Using titanium to increase crop yields

There are many additives that can be used to enhance the yield of flowering crops. Some have been covered in this blog – like silicon – while others haven't been mentioned here. Today we are going to talk about a rarely discussed additive that is infrequently used in plant culture these days: Titanium. I want to talk about this additive in light of a literature review that came up recently (April 2017) about the use of Titanium in crop production. The magazine where this review came from (Frontiers in Plant Science) is a magazine that often has good content in the field of innovative crop enhancing techniques.

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Titanium use in plant culture is not new. From the early 1980s people started to experiment with titanium as techniques were developed in order to produce titanium chelates that could be used in foliar applications. Basically all reports of yield increases – that show wonderful increases up to even 95.3% in yields – come from a paper on the biological importance of titanium by Dr. István Pais in 1983 and then another publication in 1991 by the same person (here). Other authors have also showed increased yields (here and here) although in some cases in conjunction with other additives (like Si) with results often much less dramatic than the initial 1983 papers. Titanium nanoparticles have also been tested and their effect has mostly been negative with decreases in plant growth and often DNA damage. For this reason when using titanium you want to go with a soluble chelate and not nanoparticle sources.

Creating aqueous stable Ti is not a cake walk. There is currently only one product that carries water soluble Ti (called Tytanit) and as far as I can tell no other commercial products for the application of Ti exist at this moment. This tytanit product is most probably titanium ascorbate – the most popular chelate used – but other organic chelates, like Ti citrate, might be usable as well. Preparing Ti ascorbate is not so easy to get as well – you cannot just buy it on ebay/alibaba as it's not stable as a solid – so you need to prepare it from scratch. Titanium chemistry in solution is sadly very complicated.

However there is probably a route to the easy preparation of such complexes using a simple method involving titanium dioxide and ascorbic acid. We know from dissolution studies of titanium dioxide that it can be dissolved significantly by ascorbic acid but the final concentration of these solutions is not very high with a final concentration of around 0.025M of Ti possible in solution using this method, with a surrounding concentration of 0.15M of ascorbic acid. More acid does not help dissolve more titanium dioxide as this seems to be the solubility limit of the titanium complex. This gives you around 1.2g/L of Ti which you need to dissolve 500-1000x to arrive at the recommended application rate of 1-2 ppm. This will give a final ascorbic acid concentration of 26ppm which is acceptable as an additive as well.

Obviously there are some further formulation steps necessary to get the above to work correctly but this outlines the basics to develop a concentrated titanium ascorbate product that can be used for the creation of a Titanium supplement. Industrially this can be achieved much more efficiently with the use of titanyl sulfate which is a readily soluble and easy to get industrially – but hard to get for your home – form of titanium. You can see this patent for examples of how a fertilizer using titanyl sulfate can be prepared.

Evidence about titanium – applied as titanium ascorbate in a

foliar spray – being positive for crops is significant. Various positive effects have been shown across a significant variety of plants across several different plant types – tomatoes, beans, peppers – by different authors. The effect on yields is not so clear – probably in reality not as large as shown in the original studies, but probably significant enough to warrant further studying. The development of low-cost processes for the manufacturing of titanium fertilizers will further enhance their use and increase our knowledge about their true capabilities. More studies with ascorbic/ascorbate controls will also show us clear evidence of whether we are seeing effects related with the ascorbate or the actual Ti chelate.

Phosphorous toxicity and concentration in higher plants

If you search the web for symptoms of nutrient toxicities you will often find clear pictures and descriptions for most elements. Feed a plant too much nitrogen and it will grow leggy and weak, with dark leaves and long stems, feed it too much boron and you will see yellowing and tissue necrosis. However you will struggle to find descriptions for toxicity symptoms for potassium (K) or phosphorous (P). Is there really no P or K toxicity? Why are they no pictures or clear ideas of how these problems look? Today I am going to talk a bit about P toxicity and why it’s so difficult to reach levels where plants react very negatively to ions from the phosphate family. *Images posted were taken from articles cited within this post.*

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You will often find websites that talk about P toxicity as saying that it is rare or that what it causes is mainly problems with other elements. In general increases in P concentration can cause problems with other elements particularly because the solubility of dihydrogen phosphate salts ($H_2PO_4^-$), salts that form with the ionic form of phosphate that's mainly present around the pH values used in hydroponics (5.5-6.5) can be very insoluble. You will struggle to find solubility values for heavy metal dihydrogen phosphates, but Fe, Zn and Cu dihydrogen phosphates can be reasonably presumed to be poorly soluble. However calcium dihydrogen phosphate has a solubility of 20g/L at 25°C and is therefore very soluble, so no problems with Ca due to having a lot of phosphorous (this salt is also known as mono calcium phosphate).

The solubility of Ca dihydrogen phosphate is in fact very important because rock phosphate – tricalcium phosphate – is one of the main sources of phosphorous in soil and it dissolves to form protonated phosphate species at the pH usually created around plant roots. This means that many plants evolved with very large occasional concentrations of dihydrogen phosphate around them and therefore they generated mechanisms to down-regulate the uptake of phosphorous from really high concentrations.

