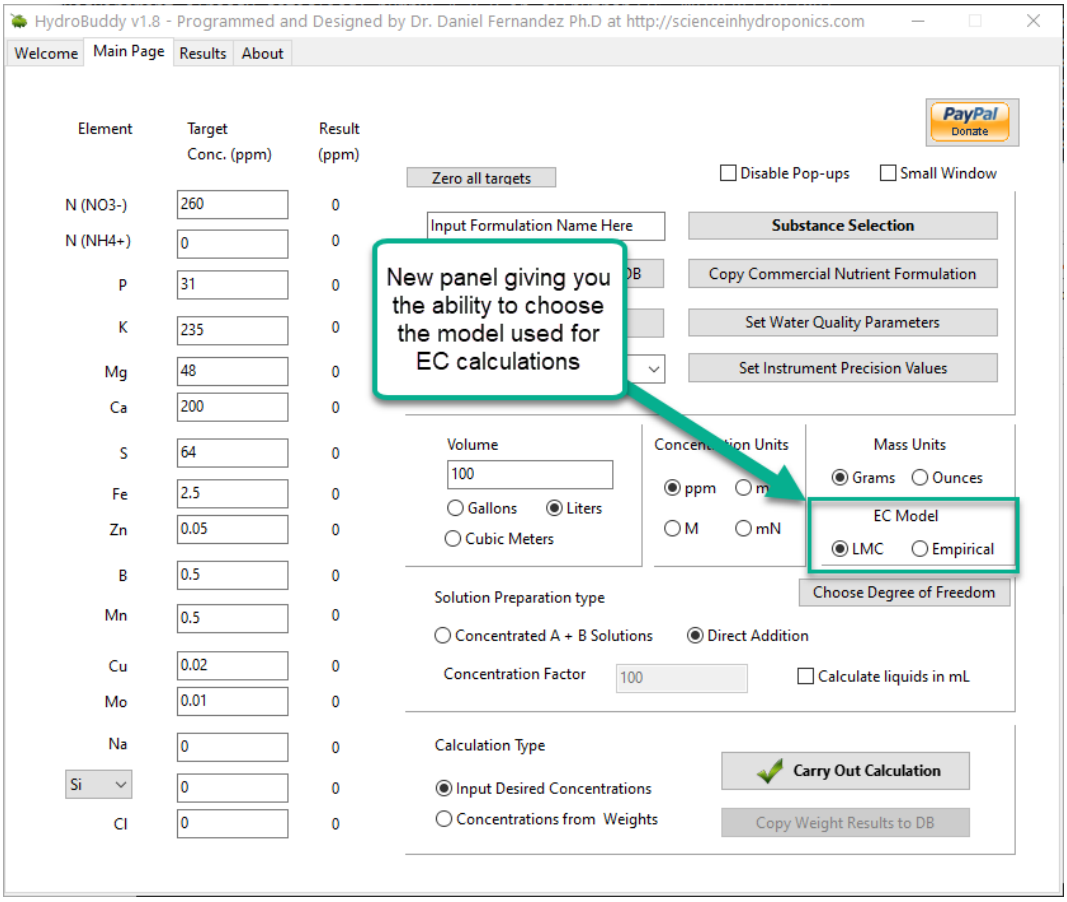
A new conductivity model in HydroBuddy

On my previous post you can read about how I ran experiments to develop a conductivity model using empirical data in order to improve our ability to predict EC values from the concentration of individual nutrients in a hydroponic nutrient solution. In this post I will now talk about how this was finally implemented in HydroBuddy, what form it took and what kind of result can be expected from it. The implementation discussed in this post has already been updated to the HydroBuddy github along with all the experimental data used to derive this empirical EC model.

Given the amount of data and the nature of the problem at hand, the easiest and most accurate way to build a model was to use a simple linear regression algorithm. As previously shown this model was able to give great results within the data, even when performing random training and testing splits. I have added a jupyter notebook to the github repository, along with all the data we measured in order to allow you to see how all the calculations were done, how the model was created and the sort of accuracy the model got within the set of experimental results. You can also play with this notebook to develop your own models or analyse the data any further if you wish. You can also try to reproduce our experiments and help verify our results. The linear model was translated into FreePascal and added to HydroBuddy although the program still retains the ability to estimate conductivity using the previously available LMC based model.



New hydrobuddy implementation now including the ability to choose between LMC and empirical EC models.

The fact that we were able to create a model to accurately determine conductivity within this experimental space does not mean that this model will work to magically determine the conductivity of any hydroponic formulation. These experiments were designed using five salts – calcium ammonium nitrate, ammonium sulfate, potassium sulfate, magnesium sulfate and monopotassium phosphate – which means that although our model is able to greatly describe conductivity in this space, the model is likely to run into trouble when attempting to describe a space that deviates too strongly from the one described above. This will be most evident whenever there are some cations or anions that are not present at all within these experiments. For example when silicates, chlorides or other such salts are used or when strong acids or bases are added to the solution.

Another important issue is the way these ions are paired. In our experimental process the concentration of Ca and N as

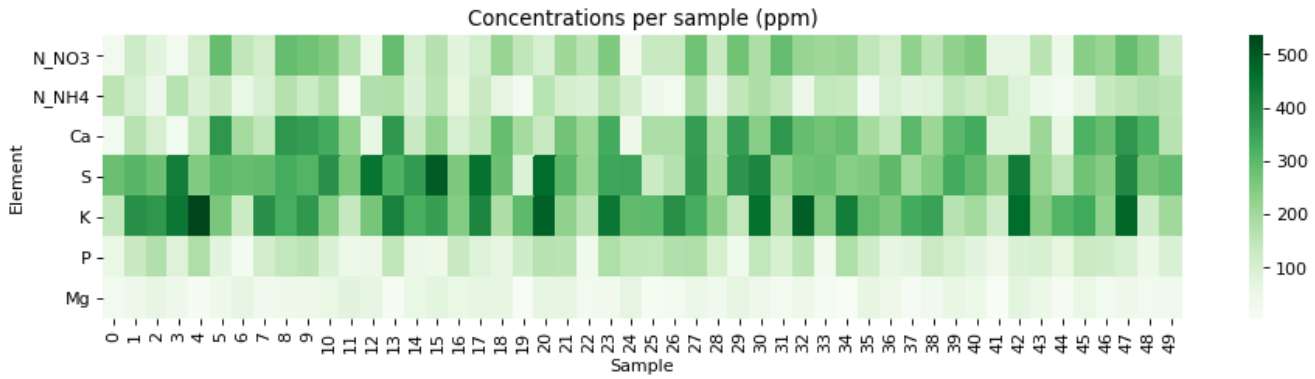
nitrate always increased at the same time, meaning that the linear model implicitly carries this assumption. A setup were magnesium nitrate or potassium nitrate are used as well, will contain deviations from the current model that it is likely not very well prepared to deal with. A similar problem might happen when salts such as ammonium monobasic phosphate are used, since our model only contained a single example of a phosphate salt (monopotassium phosphate). While it is not easy to predict how much accuracy will be lost in these cases, we do expect the model to be significantly more inaccurate as other salts are used.

Additionally, our experimental setup did not contain any corrections of pH values, so the conductivity values described include a pH drift related with the amount of acid contributed by the potassium monobasic phosphate, which was not neutralized by a base. This will also cause differences with conductivity, if the conductivity is measured after the pH of the solution is corrected to the proper range used within the hydroponic process. Although at the concentration values used in hydroponics this should not be a big issue, it is still something worth considering.

As I mentioned above, the model is already implemented within the github repository – if you want to compile the program yourself – but the binaries won't be updated to v1.8 until later this week. I look forward to your feedback about the model and hope it can help – at least some of you – to dramatically improve the estimations of conductivity of your hydroponic nutrient solutions.

Building a model to predict EC in hydroponic nutrient solutions

Electrical conductivity (EC) is one of the most useful parameters in the practical preparation of hydroponic nutrient solutions. This is because knowing the expected conductivity of a nutrient solution can allow you to prepare solutions without having to measure the total volume exactly, a parameter that is often hard to accurately determine in practice. Although determining the target conductivity is easy to do using small preparation volumes – which can be done accurately – it is often impractical to do so routinely, which is necessary if the actual composition of the nutrient solution is being changed as a function of time. Due to all the above, it is important to come up with accurate models to estimate the EC of nutrient solutions with only information about their mineral composition, without having to measure the value experimentally. In this post I am going to talk about how I created a model to do exactly this, taking advantage of multi-variable experimentation and simple modeling techniques.



