting.

For temperate fruit, foliar application of nutrients can occur when soil temperatures are too low for proper nutrient uptake, sub optimal pH and in reaction to micro nutrient disorders (Yuri, 2006). Leaf fertilization is never used to replace soil fertilization for macro elements completely (Collas, 2005). Micro elements are routinely administered via foliar application (Collas, 2005). It is more cost effective to apply macro nutrient fertilizers by broadcasting solid fertilizers on the soil or even to use fertigation lines rather than foliar sprays. It has also been noticed that Zn is poorly mobile in the plant and that soil applied Zn sources are distributed better within the plant than foliar applied Zn. Foliar application alleviates Zn deficiency in leaves but not the remainder of the plant; a warning that it is not always fully effective or feasible to add Zn (Swietlik 2002). In apple N^{15} was recovered in different organs after low concentration and high volume foliar application (Toselli et al., 2004). It was also found that N taken up by the leaves was rapidly exported to the fruit.

Citrus

Most citrus growing soils are calcareous, i.e. derived from calcium rock, or otherwise very rich in calcium and magnesium. These soils tend to have high pH's (pH 7-9) which reduces the uptake of phosphate and micro nutrients except molybdenum (Mo). These elements precipitate as calcium and phosphate salts because the equilibrium concentrations at high pH, and high calcium and magnesium levels favor precipitation of Fe and Zn phosphates or calcium phosphates. Discoloration of the leaves due to iron deficiency is common. At the flowering stage the potassium level in the plants can drop to levels low enough to cause problems for fruit set.

Foliar application of the micro elements with the exception of molybdenum is common and at the flowering stage some growers do use foliar applications of N, P and K fertilizers (Albrigo, 2001; Albrigo, 2002) because of the poor soil conditions.

Rice

Foliar fertilization of rice is often linked to the global nutrition problems of iron, zinc and selenium deficiency. Rice is also known to react favorably to silicon application (Marschner, 2012). Other elements mentioned include iron, copper, boron, zinc, nitrogen and N,P,K (Liew et al., 2012; Pooniya et al., 2013). Applying zinc, boron and copper incidentally decreases problems with fungal diseases (Liew et al., 2012). This effect on fungal control may account for some of the more spectacular yield increases found upon applying foliar micro element sprays. The uptake efficiency of zinc from foliar applied $ZnSO_4$ can be as high as 50-60%. More information on efficiency is in the discussion under the heading 'On efficiency'.

Temperate cereals

Biofortification of wheat using Zn and Fe is also mentioned in the literature. Foliar uptake of P could correct P deficiency in mid-season winter wheat and increase grain yields (Mosali et al., 2006). Cu deficiency could also be more effectively corrected using foliar or soil-incorporated applications than using surface broadcast without incorporation in wheat (Malhi and Karamanos, 2006). Foliar application of nitrate and urea was also reported for wheat (Kannan, 2010).

Maize

Foliar applications of urea, Fe, Mn, and Zn are reported. Urea can be used as replacement of soil applied N (Afifi et al., 2011). The micro elements are applied as foliar application on soils lacking those elements. No attention seems to be given to whether or not these soils can be treated. Urea may be added as a replacement of soil applied N to temporarily increase the protein content of the kernels. The dosage is 15 g L^{-1} for urea and 10 – 20 g L^{-1} for the microelements. Nitrogen as urea is applied to maize, but no effect on yield was found (Afifi et al., 2011) other than the yield increase found with normal soil applied nitrogen. Injection of labeled N into the space between ear and husks at silking raised the nitrogen use efficiency more than when treated with foliar or soil application (Ma, Li et al., 2004). This injection may have altered the N distribution within the plant and improved the NUE. They conclude that this could potentially enhance grain protein content. The timing of foliar application of N in maize especially in areas with soil leaching (N.W. Pakistan) affects grain yield (Yasir et al., 2010).

3.5 Common practice of foliar application

3.5.1 General

The information below summarizes the results obtained from general crop handbooks and from personal communications with consultants. The results of the interviews are limited to the crops and situations considered in this study. For a detailed picture of this information see Appendix 2.

3.5.2 Crops

Greenhouse crop

Soilless grown crops are not or very rarely treated with foliar application, since nutrient supply and availability are fully under control (Corsten, 2013; Bleyaart, 2013, van der Steen, 2013; Sonneveld and Voogt, 2009). The advisers consulted mention that foliar application is only occasionally used in the case of micro nutrient deficiencies and this is almost exclusively the case for soil grown crops. In the past, Mg was effectively used in tomato. Better growth control and other varieties have reduced this, but mainly the change-over to soilless culture has had an impact. Ca spray in Chinese cabbage and endive is done preventively against tip burn (Bleyaart, 2013; Incrocci, 2013). One consultant mentioned that a standard routine schedule is applied for rose production in Kenya (Hartog, 2013). In practice only chlorosis, related to Fe or Mn deficiency is a reason for a foliar treatment. This is for some soil grown cut flowers (gerbera, rose) and lily (de Groot, 2013). The occurrence of chlorosis is mainly caused by high pH in soils in combination with insufficient root development (Sonneveld and Voogt, 2009). It is hard to discriminate between Fe and Mn induced chlorosis, therefore the application is usually done with both Fe and Mn fertilizers. This makes sense, since high pH in the root environment, will affect both nutrients. Usually Fe-DTPA and $MnSO_4$ are used as fertilizers. The concentration is usually 5 g L^{-1}, for lily, for some cultivars, this is done in a routine weekly or fortnightly schedule (van der Steen, 2013; Hartog, 2013). Chinese cabbage and endive are usually treated with $CaCl_2$ liquid fertilizer with 5 – 10 g L^{-1} (active ingredient) (Bleyaart, 2013).

Consultants mention that in their experience the efficacy is rather poor. Only in case of early emergence of the symptoms, the application of Fe will help to a certain extent. However, proper fertigation, using for instance NH_4^+ in the nutrient solution to reduce pH is far more effective in chlorosis treatment than foliar spray (Sonneveld and Voogt, 2009).

Field vegetables

In field vegetables, foliar application is not commonly used. The general comment of the consultants is that there are no major problems in the supply and the availability of nutrients. A few exceptions are mentioned: in case of observed deficiency symptoms and in case of crops with a very long growing period, which extends into the late autumn and winter. From our information there were no standard schedules for applications; the recommendations are mainly based on experience (Fink, 2013; Coopman, 2013; Incrocci, 2013). Foliar sprays are applied in case of emerging deficiencies. This was mentioned for Mg, B Fe and Mn and occasionally Zn. A second reason mentioned is that due to precipitation in late summer and autumn, nutrients (specifically N) are leached out, and top dressings are not so suitable for some crops. This was mentioned in particular for leek and celeriac and specifically on sandy soils. Also the constraints in N application due to regulations for inputs or mineral-N residuals in the soil profile sometimes is a reason for late season foliar applications. A third reason for application is to 'harden' the foliage, making it more resistant against climatic conditions or, as it is believed, to have a better quality in the product chain (endive, lettuce). For this purpose $MgSO_4$ is used (Fink, 2013; Coopman, 2013; Incrocci, 2013).

Without exception, the foliar sprays are combined with plant protection products. The late season N application is applied as KNO_3, sometimes $Ca(NO_3)_2$, or urea. In this case it is a routine application. The quantities and concentrations mentioned range widely, from 10 – 50 kg ha^{-1} and concentrations of 5 – 50 g L^{-1}. In the case of $MgSO_4$, application is usually at concentrations of 20 – 50 g L^{-1} (Fink, 2013; Coopman, 2013; Incrocci, 2013).
Consultants are convinced of the positive effect of the late season N foliar application in some vegetables. However, they state that the effectiveness can be improved, since now it is used routinely but due to the unpredictability of the climate (precipitation) even when application is not necessary (Coopman, 2013).

Fruit crops

Foliar sprays are commonly used in pears and apples. It is mainly used for N application, but recently also P-fertilizers are applied in pear. For some apple cultivars susceptible to bitter pit, Ca fertilizers are sprayed. Occasionally applications with Fe, Mn or Zn are applied in case of deficiency (Elsen, 2013; Deckers, 2013; van der Maas, 2013). Only limited nitrogen fertilization on apple and pear is applied, to prevent vegetative development. However the N availability can be limited for fruit development and bud formation in late summer and early autumn. In that case foliar application with N fertilizers are applied to stimulate the process of fruit swelling, mainly in pear. In apple sometimes urea is used immediately after harvest and before leaf senescence. Bitter pit in apple, a Ca disorder in some typical cultivars (Coxs Orange, Pippin), occurs mainly during storage. Preventive sprays with Ca fertilizers are used in a standard schedule. In pear positive effects on fruit quality were reported (Elsen, 2013; Deckers, 2013; van der Maas, 2013). For the nitrogen spray, mainly KNO_3, $Ca(NO_3)_2$ but sometimes urea is used, in concentrations varying from 5 – 10 g L^{-1} and quantities of 25 – 50 kg N ha^{-1}. For Ca sprays usually $CaCl_2$ is used, occasionally deliberately $Ca(NO_3)_2$ if N is needed at the same time. Both the recommended N and Ca sprays are undisputed among consultants and common practice.