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There is strong evidence about the above. In fact plants that

evolved in phosphorous-poor soils did not evolve mechanisms for down-regulation and do exhibit P toxicity even at moderate concentrations of this element. A few plants native to Australia exhibit this behavior, you can read more about this here. Due to this fact many plants can be cultured in media that is amended with fertilizers that generate large local concentrations of phosphorous when watered without showing any strongly negative effects. Note however that plants will eliminate these down-regulation mechanisms significantly if they are in a P deficient media and if you feed them P rapidly you can cause P toxicity just because the plant couldn't react fast enough to the large increase in P concentration. See for example this study using P deficient Barley which accumulated toxic levels of P upon supplementation although this did not happen when the plants were constantly exposed to high P levels.

In hydroponics we do see excess of P manifest itself as deficiencies of other elements because of the solubility issues for heavy metal acid phosphates mentioned above. Several studies show the strong link between P concentration and the availability of some micro-elements. For example this paper shows the relationship between P and Zn and how the relationship corresponds with Zn phosphate precipitation in the roots. However if heavy metals are properly chelated we in fact don't see these problems. I have made experiments with plants – basil and mint – cultivated in 600 ppm of P where I have failed to see any significant problems although I have failed to find any papers that describe experiments under such extreme P concentrations.

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Is more P always better then? Studies in tomatoes show better

responses to salinity at higher P concentrations (for example here). Although the highest concentration tested here is 61 ppm (2mM) which is higher than but still close to what is generally used in hydroponic culture of tomato plants (30-50 ppm). Tabasco pepper has also been found to grow better under higher P concentrations (see here). A study varying P concentration in hob marjoram found lower essential oil concentrations at higher P levels, although these levels are around 60 ppm as well. Lettuce on the other hand shows increases of sesquiterpene lactones at high P levels (see here). There are a few publications about P toxicity in higher plants – notably this one about tomatoes – where problems caused by P are generally associated with the previously mentioned micronutrient issues and P concentrations in leaf tissue above 1%.

In summary P toxicity depends heavily on plant type and its ability to regulate P uptake, it is also most likely heavily dependent on micronutrient concentration and the strength and stability of the chelating agents used to prevent the precipitation of heavy metal phosphates. There are no studies I could find with P under very high concentrations (>=20mM) using chelated heavy metal sources so this is an interesting topic for research for anyone interested in exploring the limits of P uptake.

A simple Arduino based sensor monitoring platform for

Hydroponics

Last time I posted about automation I talked about how I use an Arduino to automate the monitoring and management of my home hydroponic system. Today I want to talk about how you can build an Arduino based station to monitor the most important variables of your hydroponic crop without having to solder anything, use complicated bread board setups or learn to how to do any coding. I will walk you through some of the steps to build the system, talk about the parts you need and show you the code you need to run to have this setup work.

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A basic sensor monitoring application for hydroponics should be able to get the most critical information needed to grow a crop successfully. The basic variables you would want to monitor to achieve this goal would be: temperature, humidity, carbon dioxide concentration, pH and electrical conductivity. An Arduino micro-controller can help you achieve all these goals at a reduced cost when compared with commercially available monitoring solutions of the same quality.

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- Arduino UNO R3 – 23.90 USD
- LCD 12864 screen shield – 24.05 USD
- DHT22 temperature and humidity sensor – 9.50 USD
- Gravity pH sensor – 56.95 USD
- Gravity EC sensor – 69.90 USD
- Gravity CO2 sensor – 58.00 USD

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The list above contains all the pieces you need to get this to

work. This includes the Arduino plus an LCD display that we will use to be able to read the information we obtain from the sensors. I have included links to the pieces at the dfrobot site (one of my favorite sources for DIY electronics) but you can definitely get them elsewhere if you prefer. The pH sensor included here is of industrial quality while the EC sensor has a lower quality level. However I have been able to use both for extended periods of time without anything else than a calibration around once every 2 months. If you want you can also purchase an industrial quality EC probe if you find the prove from the included Gravity kit to be insufficient for your needs.

The cool thing about this setup is that the LCD screen already contains all the connections we need for the sensors. The bottom part contains numbered analog inputs while the left part contains numbered digital inputs. In this setup we have two digital sensors – the DHT22 humidity/temperature sensor and the solution temperature sensor that comes with the EC sensor – and three analog sensors, which are pH, EC and CO_2. I have put some text on the image to show you exactly where you should connect the sensors according to the code, make sure the orders of the colors on the wires match the colors on the connector in the LCD screen. The Arduino code contains some defines with the pins for each sensor so you can just change those numbers if you want to connect the sensors in different places.