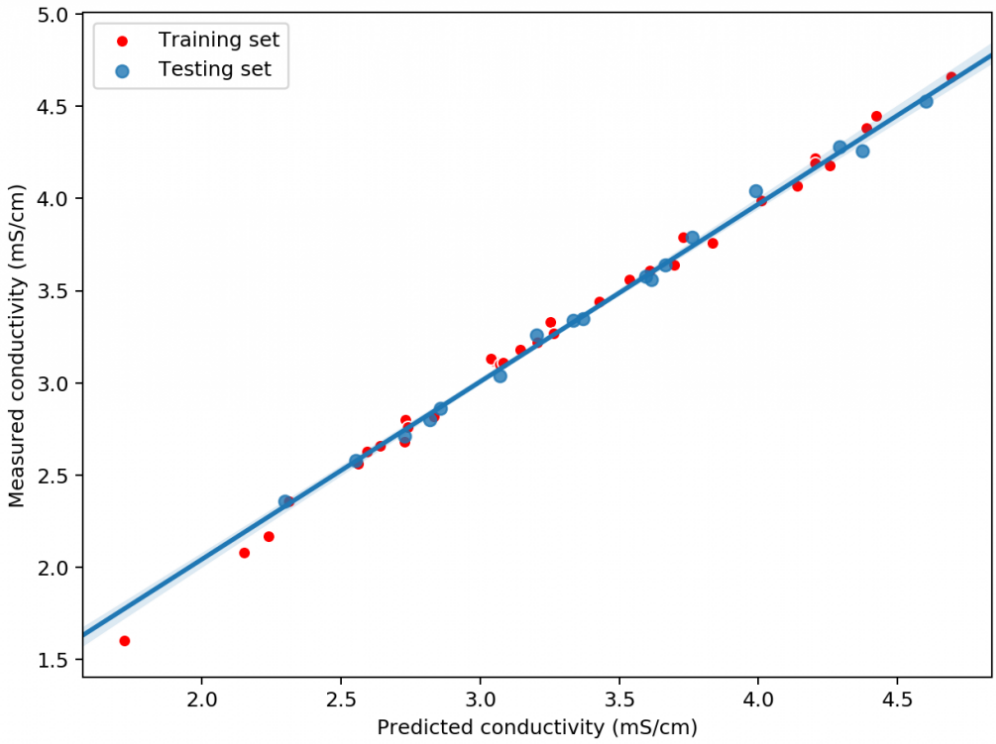
Mineral nutrient concentrations (ppm) of all the samples measured

The problem with conductivity modeling is that not all salts contribute the same to the conductivity of a nutrient solution. For example potassium sulfate can contribute

significantly more to conductivity per gram compared to a salt like monopotassium phosphate. Furthermore, the addition of some salts can affect the conductivity of others (see my previous post on conductivity modeling in Hydrobuddy for more details). In the regime we use in hydroponics, the determination of electrical conductivity using data from limiting molar conductivity can lead to very skewed results, which makes these estimations of little usage in practice.

To solve this issue, I designed an experiment where 50 different EC measurements were made for different hydroponic nutrient solutions within the range of concentrations of nutrients that are reasonably expected in hydroponic culture, with some values being above these in order to ensure that all values encountered in practice will be within the measured ranges. The image above shows you all the concentrations that were measured within the experiment. To prepare the solutions I used calcium ammonium nitrate, potassium sulfate, magnesium sulfate heptahydrate, monopotassium phosphate and ammonium sulfate. All of these were agricultural grade salts in order to reflect the same impurities expected in a normal hydroponic setup. Note that no heavy metal salts were used since their contribution to the EC of a hydroponic nutrient solution is negligible.

Concentrated solutions of all the salts were prepared in 250mL volumetric flasks using a +/-0.001g scale and aliquots of these solutions were drawn using 5mL plastic syringes (+/- 5%) in order to prepare final 250mL solutions using volumetric flasks. Conductivity measurements were done using an Apera EC60 conductivity meter that was previously calibrated using a 2 point calibration method. All the solutions were prepared using distilled water. The target concentrations for the solutions were determined using a pseudo random number generator in order to try to ensure a random distribution of samples within the concentration space of interest.

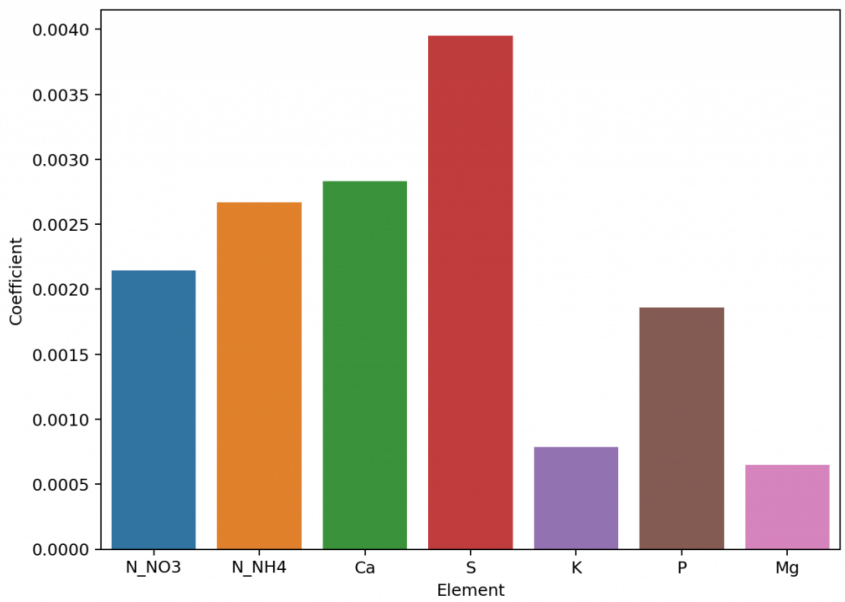


A sample modeling results for a random split with training (33 data points) and testing sets (17 data points)

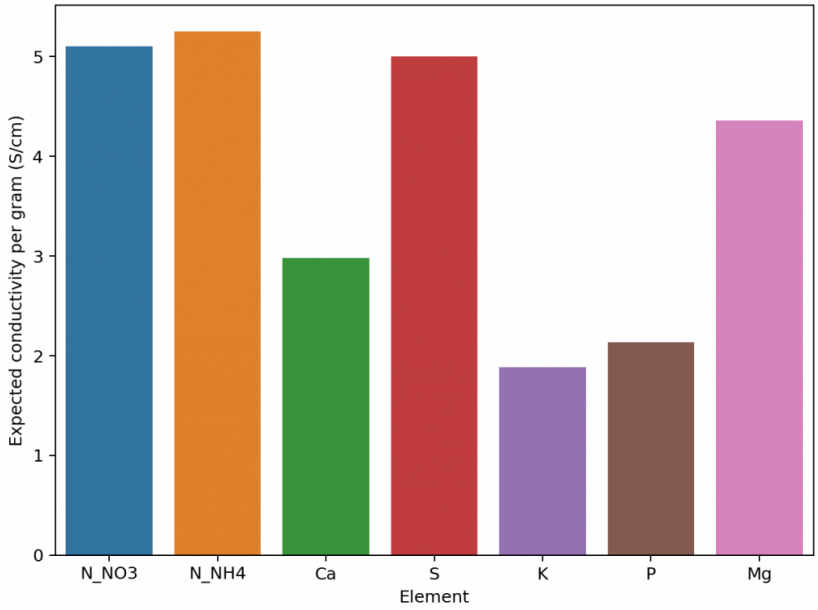
Using this data we constructed a linear model to attempt to predict conductivity. In order to evaluate the model we randomly split the results to get 33 data points used for model construction and 17 points left for model validation. Performing this process 100 times shows that the mean R2 of the model on the training set is 0.995 while the average on the training set is 0.994. This shows that the model is able to properly generalize the conductivity data in order to properly predict the conductivity of the solution across the space studied. **The mean absolute error in the testing set was 0.036 mS/cm. This shows the high certainty with which we can make conductivity predictions.**

Exploring the model coefficients can also show us how different the contributions of the different elements to the conductivity of the nutrient solution can actually be. These results are surprising if you compare them to the conductivity contributions per gram that are expected from the limiting molar conductivity values, which are the conductivity values the ions exhibit on their own under very high dilutions (this

is also the method used in HydroBuddy <=v1.65). We can clearly see here that in reality we are getting way more conductivity out of sulfate compared to the other elements and significantly less from magnesium. This means that at the makeup and concentration values used in hydroponics the Mg ions are not being able to contribute as much as they can when they are alone because their activity is being lowered by the other ions in solution, while the opposite case applies to sulfate.