Citrus

Applications of K and P are quite common in citrus. K is applied mainly as KNO_3 or in combination with P as KH_2PO_4. Micro nutrients (Mn, B, Zn, Cu) are applied in calcareous soils. The spray of Fe-chelates is sometimes recommended, however discouraged by others because of the risk for leaf burn. Moreover, the effect of Fe is poor due to limited or no translocation in the plant (Obreza et al., 2008). The application of micro nutrients is believed to improve fruit set and fruit quality. Micro nutrient deficiencies are often seen on calcareous soils (Obreza, 2008, Eymar, 2013). Mn, Zn and Cu are usually applied as sulfates, B as borax or boric acid. Doses in

Citrus are normally established as a function of the age of trees, top tree diameter, rootstock/variety and crop conditions (Eymar, 2013).

Tropical fruits

In South America foliar fertilization in a range of NPK and micro nutrients for fruit trees is common and in many places more common than soil fertilization. As disease pressure in the tropics is high, many fungicide and insecticides are applied. Thus growers usually add foliar nutrients to the plant protection products mix to save costs, time and effort (Matthias, 2013). The reasons for this are:

1. Lack of soil analysis. Even though soil tests have been cheap and easily available everywhere, they are not commonly used.
2. Lack of nutritional planning. No season-long nutritional program and absorption curves are used, and nutritional deviations from the expected are 'fixed' with foliar sprays.
3. Sales pressure. Dozens of brands are being advertised, and door-to-door salespeople for foliar sprays are abundant. Allegedly this is due to the much larger profit margin that manufacturers obtain from foliar fertilizers.
4. Disease pressure in the tropics is huge; rain in open fields and high humidity and heat in plastic houses. As a consequence, more fungicides and insecticides are applied. So it is of little time and effort to add foliar fertilizers to the spay mixture (Matthias, 2013).

Although other ways to solve the lack of nutrients may be more effective, the crops do react to the foliar applications, and growers are generally positive about the crop response to foliar applications (Matthias, 2013).

Cereals

Sprays with macro elements (K and N) as well as micro nutrients, especially Fe and Zn, are quite common in rice, and are mentioned to be standard in India, Vietnam and China. This is also the case for N, P and K for wheat and corn. For wheat, N, P and K spray is used (US, Europe) (Stomph, 2013; Holwerda, 2013) because the soils are poor in exchangeable K, and N is unavailable. Low temperature in the root zone would be a reason to use foliar treatment (Holwerda, 2013). N and K are applied mainly as KNO_3, the micro elements as sulfates; however, Zn is often applied as Zn-EDTA (Holwerda, 2013).

Oils seed rape

Sulfur and micro elements, especially molybdenum, are applied as foliar application (Brink, 2013; Coopman, 2013). Occasionally S deficiency occurs on soils poor in SO_4. Crops are susceptible for Mo and B deficiency especially in sandy soils (low pH) (Brink, 2013). $MgSO_4$ is used together with micro elements (B). Mo is applied as Na_2MoO_4 (Brink, 2013) and the effects of foliar application to prevent or cure the deficiencies are good (Brink, 2013)

3.5.3 Comparing Literature and Common Practice

Not surprisingly, the literature on common practice is more detailed on the “how-to” of foliar applications. It is also understandable that practice is almost always spraying in combination with PPPs. Practice also stresses the advantages of foliar application of N and Ca, elements for which scientific literature does not offer a convincing physiological background and on which experimental data shows rarely positive yield effects and widely varying efficiencies. Despite the research data on spray formulations, no clear strategies were reported in practice, and hints were given that when, e.g., tensides were used, this was based on advice only. This type of advice was more or less passed on among users and used in and out context.

4 Discussion

This section is organised into a limited number of recognisable main topics. Whenever possible, findings from literature, including the most important expert interviews, were condensed in tables showing the outcomes on specific topics. The main topic structure applied here have been continued in the conclusion section.

The discussion's main topics are: "Reasons to apply;" "Efficiencies" and "Concentrations;" Leaf uptake" and "Metabolic efficiency". They start with the more practical topics and develop towards the much more complex and fundamental aspect of foliar spraying: Iron (Fe) is used as an example to integrate the topics identified.

The first paragraph, "Reasons to apply", deals with the apparent "why" of foliar applications. As almost every author mentions the reason why foliar application is deemed necessary, this topic is well documented.

The second paragraph, "Efficiencies and concentrations" shows a wide range in both efficiencies and concentrations used. The outcomes seem to contradict in places, but further analysis is possible when combining efficiency and concentration data with assumed volumes applied. Along these lines, increased insight in the successful use of foliar applications can be made available.

The third paragraph, "Leaf uptake" deals with the much more diffuse knowledge on increasing the transport of nutrients from the leaf surface into the leaf tissue. Even though, or perhaps because, many interacting techniques are available to boost the direct uptake, it proved difficult to structure the discussion. An approach to order the discussions is chosen.

The fourth paragraph "Metabolic efficiency" deals with an even more fundamental issue: once the elements have entered in the leaf, do they, and how do they reach the target organs? The complicated context as well as the lack of knowledge is apparent here but selected examples of highly specific literature show indications as to how to develop this topic.

The fifth paragraph "unravelling knowledge" elaborates the complex interactions between the physico-chemical and plant physiological factors involved, using Fe as example. The large amount of data from the literature is confusing as it is often quite crop specific or crop-stage dependent and the results are not always unequivocal. An attempt is made to unravel the available information and structure this into tables.

Reasons to apply

In Tables 5 and 6 one can find reasons for foliar application of fertilizers. It is clear there are many reasons to apply foliar fertilizers. On reading the articles, it becomes apparent that the reasons to apply are accepted as a given, and no alternative application methods or even adapted foliar application techniques are considered.

Table 5. Reasons for foliar application of macro elements (N, K, P, Ca, Mg, S) with corresponding literature reference

Element	Reason for use as foliar application	Authors
N	Poor availability	Fernández et al., 2013
	Asynchronous availability/ requirement	Elsen, 2013, Deckers,2013
	Soil depletion/leaching	Incrocci, 2013, Coopman, 2013
	Low root temperature	Holwerda, 2013, Incrocci, 2013
	Flowering stage citrus	Albrigo, 2001; Albrigo, 2002
	Increase uptake of microelement e.g., iron	Aciksoz, Yazici et al., 2011
Urea	Increase protein content kernels	Ma, Li et al., 2004
K	Poor availability	Incrocci, 2013, Coopman, 2013
	Positive against flattened wheat	Fernández et al., 2013, Howerda, 2013
	Low root temperature	Incrocci, 2013, Coopman, 2013
	Flowering stage citrus	Albrigo, 2001; Albrigo, 2002
P	Poor availability due to high pH in soil	Marschner, 2012, Fernández et al., 2013)
	Low root temperature	Incrocci, 2013, Coopman, 2013
	Flowering stage citrus	Albrigo, 2001; Albrigo, 2002
Ca	Reduce Ca-related disorders, e.g., blossom end rot in tomato and sweet pepper, tipburn lettuce, butter pit apples	Incrocci, 2013, Bleyaart, 2013. Sonneveld and Voogt, 2009 Wada et al., 1996; Marcelis and Ho, 1999; Corrivaeu et al., 2012
	Improve leaf quality (hardens leaf)	Corsten, 2013, Hartog, 2013
Mg	Improve leaf quality	Corsten, 2013, Hartog, 2013
S	Oil seed rape – possible S deficiency in soil	Brink, 2013; Coopman, 2013

Table 6. Reasons for foliar application of micro elements (Fe, Mn, Zn, Co, Si) with corresponding literature reference

Element	Reasons	Authors
Microelements in general Fe, Mn, Zn, Co	Poor availability due to high pH (calcareous soils, saline soils, leached soils such as sand or peat)	Bleyaart, 2013; Incrocci, 2013; van der Steen;2013, Corsten, 2013; de Groot, 2013; Dings, 2013
	Prevent deficiency at emergence	
	Poor availability of microelements citrus	Obreza, 2008
	Poor availability of microelements nut trees	Fernandez et al., 2013
Zn	Prevent deficiency at emergence in rice	Stomph, 2013; Liew, 2012; Pooniya, 2013
Fe	Cure chlorosis due to high pH and insufficient root development in greenhouse crops	Sonneveld and Voogt, 2009
Mn	Cure chlorosis due to high pH and insufficient root development in greenhouse crops	Sonneveld and Voogt, 2009
Si	Positive effect on rice	Liew et al., 2012; Pooniya et al., 2013

The literature referenced in Tables 5 and 6 is often focused entirely on the effect of foliar application, and does not reflect these effects with for instance alternative fertilization methods. It is therefore possible that nutrient related problems could have been more efficiently alleviated with methods other than foliar sprays. To at least be able to draw the conclusion that foliar application is the most efficient way to deal with a problem, literature in Table 5 and 6 needs to put the use of foliar application in a broader context, i.e. compare foliar spray against other application methods. This is analogous to the evaluation of chemical spraying against diseases without analyzing the role of climate on the disease incidence: yes spraying is effective; no, it is not the best solution. To illustrate how a broader context improves agricultural practice two examples are given:

1. The literature claims some plants, like epiphytes as Bromelia Tillandsia have no or hardly any roots and obtain nutrients through their leaves mainly (Benzing et al., 1976). Research in production situations shows unequivocally this is not the case in production circumstances (Kämpf, 1982; Mulderij, 1994; both in Sonneveld and Voogt, 2009). Apparently epiphytes do use their roots when they can and only use the foliar route when they have to.
2. It is quite often mentioned that foliar application is more environmentally friendly (Fernández et al., 2013) than other methods. The arguments for this are a lower application rate and less leaching from the soil. This might be obvious, however should be evaluated in a much broader context, taking into account the total nutrient requirement of the crop and the various alternatives for soil applications and measures to reduce volatilization and leaching of the soil, such as: smart irrigation, specific fertilizers and application techniques (coating, band application, deep placement) and fertigation. Moreover for some nutrients, the application might be less effective due to the previously mentioned immobility in the plant. Additionally the complexity of interactions between foliar application, the environment and physiological characteristics of the plant on the efficacy of foliar applications complicates the interpretation of the efficacy.