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```
//Libraries
#include <DHT.h>;
#include <U8glib.h>
#include <stdio.h>
#include <OneWire.h>
#include <Wire.h>
#include <Arduino.h>
#include <Adafruit_Sensor.h>
```

```
//PINS
#define DHT_PIN        5          // DHT pin
#define DHTTYPE        DHT22      // DHT 22  (AM2302)
#define PH_PIN         2          //pH meter pin
#define CO2_PIN        3          //ORP meter pin
#define EC_PIN         1          //EC meter pin
#define DS18B20_PIN    6          //EC solution temperature
pin

// AVERAGING VALUES
#define MEDIAN_SAMPLE 8
#define MEASUREMENTS_TAKEN 100

// EC - solution temperature variables
#define StartConvert 0
#define ReadTemperature 1

// EC values // CHANGE THESE PARAMETERS FOR EC PROBE
CALIBRATION
#define EC_PARAM_A 0.00754256

//pH values // CHANGE THESE PARAMETERS FOR PH PROBE
CALIBRATION
#define PH_PARAM_A 1.0
#define PH_PARAM_B 0.0

#define XCOL_SET 55
#define XCOL_SET2 65
#define XCOL_SET_UNITS 85

//-------------------------

DHT dht(DHT_PIN, DHTTYPE);
U8GLIB_NHD_C12864 u8g(13, 11, 10, 9, 8);
unsigned long int avgValue;
float b, phValue;
int buf[MEASUREMENTS_TAKEN],tmp;
int chk;
float hum;
float temp;
unsigned int AnalogAverage = 0,averageVoltage=0;
```

```
float solution_temp,ECcurrent;
unsigned int levelAverage;
float co2;
OneWire ds(DS18B20_PIN);

//--------------------------

void draw() {
  u8g.setFont(u8g_font_04b_03);
  u8g.drawStr( 0,11,"Temp:");
  u8g.setPrintPos(XCOL_SET,11);
  u8g.print(temp);
  u8g.drawStr( XCOL_SET_UNITS, 11,"C" );
  u8g.drawStr(0,21,"Humidity:");
  u8g.setPrintPos(XCOL_SET,21);
  u8g.print(hum);
  u8g.drawStr( XCOL_SET_UNITS,21,"%" );
  u8g.drawStr(0,31,"pH:");
  u8g.setPrintPos(XCOL_SET,31);
  u8g.print(phValue);
  u8g.drawStr(0,41,"EC:");
  u8g.setPrintPos(XCOL_SET,41);
  u8g.print(ECcurrent);
  u8g.drawStr( XCOL_SET_UNITS,41,"mS/cm" );
  u8g.drawStr(0,51,"Sol.Temp:");
  u8g.setPrintPos(XCOL_SET,51);
  u8g.print(solution_temp);
  u8g.drawStr( XCOL_SET_UNITS,51,"C" );
  u8g.drawStr(0,61,"CO2:");
  u8g.setPrintPos(XCOL_SET,61);
  u8g.print(co2);
  u8g.drawStr( XCOL_SET_UNITS,61,"ppm" );
}

float TempProcess(bool ch)
{
  static byte data[12];
  static byte addr[8];
  static float TemperatureSum;
  if(!ch){
          if ( !ds.search(addr)) {
```

```
            ds.reset_search();
            return 0;
        }
        if ( OneWire::crc8( addr, 7) != addr[7]) {
            return 0;
        }
        if ( addr[0] != 0x10 && addr[0] != 0x28) {
            return 0;
        }
        ds.reset();
        ds.select(addr);
        ds.write(0x44,1);
  }
  else{
        byte present = ds.reset();
        ds.select(addr);
        ds.write(0xBE);
        for (int i = 0; i < 9; i++) {
          data[i] = ds.read();
        }
        ds.reset_search();
        byte MSB = data[1];
        byte LSB = data[0];
        float tempRead = ((MSB << 8) | LSB);
        TemperatureSum = tempRead / 16;
    }
        return TemperatureSum;
}

void calculateAnalogAverage(int pin){
 AnalogAverage = 0;
  for(int i=0;i<MEASUREMENTS_TAKEN;i++)
  {
    buf[i]=analogRead(pin);
    delay(10);
  }
  for(int i=0;i<MEASUREMENTS_TAKEN-1;i++)
  {
    for(int j=i+1;j<MEASUREMENTS_TAKEN;j++)
    {
      if(buf[i]>buf[j])
```

```
      {
        tmp=buf[i];
        buf[i]=buf[j];
        buf[j]=tmp;
      }
    }
  }
  avgValue=0;
               for(int       i=(MEASUREMENTS_TAKEN/2)-
(MEDIAN_SAMPLE/2);i<(MEASUREMENTS_TAKEN/2)+(MEDIAN_SAMPLE/2);i
++){
    avgValue+=buf[i];
  }
  AnalogAverage = avgValue/MEDIAN_SAMPLE ;
}

void read_pH(){
  calculateAnalogAverage(PH_PIN);
  phValue=(float)AnalogAverage*5.0/1024;
  phValue=PH_PARAM_A*phValue+PH_PARAM_B;
}

void read_EC(){
  calculateAnalogAverage(EC_PIN);
  solution_temp = TempProcess(ReadTemperature);
  TempProcess(StartConvert);
  averageVoltage=AnalogAverage*(float)5000/1024;
  float TempCoefficient=1.0+0.0185*(solution_temp-25.0);
                                                      float
CoefficientVolatge=(float)averageVoltage*TempCoefficient;
  ECcurrent=EC_PARAM_A*CoefficientVolatge;
}

void read_CO2(){
  float voltage;
  float voltage_difference;
  calculateAnalogAverage(CO2_PIN);
  voltage = AnalogAverage*(5000/1024.0);
  if(voltage == 0)
  {
    co2=-100.0;
```

