7. Perspectives of foliar fertilization

Foliar fertilization has been widely adopted in modern crop management where it is used to ensure optimal crop performance when nutrient supply from the soil is inadequate or uncertain. Foliar fertilizers offer specific advantages over soil fertilizers when plant demand for nutrients exceeds the capacity for root nutrient uptake; when elemental mobility within the plant limits delivery to tissues; and when environmental conditions limit the effectiveness or prevent the application of nutrients to the soil. In many risk-averse, high-value production systems foliar fertilizers are marketed as 'insurance' to minimize the potential impacts of unpredictable nutrient deficiencies.

The supply of nutrients by foliar fertilization represents a significant cost (per kg of applied element) and requires careful consideration of the relative benefit over conventional soil fertilizer applications. Determining the cost:benefit ratio of foliar fertilizers is not trivial and requires a realistic assessment of the economic risk of a nutrient deficiency occurring; quantification of the biological efficacy of the foliar fertilizer; and consideration of the full costs of the application (such as spraying). While it is relatively straightforward to estimate application and yield-lost costs it is much more difficult to determine: 1) the likelihood of an economically relevant nutrient deficiency occurring during the growing cycle; and 2) the biological efficacy of the foliar fertilizer applied. Given the widespread use of foliar fertilizers and the cost of these practices it is remarkable that there are very few examples where the economic viability of foliar fertilizers has been critically assessed. This is at least partially a consequence of the difficulty in knowing accurately the true risk of an economically important nutrient deficiency occurring and the uncertainty as to the effectiveness of the foliar materials used as a solution in treating the effects of the deficiency. The goal of this book is to provide insight into these two uncertainties so that more informed decisions can be made and improved practices can be developed.

As illustrated in the preceding chapters there is a good deal of complexity in determining if plants in a given environment have the potential to experience a nutrient demand that cannot be adequately provided by soil nutrients. Equal complexity exists in predicting if a given foliar application will adequately supply the required nutrients in a timely manner. Regardless of these complexities a fundamental understanding of the principles of foliar fertilization will minimize uncertainty and help improve the efficacy of foliar fertilization in modern crop production.

The factors that govern plant 'demand' for foliar fertilizers and the factors that govern the ability of a foliar formulation to 'supply' nutrients are summarized by the following:

Demand: foliar fertilization is applicable if any of the following situations prevail:

- Plant demand exceeds the capacity of the root to absorb the nutrient. This occurs when:
  - Soil conditions limit nutrient solubility or delivery to the root as a consequence of unfavorable pH or chemical composition of the nutrient; excess soil concentrations of competing ions; unfavorable conditions for root growth; or soil environmental conditions that limit nutrient uptake (unfavorable temperature, moisture or oxygen content).
  - A limitation in uptake capacity as a consequence of plant phenology such as during early spring when many deciduous species flower and set fruit during periods of unfavorable soil temperatures.
  - During periods of peak nutrient requirement such as rapid fruit growth when demand for nutrients can exceed the ability of roots to supply adequate nutrients even in a well-fertilized soil.
- When localized within-plant demand exceeds the capacity for within-plant nutrient re-distribution.
  - This commonly occurs in the vicinity of large fruit and nut clusters, or during grain fill or storage tissue development, and is related to both the highly localized demand for elements (notably N and K) or as a consequence of low phloem mobility of certain elements (notably Ca and B).
  - Within-plant element mobility can also be limited if flowering precedes leaf expansion and thereby limits xylem nutrient transport.
  - Periods of drought or high humidity can also limit both transpirational xylem flow as well as restrict the delivery of phloem-immobile nutrients.
- When plant demand cannot be satisfied due to:
  - Field conditions, application costs or growth stages that prevent the use of soil applications.
  - A perceived need for nutrient 'insurance' to minimize the potential risks of unpredictable nutrient deficiencies.

Supply: the efficacy of foliar fertilization is determined by:

- The physical and chemical characteristics of the fertilizer which determines the total quantity of nutrient that can be delivered and the compatibility of that nutrient with other chemicals.
- The characteristics of the species and the environment in which it is grown.
- The use of additives (surfactants, humectants, spreader/stickers, etc) and the method of application.
- The environment at the time of, and following, foliar application.
- The ability of the nutrient to penetrate into the cytoplasmic volume which is influenced by species; leaf type and age; chemical characteristics of the fertilizer; environmental conditions; and application method.