Linear model coefficients for the different elements (proxy for their contribution to conductivity)



Expected conductivity values per gram using data from limiting

molar conductivity values (taken from here)

The above shows us why conductivity in hydroponics is so complicated, it shows how ions do not contribute equally to conductivity and how they behave very differently in real hydroponic solutions. Thankfully the above also shows how we can create a model using experimental data that is actually able to predict conductivity, since the relationships – although different than expected – are still highly predictable when enough experimental data is available. All the above experimentation took 4 hours to do – with the help of my lovely wife, who is also a chemist – and should allow me to add a very powerful model to predict hydroponic nutrient solution EC values to HydroBuddy.

All the above experimentation data will be open source and available in a github repository soon. We also hope to show you how all of this was done in a youtube video in the near future.

Keeping plants short: Using day/night temperature differences (DIF)

In this article series about "keeping plants short", we have explored the reasons why short plants are desirable and how this can be achieved using gibberellin inhibitors. However this is not the only effective way to control plant height and several other ways – some using no chemical means – can be used to keep plants short. In this article I will be talking about the use of day/night temperature differences in order to control plant height, what the research about this says and

how it can be effectively applied by growers to achieve shorter plants.

The idea of using day/night temperature differences to control plant height can be traced back to the late eighties and some research done by people at Michigan State University (1). This research in easter lilies showed how plants grown at a constant night temperature (68F, 20C) but subjected to even lower day temperatures or simply drops in early morning temperature could grow drastically shorter. The results surprisingly showed that a 14F temperature drop during the beginning of the day – first two hours – could actually cause the plants to receive the same effect as if the day temperature was lower during the entire day, yet the plants remained highly productive. This technique of reducing temperature during a few hours during the way was referred from this point on as "DIF".



Taken from this 1986 article.

Experimenters then began testing across other plant species and found the results to be mixed. In this paper (2) chrysanthemum, poinsettia, begonia and kalanchoe were all tested in a -6 C DIF experiment and while chrysanthemum and

begonia both responded in the expected manner, the kalanchoe actually responded in the opposite way and showed stronger elongation of the flower stems. In all of these cases the use of growth regulators – gibberellin inhibitors – was still needed to ensure plants stayed at the required height. This was one of the first studies that pointed to the fact that the DIF technique is tremendously crop dependent.

During the nineties it was established that DIF did work for several common crops, for example cucumber and tomatoes showed to be sensitive to the DIF effect, particularly when the first two hours of the day showed a temperature drop. In this case the effect reduced both the inter-node distance and was directly proportional to the difference in temperature. It was also established that some plants prefer pulses of cold temperature during the end of the day, while others might prefer this pulses even in the middle of the night. It was also showed that strong negative DIF treatments caused negative effect related with a reduction in chlorophyll production, resulting sometimes in even plants showing signs of chlorosis. Plants grown in negative DIF were also shown to have lower total dry weights although depending on the magnitude of the DIF, limited or sometimes even positive effects on weight and yields could be seen. You can read more about the above in this review from the late nineties which also contains a lot of literature references for early DIF research (3).



Stem elongation effects of DIF in peas, taken from this article

More recent research from 2013 on tomatoes, eggplant and sweet pepper (4) has shown that a variety of different day/night temperature treatments can be effective in minimizing vegetative growth while having a limited effect on yields. In this case the strongest effect was seen for a 15C/25C day/night temperature cycle. This paper also looked at

nutrient absorption and noticed that Ca/Mg/K concentrations were actually highest in the 15C/25C temperature treatment, which suggests that changing the day/night temperature did not adversely affect nutrient absorption. The conclusions of this research were then reproduced and matched when looking at cucumber, melon and watermelon (5). However other research using positive as well as negative differences in temperatures has shown that for tomatoes, the ideal day/night temperature difference is positive and in the order of +6C if yields and plant growth are given the highest priority (6).

The DIF method has shown to be a reliable way to control the height and vegetative growth of many different plant species, although for some it does not work very well. In general the researchers who apply negative DIF methods for reducing stretch tend to have the most success with a -10C (-18F) increase in night over day temperatures. If testing on a new plant the recommendation would be to start with a 2 hour temperature drop in the day temperature of this magnitude for the first 2 hours of light – starting the drop 30 minutes before sunrise – and see which results you can get. This is likely going to be the cheapest in terms of both climate control and potential disruptions in yields caused by this technique.

Monitoring the quality of fertilizer stock solutions

Hydroponic concentrated nutrient fertilizer manufacturers are not held to any routine quality standards by regulatory authorities in most countries. Although fertilizers need to be properly registered and their intended minimum compositions

are shared with the public, the manufacturer never guarantees that each batch of the product will comply with any sort of quality standard and it's therefore possible for hydroponic nutrients to come out of a factory with compositions that significantly deviate between batches. People who make their own fertilizers are also not free from problems either, as issues further down the chain – with the fertilizer raw inputs – or issues related with human error, can and will still happen.

Because of these problems, a very important part of every hydroponic grower's process should be to establish some quality guidelines to evaluate whether a given batch of nutrients – either bought or self-made – complies with what is expected and can therefore be used in the hydroponic crop. In today's post I will talk about the properties that you can measure in order to ensure that the quality of your inputs is sustained through time and how these measurements should be done.



These are two measurements that should always be done whenever you receive or prepare a new batch of hydroponic nutrient stock solution:

Density of the stock solution: The density of a hydroponic stock solution should always be measured and recorded. The density needs to be measured accurately, using a pycnometer and an accurate enough balance (+/- 0.01g). A 5 or 10mL pycnometer would be recommended and the balance should be able to measure up to at least 50g, to ensure that the measurement of the final weight of the pycnometer will be in range. You should first weight the empty and dry pycnometer, then fill it with liquid to the brim, place the stopper – some liquid will spill, this is how it's intended to work – then wipe any spilled liquid and weight the full pycnometer. The difference in weight divided by the pycnometer volume will give you the density. Make sure you also record the ambient temperature when the measurement is made.

pH of the stock solution: You can use a pH meter to determine the pH of a sample of the stock solution. You can use the regular pH tester you use to measure the pH of your hydroponic nutrient solutions, however make sure the pH meter does not remain for too long in the stock solution – more than what's necessary to make the measurement – and wash it with distilled water and store it in pH meter storage solution as soon as the measurement is done. Also make sure the pH meter is calibrated right before making this measurement.

If any compounds are added incorrectly or the composition of the raw inputs was in anyway wrong, the above two parameters – pH and density – will tend to change, as they depend very strongly on the composition of inputs being the same. Of course, there are mistakes that can go undetected in these two domains but a stock solution that always records the same across batches will tend to be the same chemically. Every time you receive or prepare new solution record the above and ensure you never use any solution that deviates more than -/+ 5% from the median you have on your record. The deviation of the above two parameters also serves as a way to control how reproducible the manufacturing process of the stock solution

actually is.

If there is a strong mismatch in these measurements when compared with the median of all past values, then you need to continue to actual chemical analysis of the nutrients to figure out what's wrong.

If you prepared the fertilizer yourself then it becomes important to check notes – always keep records of weights that are added when preparing solutions – and see if there were any changes in the chemical suppliers of any of the used inputs. Sometimes the quality and composition of certain chemicals can change dramatically between suppliers, so making changes from one to another can often require chemical analysis to ensure that the composition stays the same. A good example can be potassium silicate, where the exact grade and potassium to silicon ratio of the raw material can change a lot depending on the exact fabrication process used by the company making it.