```
  }
  else if(voltage < 400)
  {
    co2=0.0;
  }
  else
  {
    voltage_difference=voltage-400;
    co2=voltage_difference*50.0/16.0;
  }
}

void setup()
{
    pinMode(13,OUTPUT);
    Serial.begin(9600);
    dht.begin();
    u8g.setContrast(0);
    u8g.setRot180();
    TempProcess(StartConvert);
}

void loop()
{

  digitalWrite(13, HIGH);
  delay(800);
  digitalWrite(13, LOW);
  hum = dht.readHumidity();
  temp= dht.readTemperature();
  read_pH();
  read_EC();
  read_CO2();

  u8g.firstPage();
    do  {
      draw();
    }
      while( u8g.nextPage() );
}

_
```

After you connect the sensors you can then upload the code above using the Arduino IDE to your Arduino via USB. You will need to install the following Arduino libraries to get it to compile and upload:

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- AdaFruit unified sensor driver
- AdaFruit DHT sensor library
- OneWire library
- U8glib library

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After you upload this to your Arduino it should start and show you a screen with the temperature, humidity, pH, EC and carbon dioxide readings. The carbon dioxide concentration might show as -100 in the beginning, which simply means that the sensor is heating up (it requires a few minutes before it can start giving readings).

It is also worth noting that you should calibrate your pH sensor. To do this you should read the pH of a 7.0 buffer (M7) – record the value you get – and then repeat the process with a pH 4.0 buffer (M4). You can then change the PH_PARAM_A and PH_PARAM_B values in the code (right at the beginning) to make the sensor match your measurements. The PH_PARAM_A parameter should be equal to 3/(M7-M4) while PH_PARAM_B should be 7-M7*PH_PARAM_A. If you ever need to recalibrate set PH_PARAM_A to 1 and PH_PARAM_B to 0 and repeat the process. For the EC sensor you should perform a calibration using the 1.412 mS/cm solution that comes with the sensor and then change EC_PARAM_A so that your sensor matches this reading (1.412/(MEC/0.00754256)).

With this new monitoring station you should now have a powerful tool to monitor your hydroponic system and make sure everything is where you want it. Of course making the arduino intereact with a computer to record these values and then

implementing control mechanisms using fans, peristaltic pumps, water pumps, humidifiers/dehumidifiers and other appliances is the next step in complexity.

What is the effect of amino acids in hydroponics?

It is very common for hydroponic nutrient manufacturers to add amino acids to their products. They often mention significant benefits that range from strengthening plants to greatly increasing yields or product quality but they rarely mention any peer reviewed evidence studying these effects. Today we are going to look at the use of amino acid applications in hydroponic culture and the effects that amino acids have been shown to have when used in a variety of different crop types. We will see some of the benefits and the problems that they have shown to cause as well and we'll discuss whether it is actually worth it to apply them in a hydroponic nutrient solution.

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Amino acids – which I am going to use here to refer to L-alpha amino acids – are basically organic molecules that are used as the basic block for protein construction in all life forms. Plants are able to synthesize all the amino acids they need internally while in the case of animals many of these amino

acids need to come from other animal or vegetable sources. However since amino acids can be added to nutrient solutions and plants can absorb them (see here) it is interesting to wonder what the effects they might have.

There are two ways in which amino acids can affect a hydroponic crop. They may be absorbed and used directly by the plant or they may create a chelate with a metal ion and affect that metal's absorption. It is very difficult to separate both effects – except when specific metal absorption studies are carried out – so the effect on yields is generally a combination of these two. The specific amino acids used and their proportion are also critical to these effects as both plant absorption and the stability of metal chelates depend on the exact structure of the amino acids in solution.

There is significant evidence that amino acid applications reduce nitrate assimilation (see here, here and here) this is not surprising given that amino acids compete with nitrate in the nitrogen cycle and may be more readily assimilated by plants. This seems to be especially the case if nitrate concentrations are low and the plants are N deprived. The effect is most important for glutamine, not surprising as glutamate synthesis is basically the mechanism used for ammonium incorporation by plants.

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There is also evidence that amino acids can help plants under stress conditions. For example strawberries in autotoxic conditions – meaning that they have made a nutrient solution toxic after a lot of recirculation – benefited greatly from an amino acid cocktail application (here) and Canola plants have

shown to have increased yields under saline conditions with proline applications (here). Plants under heavy metal stress can also benefit from the presence of amino acid, for example rice seedling have shown to benefit from amino acid applications under cadmium stress (here).

There are also limited studies in the use of amino acids as metal chelates in hydroponics. A 2012 study (here) compared different Fe chelates with Fe EDTA and showed that some of these chelates work better than the traditional EDTA chelate in Fe absorption. Fe glycine showed the best absorption across roots and shoots plus the best yields in tomatoes (second image in this post). This shows that Fe glycine may be a good candidate for the replacement of Fe EDTA in hydroponic solutions. Another study (here) also compared different Cu containing amino acid chelates and found that cysteine may be effectively used for Cu fertilization and phytoremediation.

Is it worth it to apply amino acids in hydroponics? This may depend on the exact conditions the plants are facing. While amino acids have proved beneficial for the assimilation of specific nutrients – like Fe and Cu – or the alleviation of some stress conditions (salinity, autotoxicity), there isn't any strong evidence suggesting wide range beneficial effects under normal plant growing conditions, especially if these are close to ideal. In normal hydroponic solutions introducing large amounts of amino acids may even have significant negative effects due to their effect on ion absorption and N metabolism. Further evidence is required before general recommendations for exogenous amino acid applications can be made.