Efficiencies and concentrations

Table 7 gives efficiencies found in the literature. It is clear these efficiencies vary from 2% to 70%. This partly contrasts with the presumed high efficiency of foliar application. The reason that the efficiencies are low becomes apparent when the data of Table 7 are combined with those on concentrations used in Table 9. It seems that the amount of nutrients applied does not always correspond with the amount of nutrients required by the crop. Typically the amount of macro elements added may be seriously short of the required amounts. In contrast the amounts of micro nutrients supplied sometimes are enough to cover a total requirement of the crop for one year or growing season. Hence the efficiency of micro nutrients as foliar application is likely to be extremely low.

Table 7. Recovery of elements (N, Zn, Fe, B, Zn) after foliar application in various crops with literature reference

Element	Crop	Comment / element recovery	Literature
urea	macadamia	Less than 40% was taken up through the leaves at all times. Increase in N in biomass = 4 to 4.6 kg ha^{-1}	Huett and Vimpany, 2006
urea	Prunus	47% urea N recovery	Sanchez et al., 2006
Zn	Prunus	7% Zn recovery. Most leaves were shed in autumn and must be seen as soil application.	Sanchez et al., 2006
Zn	Apple	70% of applied found in the plant.	Yuri et al., 2006
Zn	Rice	0.2% foliar spray of $ZnSO_4.H_2O$ recorded the highest Zn crop recovery efficiency 57.6 and 61.6%	Pooniya and Shivay, 2013
Fe, Zn	winter wheat	Fe 29.5 mg kg^{-1} in control, to 34.9-37.8 mg kg^{-1} in treatment with 2 g L^{-1} IF 400 L ha^{-1} and winter wheat 5 ton ha^{-1} THEN 800 g on 4000 is 200 mg kg^{-1} applied (<10% recovery).	Zhang et al., 2010
B	Citrus	Recovery labelled B by fruits 7% using foliar application	Boaretto et al., 2011
Zn	Wheat	4kg ha^{-1} foliar spray of $ZnSO_4.7H_2O$ wheat, Turkey Grain increased from 11mg kg^{-1} (control) to 22 mg kg^{-1} IF 4000 g ha^{-1} and wheat 5 ton ha^{-1} THEN 1600 g Zn on 5000 is about 500 mg kg^{-1} applied (recovery 2%).	Cakmak et al., 2010
N	Abies	Mean value of recovered N (%Nr) was 5.3% for NH_4^+ and 4.7% for NO_3^-	Chavez-Aguilar et al., 2006

Table 8 shows that the concentrations used when dosing macro and micro nutrients range from the 80 g L^{-1} to 0.02 g L^{-1}. The 80 g L^{-1} mentioned is already well above the normal range mentioned (Marschner, 2011; up to 10 g L^{-1}). Concentrations above 1% (somewhat higher for urea) bear the risk on leaf scorching due to osmotic stress, although many factors influence the actual occurrence of scorching (concentration, ion, RH, leaf nutrient status, light, counter ion e.g.; Fernandez et al. 2013).

Table 8. Concentrations for foliar application of elements (N, Zn, B, N, P, K) in various crops with literature reference

Element	Crop	Concentration in g L^{-1}	Literature
Urea	Tree crop	10, 80*	Huett and Vimpany, 2006
Zn	Tree crop	20	Huett and Vimpany, 2006
B	Field	0.6**	Tariq et al., 2010
N,P,K urea	Tree crop	0, 5, 10*	Albrigo, 2002.
Urea	Field crops	15	Afifi et al., 2011
Zn	Tree crop	0.174, 0.348	Keshavarz et al., 2011
B	Tree crop	1.05, 1.75	Keshavarz et al., 2011
Urea	Field crops	4, 8, 10	Yildirim et al., 2007
Urea	Leafy vegetable	5, 10, 15	Amor et al., 2006
Zn, B	Rice	0.02***	Liew et al., 2012
Zn	Rice	0.02*	Pooniya and Shivay, 2013
K	Olive	8	Restrepo-Díaz et al., 2009

*calculated from %

**calculated from kg ha^{-1} (basis 400 L ha^{-1})

***calculated from ppm

As already said when considering the efficiencies in Table 8, the quantities offered to the crops are often poorly related to the crop needs. The calculation to determine the proper amount to be dosed is fairly easy, using data by Marschner (2012; chapter 4) such as a concentration of 1% with 400 L ha^{-1} for most elements with the exception of 10% for urea. Thus it follows that with the concentrations in Table 8 most macro elements apart from Mg and P are under-dosed and all micro elements are overdosed.

The exact calculation is 10 g L^{-1} * 400 L ha^{-1} is 4 kg ha^{-1} or about 40 mol (grossly simplifying mol weight to 100 g for all fertilizers). This amount is not even sufficient to cover the crops need for nitrate for 1 day (estimated at 100 mol ha^{-1} d^{-1}) but when we are talking zinc (estimated uptake of 50 mmol ha^{-1} d^{-1}), it is enough to cover the crops daily need for about 400 days. Obviously this calculation needs refinement but the gist is illustrated.

Now a first improvement could be to dose amounts of fertilizers corresponding to what the crop needs in a reasonable time frame of 4-12 weeks. That amount then has to be dissolved in the amount of water used to spray the crop. That amount itself cannot be higher than the maximum amount of spray solution that will adhere to the plant. The idea being that dripping of solution onto the ground must be prevented, to avoid a decrease in application efficiency.

Following that train of thought, a better way to dose micro nutrients would be to dose micro nutrient based on calculations of the amount of water which can be made to adhere to the leaves. The amount of water to be supplied on the leaves according to Marschner's data is 400 L ha^{-1}. When we presume a Leaf Area Index (LAI) of 4 m^2 m^{-2}, the water layer covering the leaf from two sides would be 0.005 mm thick (which is 5 micrometer). A proper dose for zinc (enough for 50 days) would be 2.5 mol about 150 g in 400 L water, which is a concentration of about 400 mg L^{-1}.

Leaf uptake

In the last decade the knowledge of the plant physiological processes involved with foliar application has increased (Fernández et al., 2013) considerably. Much more is known about the effects of plant morphology and the pathways of nutrients. As far as the penetration of leaf surfaces and nutrient absorption is concerned, it may be clear that plant surfaces are permeable to nutrients, although the contribution of stomata, lenticels and other epidermal structures is still not fully understood (Eichert et al., 2008; Fernandez and Eichert, 2009). Although the chemical form in which the nutrient is applied on the foliage affects the absorption rate (Fernández et al., 2013), this is no guarantee that these chemicals affect the internal transport of the plant in a same way.

As explained in the previous paragraph, we need to know the thickness of the water layer on the plants to calculate the proper dosing concentration. The thickness of the layer of spray solution on the leaf is dependent on the nature of the leaf as well as on the surface tension of the water. Thus different leaves react differently: the leaf structure affects the thickness of the fluid layer (Fernández and Brown, 2013). The same reasoning suggests that spray efficiency can be boosted by adding substances which increase the cover layer thickness (although without affecting the leaves after application) (Fernández and Brown, 2013). But in contrast to Fernández and Brown 2013 we now have both, a reason to use surfactants (to create a finer spray and promote covering the leaf) as well as a reason not to use them (the cover layer gets thinner when using surfactants). So "surfactants" and "stickers" can give really contrasting results on different leaves. How can structured decisions be made?

There seems to be no reason to use theoretic speculation here. It is easy and certainly more reliable to gather measured facts. Just dipping a well measured area of random leaves in the solution to be sprayed will give an accurate idea of how much spraying liquid can adhere to the leaves. Once the amount is chosen, one can either prepare the proper concentration of nutrients to be dosed or decide to add adjuvants to improve leaf coverage.

Interestingly enough, the maximum uptake efficiencies reported are 70% (Table 8). This means that the application concentration is not as important as researchers claim (Fernández et al., 2013). It is presumed that the concentration on the leaf will increase rapidly when the water on the leaf starts to evaporate. So even dosing low concentrations will soon result in high leaf contact concentrations and subsequent uptake. Having said that, the uptake <u>rate</u> will of course be higher with higher initial concentrations.

Metabolic efficacy

Even when nutrients have arrived in the apoplast, either by foliar application or by root uptake, this is no guarantee that they will reach the target organs. For translocation and re-mobilization in the plant, phloem transport is essential. However, for the immobile elements, Ca, Fe, Zn, Cu, Mo and B, phloem load is almost negligible (Marschner, 2012) and therefore the benefit for the plant of these elements applied by foliar spray is potentially poor. Consequently foliar application may only benefit tissues that directly receive the fertilizers.