Another important point is the accuracy of the instruments used for the preparation of solutions. Sometimes the problem is that a scale or a volume measuring device lost calibration and generated errors in a previously unseen range. This can be particularly problematic if different instruments are used to measure different inputs, which can make some inputs subject to bigger errors that others and can therefore change the ratio between different nutrients in the hydroponic solution.

Why red and blue LED grow

lights never took off

Anyone who has been growing plants for a while has probably seen a chart showing the absorption profile of chlorophylls A and B, as shown in the image below. From this it seems that most of the light absorbed by plants has a wavelength below 500 nm or above 650nm so it seems incredibly straightforward to hypothesize that plants can be effectively grown just using light in these regions. The commercial answer to this hypothesis came in the form of the red/blue growing LED light, which give the plant energy that it is “best suited” to absorb and avoids “wasting” any energy in the generation of light that will not be absorbed anyway (but just reflected away by the plants). However these grow lights have been an overall failure so far – with the vast majority of the industry now shifting onto full spectrum LED lights – why has this been the case?

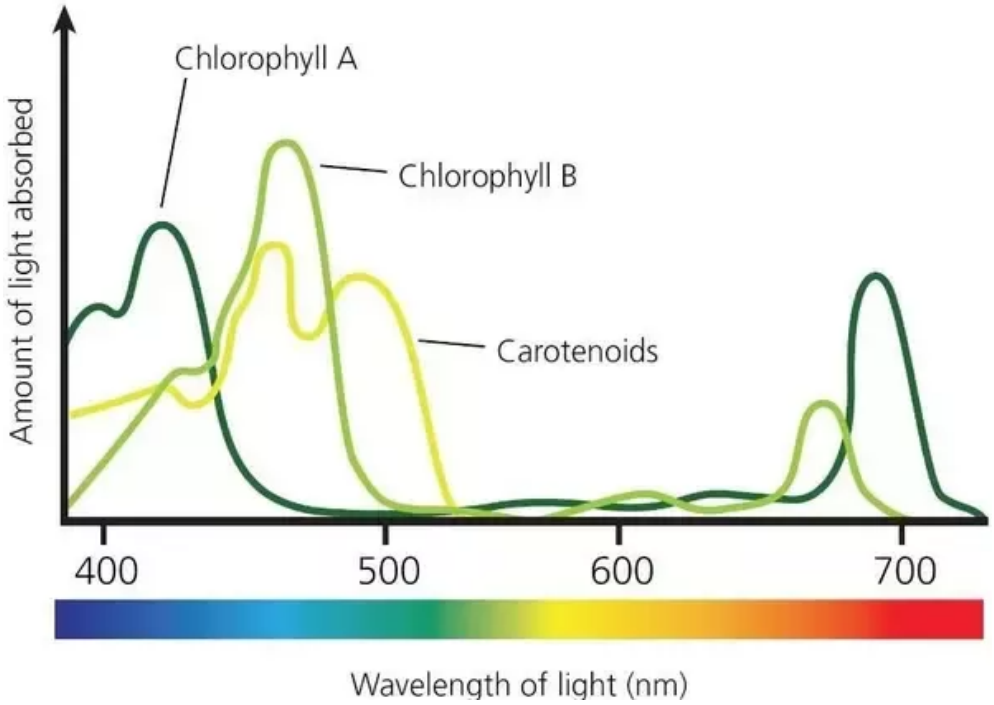


Image showing the absorption spectra of Chloropyll A, B and carotenoids

When the cost of red/blue lights dropped enough, there was a significant move to evaluate them in the scientific community to figure out how they affected plant growth. It quickly

became clear that plants could be grown with these new lights and that the products could be as healthy as those produced under normal full spectrum lights. However some issues started to become noticeable when these red/blue lights started to move onto larger commercial applications. Although the commercial application of these lights in large fruiting plants is practically non-existent due to the high cost of supplemental lighting, their use was feasible for some small leafy crops – for example lettuce and spinach – which could be grown under high density conditions in urban settings. Their main use however, was in the cannabis growing space, which is one of the only high-cost crops that is grown largely under supplemental lighting when far from the equator.

Most people who tried this soon realized that the growing of plants wasn't equal to that obtained when using fuller spectrum lights, such as HPS or even metal halide lamps, even at equivalent photon flux values. Although scientific publication in cannabis are scarce, this 2016 report (1) shows that white lights in general did a better job at growing the plants compared to the blue/red lights. Other research (2) shows that the blue/red lights can also affect the chemical composition of secondary metabolites, which makes the decision to move to red/blue LED grow lights affect the quality of the end-product.

It has also been shown that green light is not entirely unused by plants, but can actually have important functions. This review (3) goes into many of the important signaling functions of green light and why it can be important for healthy plant growth. Some researchers also started doing experiments with red/blue/green grow lights, showing the positive effects of including some green light in the composition (4). It has also been shown that other regions of the spectrum, such as the far-red (5) can also contribute substantially to photosynthesis and the regulation of plant biological processes. Ultra-violet light can also contribute

substantially to the expression of certain molecules in plants. A paper evaluating cannabis under several different light regimes shows how the composition of the light spectrum can manipulate the secondary metabolite makeup of the plants (6).

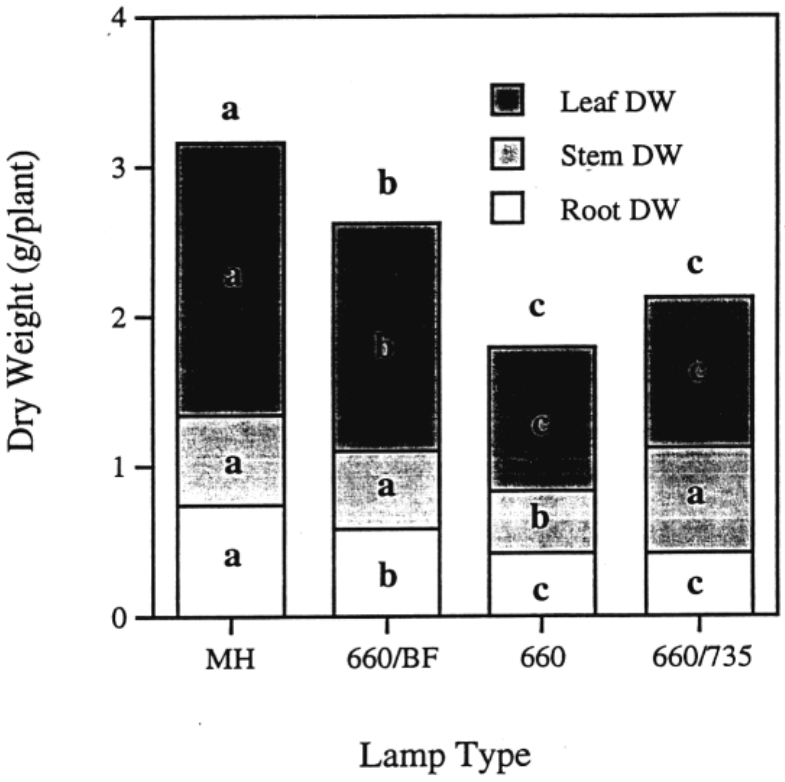


Fig. 2. Dry weight of leaves, stems, and roots of 42-day-old pepper plants grown for 21 days under metal halide (MH) lamps then transplanted under red light-emiting diodes (LEDs) plus blue fluorescent lamps (660/BF), red LEDs (660), and red plus far-red LEDs (660/735), or maintained under MH lamps for an additional 21 days. Similarly shaded portions containing different letters are significantly different based on ANOVA and protected least-squares mean separation tests ($P \leq 0.05$). The letters above the bars indicates the significance for the combined plant dry weight.

Image taken from this study (7) showing the effect of far-red light in the growth of pepper plants.