- The phytotoxicity of the foliar fertilizer mixture which limits the concentration of nutrient that can be applied.
- The mobility of the applied nutrient within the leaf that is determined by its relative phloem mobility, species characteristics, leaf age and immobilization of the element at the site of application.

Ultimately, the decision to use foliar fertilizers requires consideration of each of these demand and supply factors balanced against the relative costs. In circumstances where the soil-type, cropping system or the environment prevent soil application of the required nutrients then foliar fertilization represents an essential practice and as a consequence the primary challenge must be to develop foliar formulations and application methods that are as efficacious and economical as possible. However the majority of foliar fertilizers are not applied under circumstances where soil application is impossible but are rather being applied under the presumption that foliar application is superior to soil application. It is also probably true that the uncertainty of knowing the demand for foliar fertilizers, or the efficacy of a formulation, results in growers utilizing foliar fertilizers inefficiently; either applying them when they are not required; or failing to apply them when they are. In such scenarios which likely represent a large percentage of the conditions under which foliar fertilizers are utilized the challenge is not only to develop foliar formulations and application methods that are as effective and economical as possible, but also to develop methodology to predict if and when nutrients may become limiting and unresponsive to soil applications.

Foliar fertilization, as currently practiced, is both a science and an art and for those who ascribe to the 'spray and pray' philosophy it also resembles a faith. For the science of foliar fertilization to be optimized there is a substantial need to understand the factors that govern the efficacy of foliar fertilizers and to develop formulations and application methods that maximize the chance of beneficial response.

7.1. Conclusions

In this book, we have provided an integrated analysis of the physical, chemical and biological principles known to influence the absorption and utilization of foliar fertilizers by the plant and have reviewed the available laboratory and field results to provide insights into the factors that ultimately determine the efficacy of their application. Our goal was to provide an integrated analysis of what is known and what remains to be discovered toward reaching the goal of optimizing the utilization of foliar fertilizers in modern crop production. The factors that determine the efficacy of foliar fertilization are complex and encompass aspects of physics, chemistry, environment, biology and economics as well as intangibles such as risk aversion and ease of management. While some of the fundamental principles governing the use of foliar fertilizers are well understood there is far more about their technology that remains to be resolved or is yet to be discovered.

Certainties, uncertainties and opportunities

Previous chapters have identified the facts that are known (certainties); those that are unknown or unclear (uncertainties); and the opportunities that exist to improve the practice of foliar fertilization by optimizing our understanding of the factors that govern plant demand for foliar fertilizers as well as the factors that govern the ability of a foliar formulation to supply nutrients. The most important uncertainties that are constraining the utility of foliar fertilizers are as follows:

With regard the factors that govern the ability of a foliar formulation to 'supply' nutrients current knowledge of the following critical processes is inadequate:

- The mechanisms of cuticular penetration of polar, hydrophilic compounds are largely unknown.
- The contribution of the stomatal pathway and other epidermal structures such as trichomes and lenticels, to foliar uptake has not been adequately investigated.
- We have poor understanding of the contact phenomena between the foliar fertilizer formulation and plant surface.
- The role of surfactants, humectants, spreaders/stickers and other additives is not well understood and hence there is no mechanism to predict plant response without empirical testing.
- The factors that affect plant cuticular composition and plant response to foliar application are poorly understood and current knowledge is insufficient to predict or manipulate plant response to a foliar application.

With regard the factors that govern plant demand for foliar fertilizers current knowledge of the following critical processes is inadequate:

- The occurrence and importance of 'transient' or other nutrient deficiencies that cannot be prevented by soil fertilization has not been adequately investigated.
- It is unknown if foliar applied nutrients, once they enter the cellular space, are more or less metabolically available than soil acquired nutrients.
- The mechanism of toxicity of foliar fertilizers is not well understood.
- It is unknown if foliar-applied nutrients can be re-translocated more efficiently than soil derived nutrients.
- The significance of the counter-ion, or other molecules present in the formulation, in the metabolism or transport of nutrient elements following passage into the living cell is unknown.
- The influence of foliar sprays on shoot-to-root signalling and subsequent root growth and nutrient uptake from the soil has not been adequately investigated.