Some special cases:

1. Under conditions of deficiency or marginal nutrient availability, it has been shown that for immobile elements, more than 90% of these nutrients are bound in permanent structures and under these conditions the binding sites for the specific nutrients in leaves are unsaturated (Brown and Bassil, 2011). Consequently foliar applied nutrients will then be absorbed primarily at these sites before they become available for locations and functions elsewhere (Fernández et al., 2013).

2. If these sites are saturated, nutrients absorbed by roots may be more effectively transported to those organs still lacking these nutrients. This could be reason that foliar applications for immobile nutrients could be

effective. For example Hanson (1991) and Leite et al. (1998) showed that B sprays are most effectively translocated when B is already sufficiently present in foliage in fruit crops and coffee. Similarly Zn was translocated better to grains when a combination of foliar and soil applied Zn was used (Erenoglu et al., 2002). Similarly, some of these findings were reported for Cu also by Fernández et al. (2013).

3. In contrast to the examples above, poor movement of immobile elements from sprayed leaves has been documented as well. For example Swietlik and Laduke (1991) showed this phenomenon clearly for Zn and Mn in citrus as did Hanger (1979) in a review for Ca in maize, barley and many other plant species.

4. Ca can be considered as the most immobile of all plant nutrients, with phloem concentration almost zero (Marschner et al., 2012 Gilliham et al., 2011). Not surprisingly, many Ca-disorders, like blossom end rot in tomato and pepper, tip-burn in lettuce, bitter pit in apples, can be related to problems with Ca-translocation in young, non-transpiring growth tips and fruits (Hanger, 1979; Gilliham et al., 2011; Sonneveld and Voogt, 2009). Theoretically, foliar application would not work, if re-mobilisation from the leaf to developing organs or tissue does not take place. Nevertheless a vast number of publications can be found on efforts to enhance Ca levels in fruits and other plant organs where Ca-disorders are problematic, though with a number of disappointing results (Blanco et al., 2010, Koutinas et al., 2010).

5. There is a generally accepted consensus that for fruit crops, multiple sprays are necessary to have any effect, where at the same time it is not clear if this is due to enhanced local absorption or to a better transport (Lotze et al., 2008, Perya et al., 2007). Specific Ca sprays in apples to prevent disorders are beyond doubt, but for fruit-vegetables like tomato and sweet pepper, the effects are less clear (Incrocci, 2013; Bleyaart, 2013). The application is mainly directed to the leaf canopy, and Ca translocation to fruits is negligible. Nevertheless, some authors found a reduction in blossom end rot as an effect of Ca spray (Marcelis and Ho, 1999). The most important factors for Ca efficiency are timing of the application and the crop stage.

6. Notwithstanding the sometimes positive effects of Ca sprays reported, there seems to be no metabolic explanation for these findings. Therefore methods to get more reliable data are needed. Research with isotopic labelled Ca used in the research by Kerton et al. (2009) enabled them to find places where ion transport failed. It is suggested to use the approach of Kerton et al. (2009) into the required methods to get more reliable data (Fig. 2).

7. For the mobile nutrients N, P, K, Mg, S Cl and Ni, the nutrient status of the plant does not affect the ability to (re-)mobilize nutrients. Only a fraction is associated in permanent structures and these elements are also transported by the phloem (Marschner, 2012). Apart from absorption dynamics, the efficacy of foliar application for these elements will therefore not so much be affected by plant metabolism as it is for the immobile nutrients.

8. For B, in some plant species producing poly-ol, B is mobile in the plant, for others species B is immobile (Brown and Bassil, 2011). (Poly-ols being alcohols containing multiple hydroxyl groups). Obviously in the polyol producing plants, B transport will follow the mobile pathway.

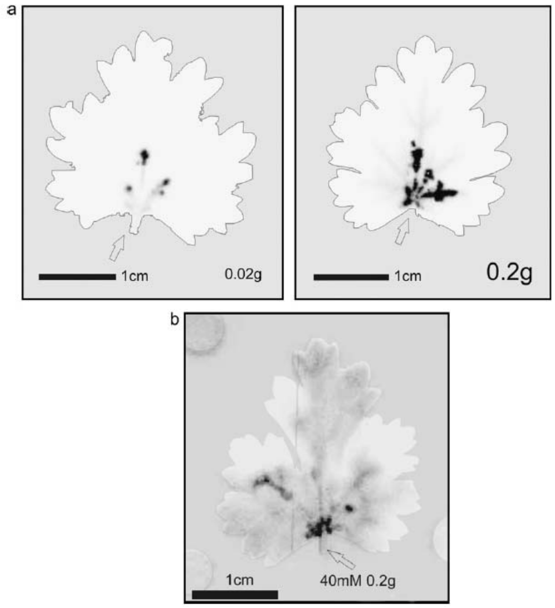


Figure 2. Accumulation of Ca, using 45Ca to visualize, in leaves of Coreandrum sativum exposed to different transpiration, showing that xylem imported Ca in the leaf accumulates in the center

This illustrates the uncoupling of water and Ca from the transpiration stream and indicates the existence of threshold for Ca for entering the symplast (After Kerton et al., 2009).

Unraveling the knowledge; case study Fe

As discussed in previous paragraphs, the efficacy of foliar sprays depends on many factors and evaluation of all factors involved is complicated. The complexity and sometimes contradictory information in literature is here demonstrated for Fe.

Fe, in contrast to Ca, Zn, and Cu, is considered an intermediately mobile nutrient (Marschner 2013). However phloem concentrations reported are very low (Marschner 2013), and phloem solution has high pH values and will cause insolubility of Fe-salts (Mass et al., 1988).

Nevertheless Garnett and Graham (2005) reported high levels of re-mobilized Fe and Cu during grain filling in wheat. This is much in contrast with findings from Hocking (1994) and Pearson and Rengel (1994) who found negligible re-mobilization of Fe in wheat. Abadia et al. (2011) and Fernández et al. (2009) suggest that the mobility of Fe in plants depends on several factors, but most importantly on the Fe-source. There is a vast number of publications on foliar Fe application with different Fe sources, showing sometimes positive, sometimes negative results with chelates as well as with salts, whether or not with additives. There are also many reports from commercial practice showing that re-greening of chlorotic crops by foliar sprays varies in success as well. Moreover, the incidence of chlorosis associated with Fe deficiency is not clearly related to Fe contents in the tissue, and in severe chlorotic plants, plant tissue sometimes seems to have sufficient Fe levels (Sonneveld and Voogt, 2009). This so-called “chlorosis paradox” (Römheld; 2000) is probably due to precipitation of insoluble Fe compounds in cell tissue, making Fe unavailable for metabolic functions.

As stated by Alvarez-Fernandez et al. (2004), the efficacy of foliar Fe application depends on many factors related to: type of Fe source (including Fe-compound, additives), leaf morphology, physico-chemical and plant-physiological factors. In Table 9 it is attempted to unravel and structure factual knowledge for Fe. Table 9a shows which physical and chemical factors affecting the efficiency of sprays have been quantitatively described in our limited search. Physiological factors have been listed in table 9b. Many of these factors will in practice interact and counteract. Some conclusions may be that chelation is neutral to positive for leaf uptake of iron, and iron salts generally result in low leaf uptake. The climate factors at least do not give contradicting trends and are in accordance to the listing in paragraph "How to apply foliar fertilization." Physiological factors do not render information on which actions can be based yet.

To understand more clearly the role and the effects of physico-chemical, plant-physiological and all other factors mentioned on the efficacy of foliar application, further elaboration of the approach above is needed. This approach can then be used to analyze and evaluate the information and focus on very specific crops and crop stage combinations. For example: The difference of the efficacy of Ca spray on the prevention of Ca disorders in fruits of tomato and apple can be understood only if the differences in fruit development in relation to crops stage, and the physiological differences (e.g., indeterminate versus determinate growth, rough versus smooth epidermis) of both crops are taken into account.

Table 9. Framework of the reported interaction effect of Fe foliar applications, related to physical chemical factors and plant characteristics, specified per crop

9A Physical and chemical factors

			Other Effect	Fe Source					Solution pH	Increase Light	Increase Concen-tration	Relative Humidity	Surfactant
Crop	Citation	Crop Effect		Fe(III) chelate)*	Fe-salts	Fe(III) citrate	Fe-salts + acid	Fe IDHA)**					
Citrus	Basiouny et al., 1970		Leaf penetration	+	-								
Citrus	Basiouny and Biggs, 1976		Mobilisation	+	-								
Apple Grape	Schlegel et al., 2006		Leaf penetration					+					
Pear	Alvarez Fernandez et al., 2004	Re-greening		=	=								
Kiwi	Rombola, 2000	Re-greening		=	=								
Groundnut	Singh and Dayal, 1992	Re-greening, yield response		=	=	=							
Kiwi	Tagliavini et al., 2000	Re-greening		=	=								
Pear	Garcia-Lavina, 2002	Re-greening			=	=	=						
Grape	Reed et al., 1998	Re-greening		=	=								
Peach	Reed et al., 1998				0								
Not specified	Fernandez et al., 2006		Fe absorption rate						pH < 5				
Not specified	Schönherr et al., 2005		Fe absorption								Negative correlation		
Not sepcified	Albano, 2001		Fe absproption							Negative correlation			
Not sepcified	Schönherr et al., 2005		Fe absorption							Negative correlation			
Not specified	Dybing and Currier, 1959		Leaf penetration									Positive correlation	
Not specified	Schönherr, 2001		Leaf penetration									Positive correlation	
Not specified	Uhlig and Wissemeier, 2000		Phytotoxicity										Reduction

\+ Positive effect = Equal effect 0 No effect

)* Various types are used, this column refers to the standard types: EDTA, DTPA and EDDHA.