This doesn't mean that amino acids might not be beneficial under normal conditions, just that we have no evidence yet showing which amino acid profiles might work best for which plants and under what concentrations and we do know that there can be potentially harmful effects if these parameters are not studied carefully.

Calibrating your digital humidity sensors

On a recent post I talked about vapor pressure deficit and its importance in hydroponic culture. To adequately control VPD it's necessary to accurately measure relative humidity and in order to do so it's necessary to have adequately calibrated humidity sensors. Since most of today's humidity sensors are digital this becomes even more important as these sensors can get damaged very easily, especially if the dew point is reached at any given point in time. Today I am going to talk about humidity sensor calibration, how it can be easily carried out and why you should do it in order to ensure that your humidity sensors are being accurate enough for your cultivation needs.

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Most modern digital humidity sensors are based on conductive polymers whose resistance changes with the amount of water in the air. If the polymer is in equilibrium with water vapor in the air then this change will be proportional to relative humidity. Sensors like those from the SHTX and DHTX series work using this principle. However if the polymer gets wet – water falls on the sensor or the dew point is reached – or if it faces very low humidity conditions for a long time then the humidity sensor will stop working correctly and it will need to be reconditioned and calibrated.

Reconditioning of these sensors is usually carried out by

exposing the sensor to higher temperature dry conditions and then exposing the sensor to a controlled higher humidity lower temperature environment. These are some typical instructions for humidity sensor reconditioning. Once this process is carried out the sensor is now ready to be calibrated. Depending on the sensor you're using you might be able to change some calibration parameters to adjust the sensor to changes in its response or you might just use the calibration procedure to check the sensor's accuracy and discard it if it isn't behaving properly.

Calibration of digital humidity sensors can be carried out by putting them in the atmosphere composition generated over a saturated solution of a given salt. This table shows the expected relative humidity values at different temperatures for different salts. Basically you want to use a glass container where you can prepare a solution that has so much salt that there are undissolved crystals within it and then place your sensor in a closed environment above this solution (without touching it!). You can achieve this by drilling a hole at the top of a container with a lid to place the sensor (like it's showed here), alternatively you can stick the sensor with electrical tape inside a glass and then place it upside down in a small amount of solution. This last process – first image in this post – completely eliminates any issues caused by potential holes and the atmosphere reaches equilibrium a bit faster. Another potential option is to create a paste with water and salt and place this past with the sensor inside a zip lock bag.

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For starters you can perform a single measurement with a saturated sodium chloride solution – which should give you a

humidity of around 75%. This is a good way to check if the sensor is working properly without the need to buy any additional materials. If you want you can then get some additional salts, like potassium chloride, magnesium nitrate and potassium nitrate, which should give you several different calibration points to draw an appropriate calibration curve to gauge how your sensor is working across the entire humidity range. Ideally you would want to have two salts with equilibrium points above 50% and two below 50% relative humidity.

Probes for constant immersion in hydroponic nutrient solutions

If you have a hydroponic crop then you probably have to measure and monitor the pH and EC of your nutrient solutions. This means taking probes out of storage, ensuring they are calibrated and then carrying out measurements. This process can be very inconvenient, reason why growers might prefer to carry it out less often, even if this means they will have a lot less data. However there are several solutions that can enable constant monitoring of hydroponic nutrient solutions without the need to constantly take out, calibrate and then store away probes. Today we will talk about why regular probes are not suited for this and what types of probes are needed if you want to do this.

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Usually low quality EC/pH pens cannot be kept within nutrient solutions because they are not built to withstand constant contact with nutrient solutions. This is both due to the electrode composition – the actual glass or metal electrodes not being robust enough – and the actual junctions and other components not withstanding the nutrient solution as well. Although hydroponic nutrient solutions are not particularly harsh environments – with a slightly acidic pH and moderate ionic strengths – probes for constant monitoring of nutrient solutions must be designed with constant immersion in mind.

For constant monitoring of pH in nutrient solution tanks you want a proper submersible electrode assembly like this one. These electrodes are usually mounted on PVC fixtures and can be easily mounted on tanks to provide constant readings for the nutrient solution. The electrode comes with a standard BNC connector meaning that it is compatible with a wide variety of pH controllers. If you don't want to mount it on the tank but you just want the electrode to be like a normal probe but constantly submerged then you can use something like this industrial probe which comes with a pH controller as well that can be used with any other probes you purchased and interfaces with an arduino or raspberry pi to get and store readings. For probes like this last one I usually wrap the entire outside body of the probe in electrical tape to give further strength to the probe/cable junction.