Finally, the last problem in the grow light phenomenon, especially in the case of plants like cannabis, came from the fact that plants look black under this red/blue light. This meant that growers were completely unaware of any potential problems that developed, as the plants were virtually invisible to them through their entire lifetimes. This was one of the main reasons why these lights were never widely adopted, as they made the diagnosing of nutrient issues and

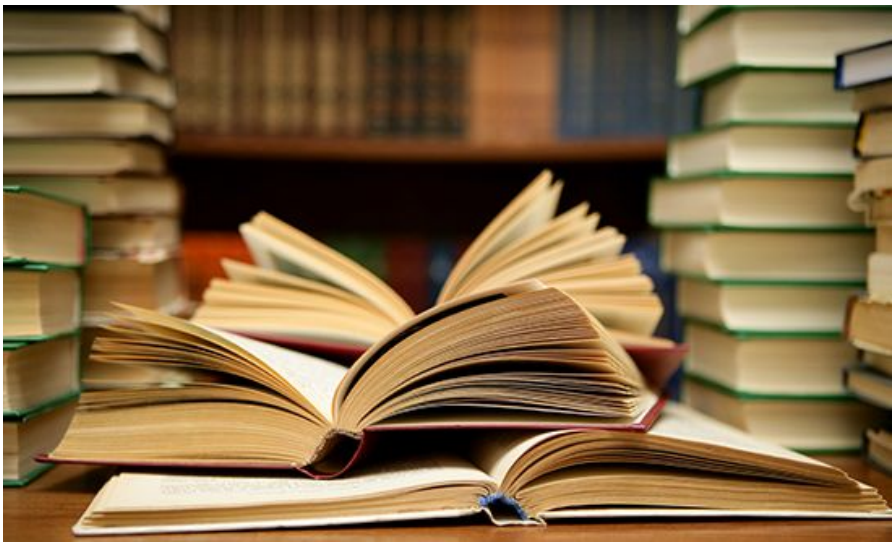
insect issues – which are relatively easy to diagnose under full spectrum lights for an experienced grower – almost impossible to do with these red/blue growing panels. In practice a large commercial operation relies heavily on the experience and on-going evaluation of the crop by the on-site personnel and failure to have this useful check in the process is a recipe for disaster.

The LED industry learned from these problems and has since gone into the development of full spectrum high efficiency growing panels for the hydroponic industry. These will certainly become the future and standard in the in-door hydroponic industry, especially if prices continue to come down as a consequence of mass adoption. Having full spectrum lights that are way more power efficient than HPS and MH lamps will offer growers the chance to save a lot on costs while maintaining, or even improving, the quality and yield of their crops.

In-depth books to learn about hydroponics at an advanced level

Growing plants without soil requires a lot of knowledge. As a hydroponic grower, it is now your duty to provide the plant with the needed chemical and environmental conditions that nature used to provide. Acquiring this knowledge can be difficult, as there are few well structured programs that attempt to teach in-depth hydroponics to students and many of these programs are graduate level programs that are inaccessible to the commercial or novice hydroponic grower.

Although there are many hydroponic books catering to the novice – as this is the most accessible market – a lot of growers want to get to the next level by digesting books that can help them become true experts in the subject of hydroponic culture. While novice books help people get around the basics of hydroponics, true higher level books are required to understand the causes and solutions to many problems found in this field.



In this post I am going to summarize some of my favorite books in the more advanced hydroponic domain. Going from nutrition to actual commercial and practical growing setups. I will go through some of the reasons why I believe these books are fundamental, as well as what the necessary prior knowledge to understand the books would be.

The mineral nutrition of higher plants. This classic book is used in almost all university level classes that teach mineral nutrition in plants. It covers how the different minerals are absorbed into plants, how this absorption works from a metabolic perspective and how the toxicity and deficiency of each one of these substances works from a chemical and biological perspective plus a ton of information about nutrient interactions. *This is however not a book you want to read "from start to finish"*, it is meant to be a reference book, that you can go through when you have specific doubts or

want to have a better understanding about a certain element and how the plant interacts with it. It also requires a strong chemistry and biochemistry background, so it is not a book that you want to get if you don't find these domains interesting. Ideally you would go to this book to answer a question like "Why does ammonium compete with potassium absorption but potassium rarely competes with ammonium absorption?".

Soilless Culture: Theory and Practice. This book covers a lot of important topics in practical hydroponics. It talks about root systems, physical and chemical characteristics of growing media, irrigation, technical equipment, nutrient solutions, etc. It is one of my favorite "well rounded" hydroponic books as it covers almost all topics you could be interested in at significant technical and scientific depth, giving the user a ton of additional references for study at the end of each one of its chapters. It also focuses on giving the user a grasp of fundamental concepts that affect a given topic before going deeper into it. It will for example attempt to give you a very good explanation of why and how certain properties of media are measured before it even starts to explain the different types of media available in hydroponic culture. This book requires a good understanding of basic chemistry and physics but is way lighter in biochemistry and botany. This is a perfect book to answer questions like: "what different types of irrigation systems exist? What are their advantages and disadvantages?".

Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. Howard Resh was one of the first people who produced a book for hydroponics that put together the combined experience of a lot of actual, commercial, hydroponic growers. The book is written in an easier way to read and gathers a lot of experience from the commercial growing space, with useful references placed at the end of every chapter. It can be

especially useful to those who are within actual commercial production operations, as the book goes into commercial crop production in a way that none of the other books here does. This makes this book more pragmatic, specifically addressing some concerns of larger scale applications of hydroponic technology. High school level chemistry and physics should be enough to understand what this book has to offer. A question this book might help answer is: "How do I adjust the conductivity of a hydroponic solution in a commercial setting?".

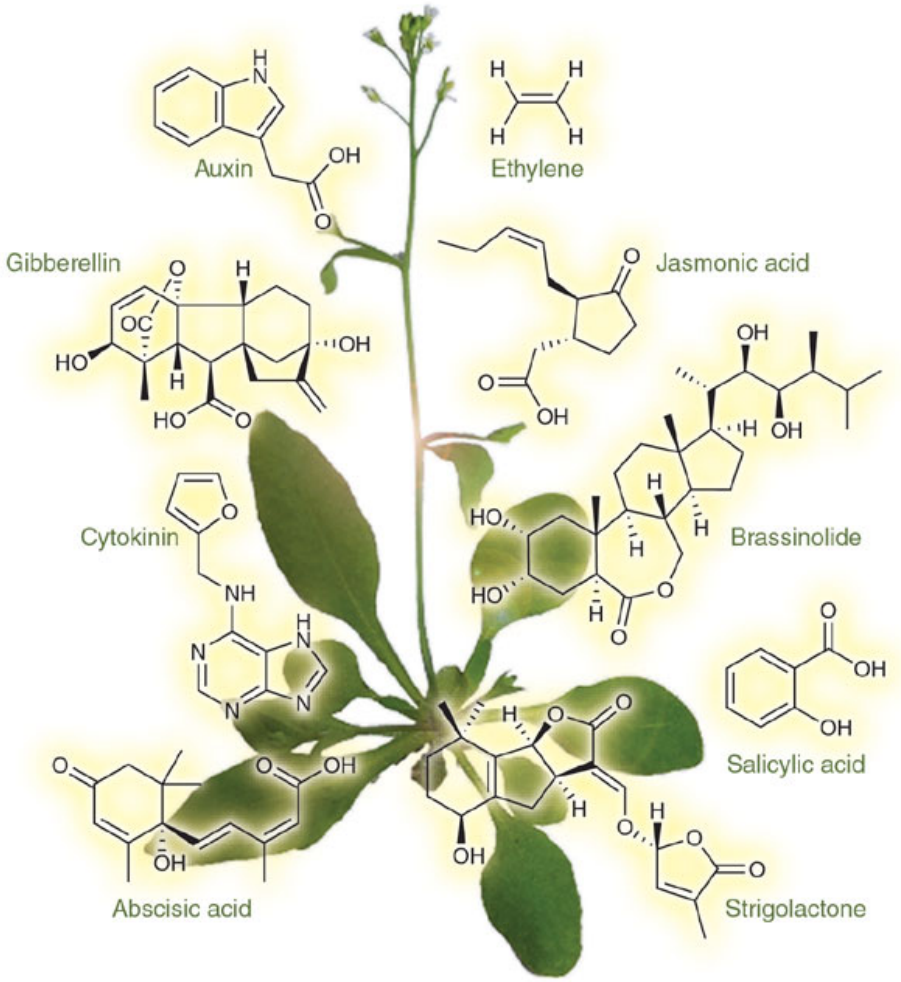
Controlled Environment Horticulture: Improving Quality of Vegetables and Medicinal Plants: This book goes more onto the botany side and explores how a grower can manipulate a plant's growing environment in order to guide its production of secondary metabolites. The book goes into some of the basics of horticulture but goes deeper into drought stress, thermal stress, wounding, biostimulants, biofortification, carbon dioxide and other such manipulation techniques available to modern growers. As all the ones before, this book also gives you a lot of useful literature references at the end of every chapter, allowing you to continue to explore all these topics on your own, by going to the academic literature. A question this book might help you answer is: "Which plant hormones can I use to increment the production of oil in spearmint plants?".