)** Specific chelate formulation

9B Physiological factors

				Observation / factor involved			
Crop	Citation	Crop Effect	Other Effect	Complexation in Plant	Plant Stage	Leaf Age	Hydraulic Conductance Cuticula
Not specified	Epstein, 2005		Immobile				
Not specified	Palmer and Guerinot, 2009		Phloem mobility	X			
not specified	Waters and Sankaran, 2011		Phloem mobility	X			
not specified	Garnett and Graham, 2005		Phloem mobility		X		
not specified	Shi et al., 2011		Phloem mobility		X		
not specified	Weinbaum, 1996		Leaf penetration			Negative correlation	
pear	Abadia et al., 1988; Abadia, 1992; Abadia et al., 2011; Monge et al., 1993		Leaf penetration				Negative caused by deficiency

x observed effect

5 Conclusions

The conclusions are structured according to the main topics in the discussion. They are followed by a listing of knowledge gaps found. Follow up on the knowledge gaps discussed is as far as possible combined with or added to the main topics in the conclusions. One topic about the knowledge gaps is added to the conclusions.

1. **Reasons to apply:** Although virtually all authors report widely different reasons to apply nutrients via the leaf, alternatives to foliar application are not simultaneously evaluated.

   It is concluded that to improve nutrient use, it is essential to assess the likely effectiveness of alternative fertilizer application methods, as well as foliar application, before deciding on the fertilization strategy.

   This can be realized or at least stimulated by expanding the list of reasons to apply foliar applications (Tables 6 and 7) into an overview showing successful alternatives. To make the final choice between application methods, measurement data and interpretation skills will be needed, i.e. the ability to read, understand and use soil and crop analyses.

2. **Concentration, volume and timing:** Wide ranges in efficacy and concentration were found between foliar applications, even when dealing with the same element. Analysis showed that the applied quantities were not always related to the crop requirements. Both under- and overdosing appear to be common.

   For at least the immobile nutrients (N, P, K and Mg) it is concluded that, in order to improve the delivery efficiency it is essential to define the correct concentration of the dosing, the quantity to be sprayed and the frequency of spraying. This conclusion may also apply for the immobile nutrients (Ca, Fe, Mn, Zn and Cu) but only for specific circumstances. When leaves are the target organ for the immobile element, the conclusion will apply. When immobile elements are necessary in plant organs other than the expanded leaves, additional analysis is necessary to be sure transport to the target organ is at all possible (see the conclusions on “Metabolic efficacy”).

   An essential tool to develop is a measurement method for the coverage per leaf in thickness (micrometer) and in volume in L m^{-2} by sprays. That volume is needed to calculate concentration, once quantity and timing are known. Such a measuring method is crop specific and can help to choose the best of alternative spray compositions.

   Increase of the efficacy then can be realized by creating crop specific tables showing the crop nutrient requirement in the crop cycle course and the maximum efficient dosage concentration and volume for a given leaf coverage. These crop nutrient requirements may then be used to calculate dosing concentration, frequency and quantity for a given leaf coverage in L m^{-2}.

3. **Leaf uptake:** The uptake concentration is influenced by 15-30 factors, each of which can be important at times. It is impossible to accurately estimate the combined effect of these factors for a particular case. As argued in the discussion section on “Leaf uptake,” a measurement may help to avoid using combined single factor experimental data from different sources. The measurement to develop can deal with complex interactions of leaf surface, plant age, climate, the use of various adjuvants, etc.

   It is concluded that it is necessary to develop a measuring method to create reliable data on the leaf uptake of a particular crop. This method will quantify the effects of complex interactions of leaf surface, plant age, climate, the use of various adjuvants, etc. in one leaf uptake value. It will also allow the comparison of different spray compositions, delivering hard data on the efficacy of single changed factors such as adjuvant concentration, counter ion, etc. Step wise application of the developed method for changes in the spray formulation will systematically improve leaf uptake efficiency.

Such a leaf uptake measurement method can be realized by adapting existing tests which measure the leaf uptake efficiency of crop protection agents. NB these are different tests than the tests for leaf coverage.

4. **Metabolic efficacy:** The efficacy of foliar applied nutrients is to a great extent determined by the mobility of nutrients. The metabolic efficacy of foliar applied nutrients regularly differs from the uptake efficacy, e.g., often for Ca and Fe; and for Ca, Fe, Mn, Zn, Cu and B when low dosing is used in combination with severe leaf deficiencies of those elements. The metabolic efficacy of foliar applied nutrients may also differs from those nutrients applied via the roots for situations with severe leaf deficiencies. The internal mobility of specific nutrients is dependent on very specific molecular pathways.

   In conclusion, very specific information for Ca, Fe, Mn, Zn, Cu and B on the internal mobility needs to be gathered. Research using isotopes to trace the translocation of applied elements will be valuable.

5. **Unravelling knowledge:** The interactions involved in foliar fertilization as described in the literature are complex and specific, and the efficacy depends on many factors. A detailed framework is needed to unravel the various results, related to the type of the nutrient source, leaf morphology, physico-chemical, plant-physiological and environmental factors. This is necessary to structure the knowledge in order to obtain a clearer picture and find leads for further development. This can be realized by a more focused literature reading on the translocation of nutrients from the leaf to target organs. Possible effects of physico-chemical, plant-physiological and all other factors mentioned on the efficacy of foliar application can then be evaluated on their relevance for the translocation. Similarly the possible effects of specific crops and crop stage combinations can then be evaluated on their relevance for the translocation.

From the literature reviewed, the efficacy of sprays of immobile elements (Ca, Fe, Mn, Zn, Cu and B) are the least unambiguous and mainly related to problems with remobilization. Therefore the development of foliar fertilizers with better leaf attachment, penetration and apoplastic absorption would not be of much help here. Much more improvement in the efficacy of foliar spays will then be achieved if ways can be found to influence the remobilization of nutrients in the symplast, like compounds that mimic the natural processes in the plant, for instance the B-polyol mechanism.

Gaps in knowledge

1. Timing of the application of foliar spray lacks guidance. Apart from some fruit crops, where the application is carried out on basis of plant characteristics (fruit size) and plant analysis, the decision to apply a foliar fertilization is based on experience or routine. More examination is needed about when, how and how much should be sprayed. This gap is addressed in conclusion 2 (concentration, volume and timing) for the crop groups chosen.

2. A better understanding of processes involved in the nutrient pathway once they reach the leaf surface and the subsequent movement into the leaf and transport to the tissue are needed. Especially the relations with parameters such as leaf age and plant stage need to be explored more deeply. This gap is addressed in conclusion 3 (leaf uptake) but not in a way leaf age and plant stage are explicitly used to improve the decisions on how to use foliar applications. It is suggested to add to the analysis accompanying the test description some general recommendations to alter the spray composition based on leaf age and plant stage.

3. The possibilities of N, P and K foliar application to avoid problems of low availability due to low root zone temperatures needs to be evaluated further. This gap is not dealt with.

4. Does foliar Ca supply have potential to ameliorate Ca disorders? Many crops and crop conditions are susceptible to Ca- related disorders. However information on targeted supply, taking into account physiological, crop stage and environmental factors is lacking. This gap is highly relevant and related to the both conclusion 3 (leaf uptake) and conclusion 4 (metabolic efficacy).

5. Related to the above, the potential of adjuvants in the spraying solution to achieve better penetration into the leaf tissue needs to be investigated. This gap is addressed in conclusion 3 (leaf uptake) and to a lesser extent by conclusion 2 (concentration, volume and timing).

6. What is true about the effect of Ca and Mg spay on leaf quality? This gap is a new topic not covered by the conclusions. A focused literature analysis is necessary to decide if this topic merits further actions.

7. A proper evaluation is needed on the environmental impact of foliar applications compared to soil application. This needs to be specified for individual macro nutrients. The state of the art of sustainable fertilization and irrigation techniques should be taken into consideration. This gap is covered by conclusion 5 (alternative application methods).

8. What is the interaction of nutrients or fertilizers and also what are interactions between nutrient application and PPP's? This gap seems to be ruled by the saturation products and the point of deliquescence of the nutrients involved whereas there is no information on interactions of PPP's with nutrients other than through pH effects. Possibly a focused literature analysis may help to decide on the importance of this knowledge gap.

6 Acknowledgements

The authors would like to express appreciation to all those who provided us with information on our request.

Jaap Brink (Kali und Salz), Franky Coopman and Peter Bleyaart (INAGRO), Rene Corsten, Ben Hartog and Theo Roelofs (DLVplant), Stan Deckers (PC fruit), Marco de Groot (Kairos), Eugenie Dings (Flori consult), Mauricio Matthias (Brazil), Enrique Eymar (univ. Madrid), Matthias Fink (Vers. anstalt Grossbeeren), Annemiek Elsen (soil service Belgium), TjeerdJan Stomph (Wageningen UR) and Harmen Tjalling Holwerda (SQM).

7 References

Abadia, A., F. Ambardbretteville, R. Remy and A. Tremolieres, 1988.
Iron deficiency in pea leaves – effect on lipid composition and synthesis. *Physiol. Plant*, 72:713-717.

Abadia, J., 1992.
Leaf responses to iron deficiency – a review. *J. Plant Nutr.*, 15:1699-1713.