There are clear opportunities to improve the efficacy, or extend the utilization, of foliar fertilizers:

- There is potential to use supplemental foliar fertilizers with soil-applied fertilizers to provide more environmentally friendly, target-oriented and efficient fertilization.

- The full potential of foliar nutrient sprays as a complementary strategy to improve the quality characteristics of crops has not been fully researched.
- The permeability of plant surfaces to nutrient solutions offers the opportunity to supply nutrients to sink organs, bypassing root uptake and translocation mechanisms that limit the nutrient supply of the plant under certain growing conditions.
- There is increasing evidence showing that nutrient deficiencies can damage plant structure and limit responsiveness to subsequent nutrient availability.
- The addition of humectants to the foliar nutrient formulations to prolong the process of solution drying improves the efficacy of the treatments especially in arid and semi-arid areas.
- There is a need for the development of a risk assessment approach to foliar fertilization which would integrate the potential for occurrence of a transient but critical deficiency with the likelihood of a positive outcome and balance these with the risk of a negative outcome based upon formulation, plant and environment conditions at the time of application.
- Methods, both experimental and model-based, are required to predict the potential for a foliar fertilizer to cause toxicity damage.
- More importantly there is a need to better coordinate foliar timing and formulation to match critical periods of plant demand where foliar application may have a specific advantage.

In Chapters 2 to 4, the mechanisms of foliar uptake of nutrient sprays in association with plant structure and function were described in detail. The characteristics of the plant surface as a barrier for the entry of water and solutes were described andremarked on the generally hydrophobic character of the lipid coating covering the epidermis, namely the cuticle. The importance of providing nutrients in formulations that may facilitate the process of foliar uptake was subsequently highlighted and developed. In order to ensure the effectiveness of foliar nutrient sprays, one of the key factors that can actually be controlled, and that may radically change the performance of a particular nutrient compound, is the addition of suitable adjuvants. Efforts should be made to improve the physico-chemical properties of nutrient spray formulations to ensure the effectiveness and reproducibility of treatments under different environmental conditions. For instance, foliar applications in arid and semi-arid areas may be hindered by the rapid drying of spray solutions after treatment, and the addition of humectants may significantly increase the rate of uptake of foliar-applied nutrients.

Research and development in the area of foliar fertilizer formulations may increase the market and improve the quality, performance and effectiveness of foliar treatments. Apart from improving the rate of uptake of foliar nutrient fertilizers research efforts should focus on analyzing the physiological effect of foliar-applied nutrients on plant metabolism and signalling. In addition, the role of plant stress physiology relating to the effectiveness of foliar-applied nutrients is still not clear and should be elucidated, since foliar sprays are often used to overcome nutrient deficiencies that are more common in arid and semi-arid areas with high pH, calcareous or saline soils.

Other key factors influencing the effectiveness of foliar nutrient sprays are the mode and timing of application. For instance to improve uptake treatments should be sprayed when stomata are open and the improvement and development of more efficient spraying technologies will increase the efficacy of nutrient sprays when applied to the foliage.

In summary, foliar fertilization is already established as a normal practice in many cropping systems. The full potential of this technology has not been fully realized due to an inadequate understanding of the principles involved. There are clear knowledge gaps that hinder the development of improved foliar fertilization strategies. However, there is also a good deal of information on the mechanisms of uptake, plant physiology, physico-chemistry and formulation that has not been fully applied. Foliar fertilization is likely to play an increasing role in maintaining crop nutrient status under a variety of environmental situations when soil supply of nutrients is inadequate, and during periods of peak nutrient demand when delivery of soil-applied nutrients may be inadequate.

Ultimately the goal should be to improve the ability to predict the likelihood of an economically relevant nutrient deficiency occurring during a crop growth cycle and to optimize the timing and biological efficacy of the foliar fertilizer applied. With this information on hand, a rational cost/benefit analysis can be performed and an informed decision made. Furthermore analyses such as these will result in better focus of research efforts which will undoubtedly result in improved foliar fertilizer formulations and their practical application.