For conductivity readings you will want to go with electrode-less EC probes (like these ones) which over PVC mountings as well with the advantage that they do not suffer from polarization issues – like normal EC pens use – so they lose calibration much more rarely and can give much more accurate readings across a wide range of different solution types and conductivity values.

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For the grower who wants it all there are also probes like the Mark I-A probe which is a tank-mounted probe assembly that does EC, pH and ORP readings, all in one single fixture. This is incredibly practical since it is able to implement all the readings you need in one single fixture. The problem of course is that calibration of any reading requires you to remove all three sensors so this can be a bit inconvenient when you want to ensure that any of the readings are indeed accurate.

Of course submersible robust probes are more expensive but they are much more convenient. They get damaged much less frequently, require much less maintenance, provide constant readings and need to be calibrated only a few times a year. For example the industrial EC and pH probes I use in my home hydroponic setup have only required calibration once a year, even then the loss in calibration was only around 0.2 units for the pH sensor and 0.3 mS/cm for the EC one so I probably could have continued using the probes without calibrating them for 2 years without having to face any dramatic consequences. If you spend 300-400 USD on high quality robust probes you will probably have them for much longer, with far more accurate results along the way.

Five things that will damage your pH probes

Since pH is one of the most important variables to control in hydroponic culture almost all hydroponic growers have and use pH probes. There are however several things that can go wrong with these probes due to the very nature of the sensor and the way in which other substances interact with it. Today we will learn about some of the worst things that you can do to your pH probes and how you can potentially avoid these issues.

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1. Let them dry. These probes are made from glass and the readings depend on the potential difference between the inside and outside surfaces of the sensor. These are determined mainly by pH since hydronium (H_3O^+) ions interact strongly with the glass surface. For measurements to be accurate the surface needs to be in equilibrium with the media that is being measured. If you let the electrode dry then the hydration of the surface will be lost and the equilibrium state will be much harder to achieve (a dry probe should be placed in a KCl solution for at least 4 hours before being used). Any junctions within the probe might also dry which will require further stabilization before the probe can be used . Dry pH probes are therefore a big no no.

2. Keep them in water. Although keeping pH probes in water is better than letting them dry this has a similar effect in that it alters the composition of the glass with time. Since the solution around the probe is much more diluted, with time ions in the glass will have no problem migrating away from the probe, creating defects within the glass that will mess with

your sensor’s calibration. Ideally you will want to store your pH probes in a concentrated KCl solution (usually around 150-300g/L) which will prevent any of these migration effects and will ensure that your probe remains stable in the longer term. If you buy KCl you can use distilled water to prepare your own pH probe storage solution.

3. Measure very basic solutions. Since pH probes are made of glass and glass is mainly made of silicates this means that basic solutions will tend to react with your pH probe. When the pH goes above 10 a pH probe will start to dissolve in solution, completely altering the surface and making the sensor lose calibration very quickly. In general avoid measuring the pH of any solution above 10 so that this effect can be kept to a minimum.

4. Measuring solutions with chemicals that react with glass. Besides basic solutions – where hydroxide ions dissolve glass – there are a variety of substances that can affect the performance of pH probes by reacting with the glass. This includes solutions containing silicate species and solutions containing fluoride ions. If the solution has ions that can react with glass then the pH probe’s lifetime will be diminished and much more frequent calibration will be required. Try to avoid long term measurements of solutions containing large amounts of these ions and beware that weekly calibration might be necessary.

5. Not cleaning the probe. When measuring solutions such as hydroponic nutrient solutions the pH probe is usually subjected to an environment filled with potentially microorganism contaminants. If the probe is not properly cleaned then microbes can form a biofilm over the glass that will seriously affect the accuracy of pH readings. A probe can be cleaned with a bleach or hydrogen peroxide solution to remove these contaminants but the probe will then need to be recalibrated as the film will have effectively changed the glass surface to some extent.

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Having pH probes that give accurate reading for a long time is not a difficult task if you take proper care of your sensors. Storing them adequately, ensuring they are not exposed to harmful conditions and cleaning them ensures that they will last for a much longer time. IF you keep track of your pH sensor calibrations you might notice changes in the calibration slope – as in the first image in this post – which indicates a loss of sensor sensibility (the slope becomes less pronounced). You can use a sensor until around 20% of the sensor's sensibility is lost, time after which you'll need to buy a new probe.

There are also several sensors that can be used for long term continuous measurements – which are made in a much more robust manner – we will talk about industrial quality and in-line sensors in a future post.

Vapor pressure deficit (VPD) in hydroponics