Abadia, J., S. Vazquez, R. Rellan-Alvarez, H. El-Jendoubi, A. Abadia, A. Alvarez-Fernandez, and A.F. Lopez-Millan. 2011.
Towards a knowledge-based correction of iron chlorosis. *Plant Physiology and Biochemistry*, 49:471-482.

Aciksoz, S.B., A. Yazici, L. Ozturk and L. Cakmuk, 2011.
Biofortification of wheat with iron through soil and foliar application of nitrogen and iron fertilizers. *Plant and Soil.* 349(1-2): 215-225.

Afifi, M.H.M., R.K.M. Khalifa and Y.E.D. Camilia, 2011.
Urea foliar application as a partial substitution of soil-applied nitrogen fertilization for some maize cultivars grown in newly cultivated soil. *Australian Journal of Basic and Applied Sciences,* 5(7):826-832.

Albano, J.P. and W.B. Miller, 2001.
Photodegradation of Fe DTPA in nutrient solutions. I. Effects of irradiance, wavelength, and temperature. *Hortscience*, 36:313-316.

Albrigo, L.G. and J.P. Syversten, 2001.
What about Foliar NPK on Citrus? Fluid Journal, summer 2001, 1-3

Albrigo, L.G., 2002.
Foliar uptake of N-P-K sources and urea biuret tolerance in citrus. *Proceedings of the International Symposium on Foliar Nutrition of Perennial Fruit Plants*. M. Tagliavini, M. Toselli, L. Bertschinger, D. Neilsen and M. Thalheimer: 627-633.

Alvarez-Fernandez, A., P. Garcia-Lavina, C. Fidalgo, J. Abadia and A. Abadia, 2004.
Foliar fertilization to control iron chlorosis in pear (Pyrus communis L.) trees. *Plant and Soil*, 263 (1-2):5-15

Amor, F.M.D, S. Molina, M.F. Espinosa, P. Varó and M.C. Gómez, 2006.
Foliar applications of urea as a tool to reduce nitrate contamination in greenhouse crops. In *Acta Horticulturae*, pp 403-408.

Basiouny, F.M., C.D. Leonard and R.H. Biggs, 1970.
Comparison of different iron formulations for effectiveness in correcting iron chlorosis in citrus. *Proceedings of the Florida State Horticultural Society,* 83:1-6.

Basiouny, F.M. and R.H. Biggs, 1976.
Penetration of 59Fe through isolated cuticles of citrus leaves. *Hortscience,* 11:417-419.

Brink, J., 2013.
Personal communication. K+S, Breda, The Netherlands.

Benzing, H., K. Henderson, B. Kessel and J. Sulak, 1976.
The Absorptive Capacities of Bromeliad Trichomes. *American Journal of Botany*, 63(7):1009-1014.

Bleyaart, P., 2013.
Personal communication. Inagro, Department of Open Air Horticulture, Rumbeke-Beitem, Belgium.

Boaretto, R.M., J.A. Quaggio, D. Mattos Jr., T. Muraoka and A.E. Boaretto, 2011.
Boron uptake and distribution in field grown citrus trees. Journal of Plant Nutrition 34 (6): 839-849.

Blanco, A., V. Fernandez and J. Val, 2010.
Improving the performance of calcium containing spray formulations to limit the incidence of bitter pit in apple (Malus x domestica borkh). *Scientia Horticulturae*, 127:23-28.

Brown, P.H. and E. Bassil, 2011.
Overview of the acquisition and utilization of boron, chlorine, copper, manganese, molybdenum, and nickel by plants and prospects for improvement of micronutrient use efficiency. In *The molecular and physiological basis of nutrient use efficiency in crops*, M.J. Hawkesford and P.B. Barraclough, editors. Wiley-Blackwell, 377-429.

Cakmak, I., M. Kalayci, Y. Kaya, A.A. Torun, N. Aydin, Y. Wang, Z. Arisoy, H. Erdem, A. Yazici, O. Gokmen, L. Ozturk and W.J. Horst, 2010.
Biofortification and localization of zinc in wheat grain. *Journal of Agricultural and Food Chemistry*, 58(16): 9092-9102.

Chavez-Aguilar, G., M.E. Fenn, A. Gomez-Guerrero, J. Vargas-Hernandez and W.R. Horwath, 2006.
Foliar nitrogen uptake from simulated wet deposition in current-year foliage of Abies religiosa. *Agrociencia*, 40(3):373-381.

Collas, D. 2005.
Bladvoeding in de teelt van pitfruit (NL). Katholieke Hogeschool Kempen.

Coopman, R. 2013.
Personal communication. Inagro, Department of Open Air Horticulture, Rumbeke-Beitem, Belgium.

Corsten, R. 2013.
Personal communication. DLV-plant, Vleuten, The Netherlands.

Corriveau, J., L. Gaudreau, J. Caron, S. Jenni and A. Gosselin, 2012.
Effect of water management, fogging and Ca foliar application on tipburn of Romaine lettuce (*Lactuca sativa L.*) cultivated in greenhouse. *Acta Hort.*, 927, ISHS 2012.

Deckers, 2013,
Personal communications, PC Fruit, St. Truiden, Belgium.

Dings, E., 2013.
Personal communication. Flori-consult, Venlo, The Netherlands.

Dong, S., D. Neilsen, G.H. Neilsen and L.H. Fuchigami, 2005.
Foliar N application reduces soil NO_3-−N leaching loss in apple orchards. *Plant and Soil*, 268:357-366.

Dybing, C.D. and H.B. Currier, 1961.
Foliar penetration by chemicals. *Plant Physiology*. 36:169-174.

Elsen, A., 2013.
Personal communication. Soil service, Heverlee, Belgium.

Eichert, T., A. Kurtz, U. Steiner and H.E. Goldbach, 2008.
Size exclusion limits and lateral het erogeneity of the stomatal foliar uptake pathway for aqueous solutes and water-suspended nanoparticles. *Physiol. Plant*., 134:151–160.

Epstein, E. and A.J. Bloom, 2005.
Mineral nutrition of plants: *Principles and perspectives*, 380.

Erenoglu, B., M. Nikolic, V. Romheld and I. Cakmak, 2002.
Uptake and transport of foliar applied zinc (65Zn) in bread and durum wheat cultivars differing in zinc efficiency. *Plant and Soil*, 241:251-257.

Eymar, E, 2013.
Personal communication. University of Madrid, Spain.

Fernandez, V., V. Del Rio, J. Abadia and A. Abadia, 2006.
Foliar iron fertilization of peach (Prunus persica L. batsch): Effects of iron compounds, surfactants and other adjuvants. *Plant and Soil*, 289:239-252.
Fernández, V. and T. Eichert, 2009.
Uptake of hydrophilic solutes through plant leaves: Current state of knowledge and perspectives of foliar fertilization. *Critical Reviews in Plant Sciences,* 28(1-2):36-68.
Fernández, V. and P.H. Brown, 2013.
From plant surface to plant metabolism: the uncertain fate of foliar-applied nutrients. *Frontiers of Plant Sci.* 4:289.
Fernández, V., T. Sotiropoulos and P. Brown, 2013.
Foliar Fertilization: Scientific Principles and Field Practices. Paris. International Fertilizer Industry Association.
Fink, M. 2013.
Personal communication. Institute of Vegetable and Ornamental Crops, Grossbeeren, Belgium.
Garcia-Lavina, P., A. Alvarez-Fernandez, J. Abadia and A. Abadia, 2002.
Foliar applications of acids with and without $FeSO_4$ to control chlorosis in pear. *Acta Horticulturae*. 594:217-222.
Garnett, T.P. and R.D. Graham. 2005.
Distribution and remobilization of iron and copper in wheat. *Annals of Botany*, 95:817-826.
Groot, de, M., 2013.
Personal communication. Kairos, Vleuten, The Netherlands.
Gilliham M, M. Dayod, B.J. Hocking, B. Xu, S.J. Conn, B.N. Kaiser, R.A. Leigh and S.D. Tyerman. 2011.
Calcium delivery and storage in plant leaves: exploring the link with water flow. *Journal of Experimental Botany* 62: 2233-2250.
Hanger, B.C. 1979.
The movement of Ca in plants. *Comm. Soil Sci. Pl. Anal.* 10:171-193.
Hanson, E.J. 1991.
Movement of boron out of tree fruit leaves. *Hortscience,* 26:271-273.
Hartog, B. 2013.
Personal communication. DLV-plant, De Kwakel, The Netherlands.
Huett, D.O. and I. Vimpany, 2006.
An evaluation of foliar nitrogen and zinc applications to macadamia. *Australian Journal of Experimental Agriculture* 46:1373-1378.
Holwerda, H.T., 2013.
Personal communications. SQM Europe, Antwerp, Belgium.
Incrocci, 2013.
Personal communication. University of Pisa, Italy.
Kannan, S., 2010.
Foliar fertilization for sustainable crop production, In: *Sustainable Agriculture Reviews Genetic Engineering*, Biofertilisation, Soil Quality and Organic Farming, Springer Science+Business Media.
Kaya, C. and D. Higgs, 2002.
Improvements in physiological and nutritional developments of tomato cultivars grown at high zinc by foliar application of phosphorus and iron. *Journal of Plant Nutrition* 25(9):1881-1894.
Kerton, M., H.J. Newbury, D. Hand and J. Pritchard. 2009.