The above are some of the books I will go to when I want to answer a question in hydroponics. These books will often provide me with a solid starting point for the topic I'm interested in – like some clear scientific references I can go to – or can even show me some interesting paths to explore. Usually I'll go into the scientific literature to get an updated view of the subject, but going into the literature with a base view has proved to be invaluable almost every time.

Six things you need to know before using plant hormones

Plant hormones are small molecules with no nutritional value that are used as chemical signaler within plants. A hormone will trigger a chemical signaling cascade that will cause the plant to carry out certain specific behavior. This fact has made them one of the most useful tools to manipulate plant growth and improve the yields and quality of many crops, especially flowering plants. This has also made them a key target for hype, with many products promising significant gains without much talk about interactions with other hormones or other fundamental aspects. In this post I want to talk about six things you should know about plant hormones, both to use them more effectively and to adequately manage your expectations when you use them. Note that although plant hormones are considered plant growth regulators (PGRs), this broad class includes other molecules – such as gibberellin synthesis inhibitors – that are not being considered in this post.

Know specifically what you want. A hormone will affect a plant in a very specific way, to achieve a specific purpose. Hormones can help you manipulate plant growth but which one you use depends fundamentally on what you want to achieve. Do you want the plant to be bigger or shorter? Do you want to have more water content in your product? More solid content? More terpenes? Do you want to fight drought conditions? Excess salinity? Insects? The specifics of what you want will guide you into choosing an appropriate hormone for your specific needs.



Examples of widely used plant hormones

Plan your hormone applications strategically. Different hormones can stimulate different processes that are needed at different points of a plant's life. If you plan the use of hormones carefully you can stimulate root growth when plants are transplanted, then stimulate flowering or other behavior when you want the plant to express that behavior more strongly. Plants take some time to steer, they react to their environment, hormone applications at the right times can give a plant a strong signal that it should follow certain behavior and you – as a grower – can ensure that the environmental conditions are perfect for the processes the plant will be carrying out next. Hormones are the flares telling the plant where to go, you should ensure you make that a smooth ride.

There is no free lunch. Plant hormones act to cause a certain behavior to happen, but this behavior comes at a specific cost. A plant that is stimulated to produce more flowers will

often grow smaller fruits, a plant that is stimulated to produce more terpenes might produce lower yields because of the additional energy spent in these molecules, a plant that grows more roots, grows less shoots while it’s doing that, etc. A plant does not magically get access to more energy because it has been stimulated with a hormone, it simply chooses to act differently with the energy it is receiving.

Hormones interact with each other. A given hormone can behave in a way when it’s applied and in a very different way when it’s applied with another hormone. As different hormones signal different paths, the net effect is often related with how these different paths are activated. Some are synergistic, the total is more than the sum of the parts, while others are antagonistic, meaning you get less than the sum of the parts. Growers interested in hormones will often make the mistake of applying a lot of things at the same time, but they have no idea what the net effects are going to be like. When dealing with hormones introduce them one at a time and make sure you’re getting a measurable positive effect before you venture into using another one with it. Incremental gains is the name of the game not “apply every hormone under the sun that has a peer reviewed paper published where it increases yields in a plant”.

Concentration is everything. To make things even more complicated, a hormone might activate one signaling path when it’s present at a given concentration but a different one when it’s present at a much larger concentration. Using the wrong concentration for the hormone might end up causing a completely different effect or an effect so pronounced that it’s negative side effects are going to out-do the positive effects. Furthermore, this can also be genetic dependent, so when using hormones on new varieties or species it is always advisable to do a concentration trial across 2-3 orders of magnitude to see where the “sweet spot” for the desired effect is. Sometimes hormones are most effective at surprisingly low

concentrations – even 0.1 to 1 ppm – while other times they need to be applied in very significant amounts (100-300 ppm).

The application route and vehicle is very important. A hormone might be very effective when applied in a foliar spray, while completely ineffective when applied in a root drench. Sometimes the hormone requires specific additives or solvents to be used in order to ensure its absorption and others it needs to be applied at a very specific pH range or even just by itself. Knowing the particular application conditions of the hormone you want to use is also important to achieve the expected results.

These are some simple guidelines to consider when using plant hormones in your crop. Hormones are no miracle but they can certainly provide amazing improvements in yields and quality if used appropriately. Formulating a good hormonal regime, with adequately formulated foliar/root drenches, applied at the right times, with the right hormones, can provide amazing results. This however requires a lot of testing, a lot of effort and a lot of understanding about the plant being grown and its crop cycle. Every crop has its own genetic and environmental conditions and requires significant experimentation to achieve the best possible results.

Keeping plants short: Synthetic gibberellin inhibitors

Plants grow both vertically and horizontally. A plant will develop branches along its stem – expanding horizontally – and the stem will grow towards the sun, making the plant taller.

This vertical growth is almost always an undesirable quality, both in extensive and intensive crops, which creates an opportunity to improve plant cultures by attempting to reduce the height of plants. You can read more about why making short plants is important in this post. Although there are many potential ways to achieve this – which I will discuss in detail in future posts – this post will deal with the most powerful tools that have been developed for this purpose, a class of plant growth regulators (PGRs) known as gibberellin inhibitors or more commonly as “growth retardants”.

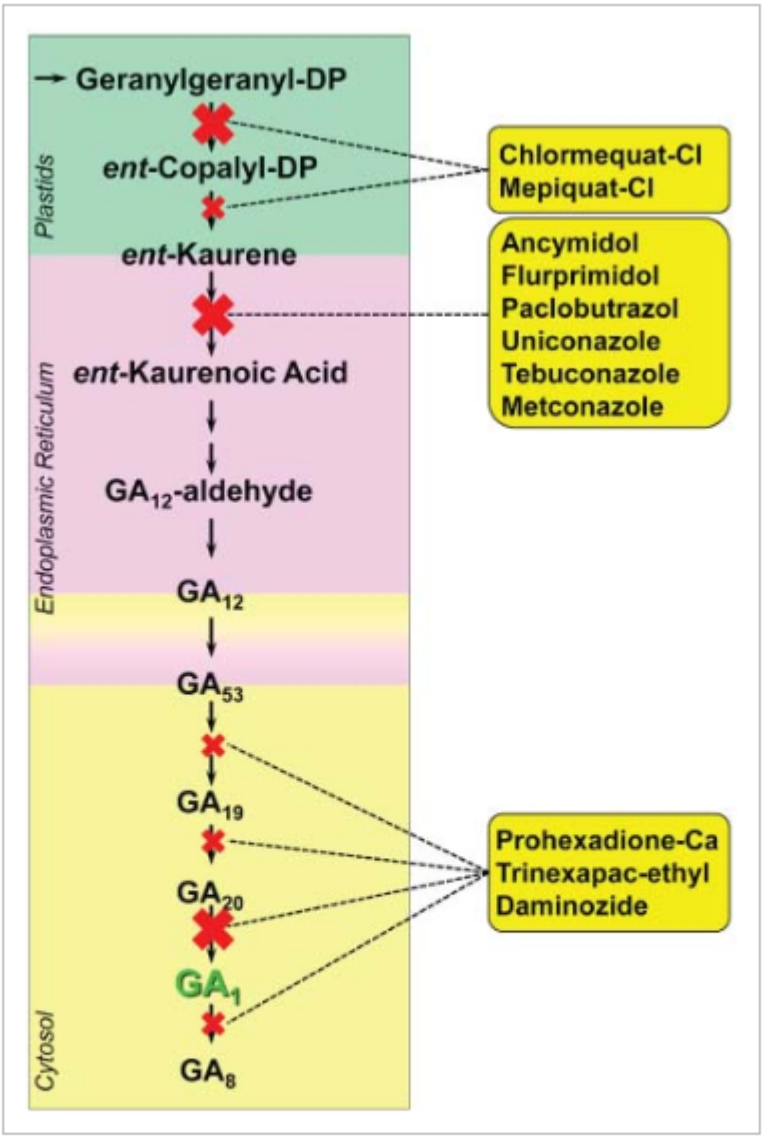


Figure 12.2 Open in figure viewer | PowerPoint

Main steps of gibberellin biosynthesis leading to biologically active GA_1 and points of inhibition by plant growth retardants. The cellular locations of the reactions is indicated by different greyscales. (The conversion of GA_{12} into GA_{53} can be located in both the endoplasmic reticulum or the cytosol.)