If you have read books or articles about greenhouse environmental control you have probably heard about Vapor Pressure Deficit, also known as VPD. This is an important variable to measure as it helps us understand the conditions our plants are facing, gauge their water use and even predict whether we will be getting better or worse yields. Today I am going to talk about vapor pressure deficit in hydroponics,

what this variable means, what it takes to control it and why it is so important to understand and even change this value to obtain better results.

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Vapor pressure deficit – measured in kPa – basically measures how much water vapor pressure we would need to put into a room with a certain humidity and temperature to get it to the point where relative humidity would be 100%. The larger the VPD the more water you need to put into the air to get it to saturate while the lower the VPD the closer the air is to full saturation. Since air holds more water with increasing temperature this means that at a fixed relative humidity the VPD is directly proportional to the room's temperature. This simply means that the hotter the room, the higher the VPD and the colder the room, the smaller the VPD if humidity remains constant.

The problem with a very low VPD – room close to 100% humidity – is two fold. First, it's difficult for any organism to evaporate water and second, it's easy for water to condense on any surface it temperature drops just a bit. For humans this basically means having to wear a t-shirt soaked with your own sweat but for plants this means both an inability to cool their surfaces and an inability to transport nutrients to their leaves. A low VPD generates a lot of stress because it makes plants unable to properly transport water.

A high VPD is equally problematic as it means that the plants need to transpire a lot. If air can hold a lot of additional water vapor this means that plants will lose more water through their stomata and this permanent loss puts pressure on the roots to transport more and more water. If root mass is

not large enough or water availability is not high enough then plants will face important problems and will simply tend to wilt as the air takes away more water than what the plant can effectively transport through its tissues. You can actually often create models using VPD to predict a crop's water usage (see image below).

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The first graph in this post (which I took from this study on tomatoes) shows the optimum VPD – in green – as a function of humidity and temperature for greenhouse production of tomatoes. In general a range between 0.5 and 1.1 seems to work best but the window under which these conditions are possible becomes narrower as temperature increases. Ideally we would want to be somewhere around 20-25°C where we should sustain humidity values between 65-70%. This would give us a VPD value between 0.7-0.8 which is around what is commonly held to be most beneficial for greenhouse crops under normal conditions.

However optimal VPD can also change depending on lighting conditions and other sources of supplementation. For example the optimal VPD during the day is usually higher than the optimal VPD during the night. In general it's better to have a drop in VPD during the night relative to the VPD that is maintained during the day. Declines in canopy carbon dioxide exchange rates can be correlated with increases in the VPD during this time (see here for a study about this on soy bean). If you're supplementing carbon dioxide – which puts further transpiration stress on the plants – the optimal VPD is also likely to be lower than if you didn't use any supplementation at all (you can see a practical application of this here).

Changing the VPD can be a challenge but under closed environments it is much easier to do. You can reduce the humidity using a dehumidifier to increase your VPD and you can use a humidifier to increase your VPD. Ideally you will want to use an AC unit to keep your temperature at exactly the value you want it to be and you can then use a humidifier/dehumidifier to control the exact point where you want your VPD to be by controlling the value of your relative humidity at the fixed temperature provided by the AC unit.

Maximizing yields per area in hydroponics

Since the 1940's hydroponics – which I use to talk about a broad variety of soilless growing methods – have promised to deliver better plant yields than soil culture with less water usage and higher fertilizer efficiency. However there are many different types of soilless cultures that vary in their initial cost, media used, irrigation method used and potential for yield. Today I want to talk about the decisions that need to be made if you want to maximize yields in a hydroponic crop and the compromises that you may have to make in order to get there.

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There are mainly two ways in which yields can be increased in crops. The first is to increase the amount of production you can achieve per plant and the second is to increase the amount

of plants you can have per area. Maximizing crop production requires using methods that allow you to reach the best compromise between these two, maximize the product of plants per area with production per plant. This often means not having the largest amount of plants you could possibly grow per square meter and not having the largest possible yields you could have per plant.

Assuming that plants are getting adequate lighting and carbon dioxide there are two things that can be done to maximize the amount of yield per plant. The first is to ensure that plants can get optimum contact with nutrient solution as often as possible. This means that nutrient solution should always be saturated with oxygen and that irrigation should happen as often as possible. This ideally means that the media should not allow for any waterlogging but should allow the solution to flow freely and constantly. The second is that the nutrient solution should contain adequate amounts of all nutrients – all within the plant's sufficiency ranges – with adequate temperature, pH and EC values. The optimum nutrient ratios in solution depend on the plant being grown and they can play a substantial role in getting better yields per plant, especially in flowering crops. Here are some scientific articles with some experiments about some of the above (1, 2, 3, 4, 5, 6).