Accumulation of calcium in the centre of leaves of coriander (Coriandrum sativum L.,) is due to an uncoupling of water and ion transport. *Journal of Experimental Botany* 60:227-235.

Keshavarz, K., K. Vahdati, M. Samar, B. Azadegan and P.H. Brown, 2011.
Foliar application of zinc and boron improves walnut vegetative and reproductive growth. *HortTechnology* 21:181-186.

Kennisakker, 2013.
http://www.kennisakker.nl/, 10 07 2013, de kennisakker, productschap akkerbouw.

Koutinas, N., T. Sotiropoulos, A. Petridis, D. Almaliotis, E. Deligeorgis, I. Therios and N. Voulgarakis, 2010.
Effects of preharvest calcium foliar sprays on several fruit quality attributes and nutritional status of the kiwifruit cultivar Tsechelidis. *Hortscience*, 45:984-987.

Leite, V.M., P.H. Brown and C.A. Rosolem, 2007.
Boron translocation in coffee trees. *Plant and Soil*, 290:221-229.

Liew, Y.A., S.R. Syed Omar, M.H.A. Husni, A.M.A. Zainal and P.A. Nur Ashikin, 2012.
Effects of foliar applied copper and boron on fungal diseases and rice yield on cultivar MR219. *Pertanika Journal of Tropical Agricultural Science*, 35(2):339-349.

Lotze, E., J. Joubert and K.I. Theron, 2008.
Evaluating pre-harvest foliar calcium applications to increase fruit calcium and reduce bitter pit in 'Golden Delicious' apples. *Scientia Horticulturae,* 116:299-304.

Ma, B.L., M. Li, L.M. Dwyer and G. Stewart, 2004.
Effect of in-season application methods of fertilizer nitrogen on grain yield and nitrogen use efficiency in maize. *Canadian Journal of Soil Science*, 84(2):169-176.

Maas, van de, R., 2013.
Personal communication. Consultant Applied Plant Research, The Netherlands

Marcelis, L.F.M. and L.C. Ho, 1999.
Blossom-end rot in relation to growth rate and calcium content in fruits of sweet pepper (Capsicum annuum L.). *Journal of Experimental Botany* 50:357-363.

Malhi, S.S. and R.E. Karamanos, 2006.
A review of copper fertilizer management for optimum yield and quality of crops in the Canadian Prairie Provinces. *Canadian Journal of Plant Science* 86(3):605-619.

Marschner, P., 2012.
Mineral Nutrition of Higher Plants, San Diego: Academic Press.

Matthias, M., 2013.
Personal communication. Consultant, Brazil.

Monge, E., C. Perez, A. Pequerul, P. Madero and J. Val, 1993.
Effect of iron chlorosis on mineral-nutrition and lipid-composition of thylakoid biomembrane in Prunus persica L. bastch. *Plant and Soil,* 154:97-102.

Mosali, J., K. Desta, R.K. Teal, K.W. Freeman, K.L. Martin, J.W. Lawles and W.R. Raun, 2006.
Effect of foliar application of phosphorus on winter wheat grain yield, phosphorus uptake, and use efficiency. *Journal of Plant Nutrition* 29(12):2147-2163.

Obreza, T.A. and T. Morgan (eds.), 2008.
Nutrition of Florida Citrus Trees, 2nd Edition.' Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Palmer, C.M. and M.L. Guerinot, 2009.
Facing the challenges of Cu, Fe and Zn homeostasis in plants. *Nat. Chem. Biol.*, 5:333-340.

Peryea, F.J. 2007.

Comparison of dormant and circum-bloom zinc spray programs for washington apple orchards. *J. Plant Nutr.*, 30:1903-1920.
Pooniya V. and Y.S. Shivay, 2013.
Enrichment of Basmati rice grain and straw with zinc and nitrogen through ferti-fortification and summer green manuring under Indo-gangetic plains of India. *Journal of Plant Nutrition*, 36, 91-117.
Reed, D.W., C.G. Lyons and G.R. McEachern, 1988.
Field-evaluation of inorganic and chelated iron fertilizers as foliar sprays and soil application. *J. Plant Nutr.* 11:1369-1378.
Restrepo-Díaz, H., M. Benlloch and R. Fernández-Escobar, 2009.
Leaf potassium accumulation in olive plants related to nutritional K status, leaf age, and foliar application of potassium salts. *Journal of Plant Nutrition* 32(7):1108-1121
Riederer, M., 2006.
Thermodynamics of the water permeability of plant cuticles: characterization of the polar pathway. *Journal of Experimental Botany*, 57(12):2937-2942.
Roelofs, T., 2013.
Personal communication. DLV-plant, Eindhoven, The Netherlands.
Rombola, A.D., W. Bruggemann, M. Tagliavini, B. Marangoni and P.R. Moog. 2000.
Iron source affects iron reduction and re-greening of kiwifruit (Actinidia deliciosa) leaves. *J. Plant Nutr.*, 23:1751-1765.
Römheld, V., 2000.
The chlorosis paradox: Fe inactivation as a secondary event in chlorotic leaves of grapevine. *Journal of Plant Nutrition*, 23(11-12):1629-1643
Sanchez, E.E, S.A. Weinbaum and R.S. Johnson, 2006
Comparative movement of labelled nitrogen and zinc in 1-year-old peach [Prunus persica (L.) Batsch] trees following late-season foliar application. *Journal of Horticultural Science and Biotechnology,* 81:839-844.
Schlegel, T.K., J. Schonherr and L. Schreiber, 2006.
Rates of foliar penetration of chelated Fe(III): Role of light, stomata, species, and leaf age. *Journal of Agricultural and Food Chemistry,* 54(18):6809-6813.
Schönherr, J., 2001.
Cuticular penetration of calcium salts: Effects of humidity, anions, and adjuvants. *Journal of Plant Nutrition and Soil Science-Zeitschrift für Pflanzenernahrung und Bodenkunde*. 164:225-231.
Schönherr, J., V. Fernández and L. Schreiber, 2005.
Rates of cuticular penetration of chelated Fe(III): Role of humidity, concentration, adjuvants, temperature, and type of chelate. *Journal of Agricultural and Food Chemistry*, 53:4484-4492.
Shi, R.L., R. Bassler, C.Q. Zou and V. Romheld, 2011.
Is iron phloem mobile during senescence in trees? A reinvestigation of Rissmuller's finding of 1874. *Plant Physiology and Biochemistry*, 49:489-493.
Singh, A.L. and D. Dayal, 1992.
Foliar application of iron for recovering groundnut plants from lime-induced iron-deficiency chlorosis and accompanying losses in yields. *J. Plant Nutr.* 15:1421-1433.
Smilde, K.W. and J.P.N.L. Roorda van Eysinga, 1968.
Nutritional Diseases in Glasshouse Tomatoes, Pudo, Wageningen, 48 pp.
Sonneveld C. and W. Voogt, 2009.
Plant Nutrition of Greenhouse Crops. ISBN 978-90-481-2531-9 e-ISBN 978-90-481-2532-6. Springer Dordrecht Heidelberg London New York.

Stomph, 2013.
Personal communication. Wageningen UR, centre for system analysis. The Netherlands.

Steen, van der,2013.
Personal communication. Flora Crop Consult. De Lier. The Netherlands.

Swietlik, D. and J.V. Laduke, 1991.
Productivity, growth, and leaf mineral-composition of orange and grapefruit trees foliar-sprayed with zinc and manganese. *J. Plant Nutr.*, 14:129-142.

Swietlik, D, 2002.
Zinc nutrition of fruit crops. *HortTechnology,* 12(1):45-50.

Tagliavini, M., J. Abadia, A.D. Rombola, A. Abadia, C. Tsipouridis and B. Marangoni, 2000.
Agronomic means for the control of iron deficiency chlorosis in deciduous fruit trees, *J. Plant Nutr.* 23:2007-2022.

Tariq, M., A. Akbar, H. Lataf ul and A. Khan, 2010.
Comparing Application Methods for Boron Fertilizer on the Yield and Quality of Tobacco (Nicotiana tabacum L.). *Communications in Soil Science and Plant Analysis*, 41(13):1525-1537.

Toselli, M., M. Thalheimer and M. Tagliavini, 2004
Leaf uptake and subsequent partitioning of urea-N as affected by the concentration and volume of the spray solution and by the shoot leaf position in apple (Malus domestica) trees. *Journal of Horticultural Science and Biotechnology*, 79(1):97-100.

Uhlig, B.A. and A.H. Wissemeier, 2000.
Reduction of non-ionic surfactant phytotoxicity by divalent cations. *Crop Protection,* 19:13-19.

Wada, T., H. Ikeda, H., M. Ikeda and H. Furukawa, 1996.
Effects of foliar application of calcium solutions on the incidence of blossom-end rot of tomato [Lycopersicon esculentum] fruit. *Journal of the Japanese Society for Horticultural Science*, 65(3):553-558.

Waters, B.M. and R.P. Sankaran, 2011.
Moving micronutrients from the soil to the seeds: Genes and physiological processes from a biofortification perspective. *Plant Science*, 180:562-574.

Weinbaum, S., 1988.
Foliar nutrition in fruit trees. In *Plant Growth and Leaf Applied Chemicals*. P.M. Neumann, editor. CRC Press, Boca Raton. 81-100.