This figure was taken from [this article](#).

Making a plant grow shorter is no trivial task. This is because we do not want to make the plant less productive, but we want the same productivity of a tall plant in a much bushier and compact package. We therefore need to inhibit vegetative growth without affecting the flowering stages of our plant. Scientists figured out around 30 years ago that a set of plant hormones called gibberellins played a critical role in the vegetative growth of plants – especially the elongation of a plant -so these became a prime target to stop

growth. If you can disrupt the gibberellin creation pathway right when the plant is supposed to stretch, then the plant will stop growing vertically without the flowering development of the plant being affected at all.

We have found several different types of compounds that can do this. The figure above shows you the gibberellin synthesis path and the steps where different molecules have been shown to disrupt it. Among the most powerful and commonly used were the ones that disrupted the conversion of kaurene to kaurenoic acid, with the most famous one being paclobutrazol. In the other groups the most commonly used ones were chlormequat and daminozide. These molecules are all part of the first generation of gibberellin inhibitors and they did exactly what they were supposed to, proving to be extremely powerful growth retardants that were able to keep plants compact and strongly increased yields in several different crops.

However it soon became evident that their toxicity and retention in plant tissue is significant. Paclobutrazol has been shown to be toxic, having developmental and reproductive effects in rats (1) although it has been shown not to be carcinogenic in humans but still very toxic to aquatic life (2). The use of paclobutrazol on food crops is therefore not recommended, but whether or not it’s actually allowed or not depends on the legislation of the country where you’re in. Some countries will allow paclobutrazol to be used as long as enough time is given between application and the development of the edible parts of the crop and then again this usually only applies to a limited number of crops where the time between use and harvest can be guaranteed to be long enough. Chlormequat and daminozide follow similar stories, although in the case of daminozide it was discovered that it was carcinogenic and its use in edible crops was completely banned world wide in the late 1980s.

Table 2. Pesticide analytes and their action levels

Analyte	Chemical Abstract Services (CAS) Registry number	Action level ppm	Analyte	Chemical Abstract Services (CAS) Registry number	Action level ppm
Abamectin	71751-41-2	0.5	Imazalil	35554-44-0	0.2
Acephate	30560-19-1	0.4	Imidacloprid	138261-41-3	0.4
Acequinocyl	57960-19-7	2	Kresoxim-methyl	143390-89-0	0.4
Acetamiprid	135410-20-7	0.2	Malathion	121-75-5	0.2
Aldicarb	116-06-3	0.4	Metalaxyl	57837-19-1	0.2
Azoxystrobin	131860-33-8	0.2	Methiocarb	2032-65-7	0.2
Bifenazate	149877-41-8	0.2	Methomyl	16752-77-5	0.4
Bifenthrin	82657-04-3	0.2	Methyl parathion	298-00-0	0.2
Boscalid	188425-85-6	0.4	MGK-264	113-48-4	0.2
Carbaryl	63-25-2	0.2	Myclobutanil	88671-89-0	0.2
Carbofuran	1563-66-2	0.2	Naled	300-76-5	0.5
Chlorantraniliprole	500008-45-7	0.2	Oxamyl	23135-22-0	1
Chlorfenapyr	122453-73-0	1	Paclobutrazol	76738-62-0	0.4
Chlorpyrifos	2921-88-2	0.2	Permethrins*	52645-53-1	0.2
Clofentezine	74115-24-5	0.2	Phosmet	732-11-6	0.2
Cyfluthrin	68359-37-5	1	Piperonyl_butoxide	51-03-6	2
Cypermethrin	52315-07-8	1	Prallethrin	23031-36-9	0.2
Daminozide	1596-84-5	1	Propiconazole	60207-90-1	0.4
DDVP (Dichlorvos)	62-73-7	0.1	Propoxur	114-26-1	0.2
Diazinon	333-41-5	0.2	Pyrethrins†	8003-34-7	1
Dimethoate	60-51-5	0.2	Pyridaben	96489-71-3	0.2
Ethoprophos	13194-48-4	0.2	Spinosad	168316-95-8	0.2
Etofenprox	80844-07-1	0.4	Spiromesifen	283594-90-1	0.2
Etoxazole	153233-91-1	0.2	Spirotetramat	203313-25-1	0.2
Fenoxycarb	72490-01-8	0.2	Spiroxamine	118134-30-8	0.4
Fenpyroximate	134098-61-6	0.4	Tebuconazole	80443-41-0	0.4
Fipronil	120068-37-3	0.4	Thiacloprid	111988-49-9	0.2
Flonicamid	158062-67-0	1	Thiamethoxam	153719-23-4	0.2
Fludioxonil	131341-86-1	0.4	Trifloxystrobin	141517-21-7	0.2
Hexythiazox	78587-05-0	1			

Table taken from here, these are substances banned for use in cannabis by the state of Oregon. You can see how several of the above mentioned growth retardants are present.

The above developments caused chemical companies to search for and develop new gibberellin synthesis inhibitors with lower toxicities and lower accumulation in plants that could be approved for use in edible crops. This led to the development of Prohexadione-Ca and Trinexapac-ethyl, which are two of the most commonly used growth retardants right now. These two have considerably lower toxicities and lower half-lives in the environment. For this reason trinexapac-ethyl has been approved for general use in places like New York (3). In this document the toxicity for mammals and aquatic life is discussed and trinexapac-ethyl is not found to be a threat to humans or animals at the maximum suggested application rate.

This is mainly due to the fact that it’s quickly bio degraded in the environment. A risk assessment made by the EFSA also reached similar conclusions (4). Another EFSA risk assessment for prohexadione-Ca also points in the same direction (5). Prohexadione-Ca is currently approved by the EPA for use in apples, grass grown for seed, peanuts, pears, strawberries, sweet cherry, turf, watercress, alfalfa and corn (6).

Optimal results with these new growth retardants also require careful consideration of the application formulation, the application time and adequate pairing of the PGR with the plant being grown . For example in apple trees much larger doses of Trinexapac-ethyl are required compared to Prohexadione-Ca to achieve the same results and trees that have been treated with Trinexapac-ethyl can have important reductions of flowers in subsequent crops (7).

With the development of less toxic and still highly active growth retardants, it might seem like a no-brainer to use these in crops to prevent elongation and increase yields. However the introduction of inhibitors in the gibberellin pathway is not without further consequence as this path is also important to guide the production of important phytonutrients and essential oils. When using these growth retardants it’s important to evaluate their effect in the quality of the product, as they can also lead to a change in the properties of the end product. For example in apples these PGRs can induce the production of luteoforol, a flavonoid they normally do not produce (8).

Keeping plants short: Why is it important?

Plants have evolved to grow vertically – to reach more sunlight – and horizontally – to increase their surface area and capture more sunlight. However, vertical growth is almost always undesirable because of the many problems it can generate. With this article I am starting a series of posts about "keeping plants short" which will cover a lot of the practical methods that have been developed in order to stop and modulate the vertical growth of plants. In this first post I want to look at the reasons why keeping plants short is desirable in almost all plant species and growing conditions and give you some hints about the methods that I will be discussing in future posts about the practical actions we can take to keep our plants small, yet highly productive. So why is it important to keep plants short?



A picture of severe lodging in cereal crops (taken from this article)

Lodging prevention. Mechanical stability is very important when growing plants. Tall plants are mechanically less stable because the upper parts of the plant can apply a lot of leverage to the base of the plant. If enough weight is accumulated and force is applied – through wind for example –

the plant can easily break or the stem be displaced for the vertical position, leading to huge losses in the crop. Plants that are shorter are naturally more resistant to lodging because there is less mechanical advantage to apply leverage on the base of the plant, the plant is therefore less likely to move from its vertical position, even if some force is applied.