Yasir, A.M., S.K. Khalil, M.T. Jan and A.Z. Khan, 2010.
Phenolgy, growth and grain yield of maize as influenced by foliar applied urea at different growth stages. *Journal of Plant Nutrition*, 33 (1):71-79.

Yildirim, E., I. Guvenc, M. Turan and A. Karatas, 2007.
Effect of foliar urea application on quality, growth, mineral uptake and yield of broccoli (Brassica oleracea L., var. italica). *Plant, Soil and Environment*, 53,120-128.

Yuri, J.A., Y. Jorquera, V. Lepe, C. Moggia and A. Neira, 2006.
Estimating deposition of foliarly-applied compounds on apple trees. In *Acta Horticulturae*, 239-244.

Zhang, Y.Q., R.L. Shi, K.M. Rezaul, F.S. Zhang and C.Q. Zou, 2010.
Iron and Zinc Concentrations in Grain and Flour of Winter Wheat As Affected by Foliar Application. *Journal of Agricultural and Food Chemistry*, 58(23):12268-12274

Appendix I. Literature database results

	ANY FIELD	TITLE	KEYWORD
Foliar spray + nutrient*	360		
Foliar + fertiliz*	711		
ELEMENTS			
+ boron		56	32
+ iron		50	47
+ nitr*		200	187
+zinc		85	59
+calcium		36	39
+potassium		49	47
+ phosph*		48	69
+silic*		14	13
+ magnesium		11	12
+sulph*		3	4
+ mangan*		24	22
+ molybd*		5	3
+ copper		12	11
CROPS			
Field vegetables (excl. cereals)		**66**	**36**
+ leek		0	0
+ Brassica (excl. rapa)		8	5
+ onion		4	1
+ celery		1	0
+ lettuce		9	3
+ cotton		23	12
+ soybean OR soya		21	15
Fruit crops (excl. citrus)		**69**	**35**
+ apple*		44	19
+ pear*		11	10
+ olive		14	6
+ Citrus		**35**	**21**
Tropical Fruits		**19**	**9**
+ mango		13	7
+ banana		3	0
+ pineapple		0	0
+ papaya		3	2
Cereals		**254**	**240**
+ rice		45	34
+ millet		6	2
+ maize OR corn		122	101
+ sorghum		3	3
+ oilseed OR canola		3	8
+ wheat		70	77
+ barley		4	12
+ alfalfa		1	3
Other search terms			
+ tropical AND vegetable*		0	0
+ vegetable*		0	0
+ tree		70	54
+ fruit		88	64

Appendix II. List of contacts consulted for the common practice of foliar application

Name	Company/Institution	Place	Country
Bleyaart, P.	Inagro, department of open air horticulture	Rumbeke-Beitem	Belgium
Bries, J.	Soil Service Belgium	Heverlee	Belgium
Coopman, R.	Inagro, department of open air horticulture	Rumbeke-Beitem	Belgium
Corsten, R.	DLV-plant	Vleuten	NL
De Groot, M.	Kairos	Vleuten	NL
Deckers, S.	PC fruit	St Truiden	Belgium
Dings, E.	Flori-consult	Venlo	NL
Elsen, A.	Soil Service Belgium	Heverlee	Belgium
Eymar, E.	University of Madrid	Madrid	Spain
Fink, M.	Institute of Vegetable and Ornamental Crops	Grossbeeren	Germany
Hartog, B.	DLV-plant	De Kwakel	NL
Holwerda, H.T.M.	Product development, SQM	Antwerp	Belgium
Incrocci, L.	University of Pisa	Pisa	Italy
Matthias, M.	Consultant	S. Paolo	Brazil
Roelofs, T.	DLV-plant	Eindhoven	NL
Stomph, T.J.	Wageningen UR, centre for crops system analysis	Wageningen	NL
van der Maas, R.	Applied Plant research	Randwijk	NL
van der Steen, J.	Flora crop consult	De Lier	NL

Appendix III. Summary of information from consultants

number	information source				Deficiency		root env.problems		other					Application strategy							Remarks
	name	Crop	category	nutrient	immediat intervention	emerging def.	problems	description	reason	experience	standard routine	equal as PPP's	volume l/ha	standard schedule	together with PPP's	leaf samples	benchmark for decision	replication frequency	monitoring the effect	control by leaf samples	
1	Bleyaart, P.	tomato	vegetable	Ca					deficiency			x			x						to prevent blossom end rot
2	Bleyaart, P.	lettuce	vegetable	Ca					deficiency		x	x	1000	x	x						prevention of tipburn
3	Bries, J.																				
4	Brink, J.	oil seed rap	field crops	Mg, K, B																	Preventeion and cure of Mg deficiency , as well as Boron
5	Coopman, R.	Celeriac	vegetable	N, micro elements	x	x	x	sandy soils, leaching	leaf color			x	2000	x	x		consultant	2-3			Mainly done as routine, because of long growing seasons and to enhance leaf color
6	Coopman, R.	Leek	vegetable	N	x	x	x		Standards for N soil are low, possible escape		x			x	x		consultant	1-4	x	x	To escape from too high N in soil after crop, foliar application as means to supply sufficently
7	Coopman, R.	Plant nursery, brassica's	vegetable	NS		x	x		too low nutr.quant. in tray plants		x			x				2			To prevent too lush growth, nutr. suppl in trays is low, Brassica stay long time in trays, therefore nutrietns are depleted. FA is correction
8	Corsten, R.	chrysant	floriculture	Ca, Mg, Fe		x					x	x	2000	x	x		Grower				not widely used, some growers do, but these report very postive on effect on leaf quality
9	De Groot, M.	alstroemeria	floriculture	Fe	x	x											Grower				some growers us it, but results are rather poor
10	Deckers, S.	pear, apple	fruit crop	N			x		low N soil application		x	x	1500	x	x	x	consultant	2-3			This is standard procedure to make sure sufficient N uptake, soil mineral N is deliberately low
11	Deckers, S.	apple	fruit crop	Ca							x	x	1500	x	x			3			to prevent bitter pit in certain varieties
12	Dings, E.	gerbera	floriculture	micro elements		x								x	x		Grower				done as routine
13	Elsen, A.	0	fruit crop	NS	x						x	x	2000	x	x	x	consultant	2-3	x	x	Just done as an easy way to supply top dressing. And as an insurance. More and more now fertigation is used
14	Elsen, A.	pear	fruit crop	N							x			x	x	x					N supply by base and top dr. is low. For frtui development, in later stage, at heavy fruit swelling, N is sprayd
15	Eymar, E.	citrus	citrus	N,P,K, micro			x		soil pH												Several nutritional imbalances with micronutrients are treated very often with foliar applications, specially iron quelates. Sometimes NPK solutions (high potassium levels) with micronutrients are used for fruit growth and ripening

num ber	information source				Deficiency		root env.problems		other					Application strategy							Remarks
	name	Crop	category	nutrient	immediat intervention	emerging def.	problems	description	reason	experience	standard routine	equal as PPP's	volume l/ha	standard schedule	together with PPP's	leaf samples	benchmark for decision	replication frequency	monitoring the effect	control by leaf samples	
16	Fink, M.	gherkin	field crops	N							x	x	1500	x				2			Opinion that application is meant just to supply fertiliser, is washed from the leafs and uptake is by roots mainly
17	Fink, M.	potato	field crops	K					tuber quality	x		x	1500	x	x	x	table	3-4			
18	Hartog, B.	rose	floriculture	P,Mg, K, Ca, NO3, SO4							x		3000	x	x		consultant	2 wks			to harden the leaves
19	Holwerda, H.T.M.	wheat	field crops	N, P, K			x		soil temp.	x											effect on
20	Incrocci, L.	Tomato	vegetable	Ca	X				Reduce blossom-end -rot in saline condition		x	x	2000	x			consultant	4-5	x		To prevent blossom-end rot
21	Incrocci, L.	Gerbera	cut flower	Fe		X		in the root zone	deficiency			X	1500		X		consultant	2-3	x		To prevent iron chlorosis in Gerbera
22	Incrocci, L.	Olive, fruit tree	fruit crop	B, Mn					Standards to increase fruit-set on olive tree		X	X	2000	x			consultant	1-2			To increase the fruit set on fruit tree and in olive tree.
23	Incrocci, L.	Plant nursery	vegetable	Cu					Standards to control plant height in the nursery		X	X	1500	X			Grower				To control plant height in the last phases of nursery.
24	Matthias, M.	tree crops	tree crops	micro elements			x				x			x	x		consultant	2 - 3 wks			FA is done as a standard routine, togethet with PPP's spraying
25	Roelofs, T.	chrysant	floriculture	Ca		x					x						Grower				"results are questionable"
26	Stomph, T.J.	rice	field crops	Zn	x	x	x	poor soils					?		x	x		1-3	x	x	on soils poor in Zn
27	Stomph, T.J.	rice	field crops	Fe	x	x			deficiency			x	?		x	x					
28	Stomph, T.J.	rice	field crops																		
29	van der Maas, B.	pear	fruit crop	P						x											fruit quality
30	van der Steen, J.	gebera	floriculture	micro elements		x	x		deficiency						x						only soi grwon crops (past) not in soil-less culture. Reason not effective !

VFRC

PLANT RESEARCH INTERNATIONAL

WAGENINGEN UR

More information: www.vfrc.org

Virtual Fertilizer Research Center
1331 H Street, NW
11th Floor
Washington, D.C. 20005
USA
E-mail: contact@vfrc.org