Ease of harvesting. The taller a crop, the more inconvenient it is to harvest the product. For fruiting crops it becomes more inconvenient to pick fruits from higher positions while for crops like potatoes more material from above the ground needs to be removed. This difficulty to harvest the fruits is the main reason why some perennial crops, like African palm, become unproductive. At some point in time the fruits are so far up that it is no longer feasible to mechanically harvest them. In hydroponic crops like tomatoes the height of the plant is limited by the mechanical constraints of the greenhouse, if a plant is shorter and more trusses per meter can be grown, then this immediately leads to an increase in potential productivity.

Table 12.1. Negative Impacts of Lodging on Wheat Yield and Quality (Typical Values after P inthus, 1973; A nderson, 1979; J ung and R ademacher, 1983; H offmann, 1992; E sson *et al* ., 1993; B erry *et al* ., 2004; B aker *et al* ., 2014 and after Results of BASF Field Trials)

Parameter	Effect
Total grain yield	Decreased by 10–40% (up to 80% in extreme cases)
1000-grain-weight	Decreased by 8–15%
Crude protein content of seeds	Relative increase by 3–20%
Carbohydrate content of seeds	Relative decrease by 10–17%
Milling quality	Decreased
Baking quality	Decreased
Presence of mycotoxins	Significantly increased risk
Costs for harvesting	Increased by up to 50%
Costs for grain drying	Increased by 20–30%

Lodging in wheat heavily affects yields and quality. Taken from this review.

Ease of transport. When a plant is shorter, the movement of nutrients and water from the roots to the leaves is easier, as the distance is smaller. Plants that are shorter need to fight gravity less and will therefore be able to transport nutrients more efficiently to their fruiting bodies. This is why the first flowers of all plants are usually the most productive – because they are the closest to the root system – and why the further away you go from the ground the smaller and smaller the fruits tend to become. Having short crops means that the top fruits and flowers will receive a higher degree of nutrition than they would if the crop was taller.

More homogeneity. Related with the above, when plants are shorter the distribution of nutrients among the plant is better because leaves, flowers and roots are all in closer proximity. Taller plants with larger inter-nodal distances will tend to have more distance between leaves and fruits, which will decrease homogeneity as the difference in light irradiation and root-to-leave transport between the nodes will

be greater. A plant with the same number of leaves and flowers with lower inter-nodal distances will have much more homogeneous products for this reason.

The above are some of the most important reasons why it is usually desirable to have plants that are short. However, we do not want plants that are just short, but we want plants that are short but preserve the same yield as taller plants. This means we must get creative and use solutions that can manipulate the plants to give us the best of both worlds. There are a potential array of solutions to this problem. For example we can attempt to directly interfere with the chemistry of stem elongation (synthetic gibberellin inhibitors), to indirectly interfere with the chemistry by trying to stimulate other processes, to do genetic selection of plants that are naturally shorter, to provide mechanical stimulation to prevent elongation, to change light characteristics to inhibit elongation or to use day/night manipulations to achieve this same goal. We will explore many of these potential solutions within subsequent posts.

Using calcium sulfate in hydroponics

Calcium is a very important element in plant nutrition and can be supplied to plants through a wide variety of different salts. However, only a handful of these resources are significantly water soluble, usually narrowing the choice of calcium to either calcium nitrate, calcium chloride or more elaborate sources, such as calcium EDTA. Today I am going to talk about a less commonly used resource in hydroponics – calcium sulfate – which can fill a very important gap in

calcium supplementation in hydroponic crops, particularly when Ca nutrition wants to be addressed as independently as possible and the addition of substances that interact heavily with plants wants to be avoided.



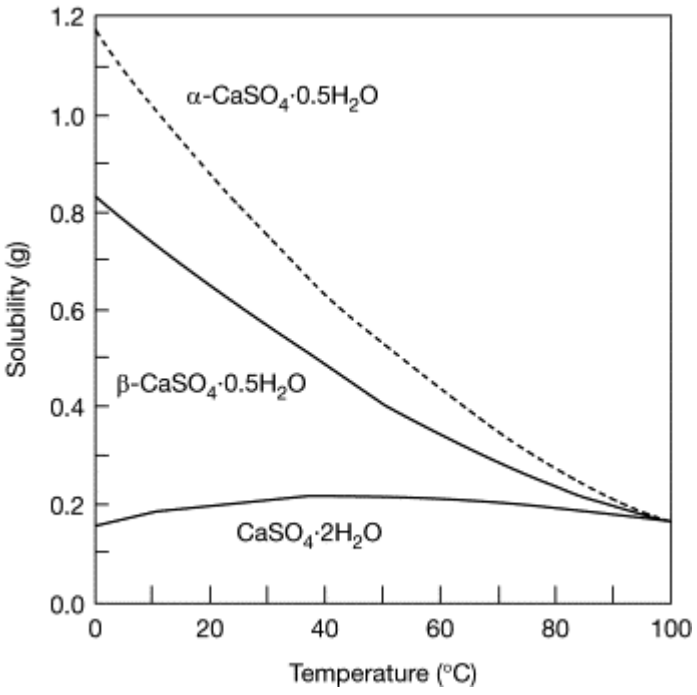
Calcium sulfate dihydrate (gypsum)

There are some important reasons why you don’t hear too much about calcium sulfate in hydroponics. Some websites actually recommend heavily against using this substance in hydroponic nutrient solutions. Why is this the case? The core issue is calcium sulfate’s solubility, with this substance traditionally considered “insoluble” in chemistry. However all substances are soluble to one or another degree – even if to an extremely small degree – but calcium sulfate is actually at the very border of what is considered a soluble substance in regular aqueous chemistry.

At 20C (68F), calcium sulfate dihydrate – the form most commonly available – has a solubility of around 2.4 g/L. In practice this means that you can have up to around 550 ppm of Ca in solution from calcium sulfate dihydrate before you observe any precipitation happening. This is way more than the normal 150-250 ppm of Ca that are used in final hydroponic nutrient solutions that are fed to plants. You could supply the entire plant requirement for calcium using calcium sulfate

without ever observing any precipitate in solution. *At the normal temperature range that hydroponic nutrient solutions are kept, the solubility of calcium sulfate is just not an issue*. To add 10 ppm of Ca from calcium sulfate you need to add around 0.043g/L (0.163g/gal). You should however avoid using calcium sulfate for the preparation of solutions for foliar sprays as it will tend to form precipitates when the foliar spray dries on leaves, the leaves will then be covered with a thin film of gypsum, which is counterproductive.

Calcium sulfate has a great advantage over other ways to supplement calcium in that the anion in the salt – sulfate – does not contribute as significantly to plant nutrition. Other sources, such as calcium chloride or calcium nitrate, will add counter ions that will heavily interact with the plant in other ways, which might sometimes be an undesirable effect if all we want to address is the concentration of calcium ions. Other sources such as Ca EDTA might even add other cations – such as sodium – which we would generally want to avoid. Calcium sulfate will also have a negligible effect in the pH of the solution, unlike other substances – like calcium carbonate – which will have a significant effect in the pH of the solution.



Solubility (g per 100mL) of calcium sulfate as a function of temperature for different crystalline forms (see more here)

A key consideration with calcium sulfate is also that its dissolution kinetics are slow. It takes a significant amount of time for a given amount of calcium sulfate to dissolve in water, even if the thermodynamics favor the dissolution of the salt at the temperature your water is at. For this reason it is very important to only use calcium sulfate sources that are extremely fine and are graded for irrigation. This is sometimes known as "solution grade" gypsum. I advice you get a small amount of the gypsum source you want to use and test how long it takes to dissolve 0.05g in one liter of water. This will give you an idea of how long you will need to wait to dissolve the calcium sulfate at the intended temperature. Constant agitation helps with this process.

An important caveat with calcium sulfate is that its relatively low solubility compared with other fertilizers means that it cannot be used to prepare concentrated nutrient solutions. This means that you will not be able to prepare a calcium sulfate stock solution or use calcium sulfate in the preparation of A and B solutions. As a matter of fact the formation of calcium sulfate is one of the main reasons why concentrated nutrient solutions usually come in two or more parts, to keep calcium and sulfate ions apart while they are in concentrated form. *Calcium sulfate should only be added to the final nutrient solution and adequate considerations about temperature and dissolution time need to be taken into account.*