A typical problem when maximizing yields per plant is that this immediately means larger energy expenditure. It often means close to constant irrigation systems with highly efficient oxygen pumps. It also means potentially more expensive media – such as expanded clays or rockwool – with closed systems where solutions need to be closely monitored. Systems of this sort are more vulnerable to power outages and they are much less forgiving with grower mistakes. Plants are much more dependent on the ideal conditions being created around them and deviations from these conditions can eliminate any potential advantages that were obtained when going for

this system class.

Our next area of yield maximization is to increase the number of plants per area. To do this we basically need to increase two things: light and ventilation. The main limiting factor in having more plants is the light that they can receive so either changing to systems where light can be better distributed – such as growing towers – or using more lights can alleviate this problem. Some growers have even used high power LED strips between plants to fix this issue. Since plants also absorb carbon dioxide around their leaves we also need to ensure we have stronger ventilation to ensure none of our plants are getting starved. Increasing plant density also increases the propensity of our plants to catch and transmit diseases so environmental manipulations like lower humidity are often coupled with increases in density to decrease these risks. See these articles for more on yields, light and density (1, 2, 3, 4).

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Increasing plants per area automatically decreases yields after one point but it is often the case that you can get larger final yields per area by compromising some yield per plant in the process. Even if plants yield 10% less this might be worth it if you can include 2 more plants for every 10 within your hydroponic crop. The key to maximizing yields per area is to find how far you can push this before getting substantial issues that may dramatically decrease plant yields.

It is worth noting that steps taken to maximize yields are also often steps taken in making the crop more susceptible to problems. While lower yielding setups, like for example run to

waste setups with sparse plant density, are often easy to manage and very forgiving, more technical setups like closed loop constant irrigation systems at high plant densities can be much better yielding but much more prone to problems, requiring much closer monitoring and attention. This is why many growers might get better yields with setups with lower yielding potential, because their mistakes are punished much less harshly under these conditions.

A few basics of leaf tissue analysis in hydroponic crops

Adequate nutritional control is difficult. Although there are several tools to control your plant's chemical environment – such as pH, EC and ORP – in the end the main interest we have is to control the composition of plant tissue and how this composition affects plant development and yields. One of our sharpest tools to achieve this is leaf tissue analysis which allows us to look at plant composition levels and figure out if anything is wrong with our plants. Today I want to talk about this powerful tool, why it is not so simple to use, how to use it and why it can be so important in helping you figure out what's wrong with your crops.

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The general model for nutrients and crop yields explains that plants will absorb nutrients till a point of maximum yield. After this point increasing nutrients will not increase or

decrease yields substantially for a while but after a given point toxicity will prevail and plant yields will decrease due to nutrient toxicities and potentially osmotic pressure issues. This model is simplistic as it leads to an overall linear understanding of plant nutrients which is why growers often find leaf tissue analysis puzzling and confusing.

In leaf tissue analysis we most commonly obtain a sample from the plant's most recent mature leaves. This tissue is analyzed by a lab and we obtain a chart where the percentage composition of the plant tissue for the different elements is given. We can then look at reference values for healthy plants and if any of our nutrients are outside this range then there is certainly something wrong with our crop's nutrition. Sometimes the lab will also give you some reference values but bear in mind that this aren't necessarily healthy plants but the average of what the lab gets for the plant specie you are growing. You either want an academic/government reference for healthy sufficiency ranges or you want to grow healthy plants yourself and take a reference sample to use for your future crops.

The tricky part is to interpret the tissue analysis. For example let's suppose that your tissue analysis comes up with low phosphorous. The immediate intuitive response that we get from the general model of nutrient sufficiency is that we should increase P in solution to get the P up within the leaves. However nutrient relationships are non-linear and in many cases what you have isn't a general lack of enough nutrient in solution but a problem getting that nutrient up to the leaves. In the case of P for example it might range from having excess chloride to having a nutrient solution that is too cold. I haven't seen a single case in hydroponics where low P in leaf tissue has actually been due to low P in the nutrient solution.

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It is important then to realize that a problem within leaves is not necessarily a problem with concentration for that specific nutrient being too low or high in solution – in my experience it rarely is – but more so a problem with the balance of nutrients in solution or the environment that is causing a nutrient absorption issue. There are all sorts of antagonic and synergistic relationships between the different nutrients and the environment that will make this hard to interpret in many cases. To know what might be the cause first you will want to address all environmental issues that are known to cause toxicities/deficiencies and then look into addressing nutrient issues relative to the solution. You will want to pay a lot of attention to ratios instead of absolute concentrations.

You can have a perfectly good nutrient solution and the absorption problem might be related with something like transplant stress, root pathogens, incorrect carbon dioxide supplementation, light issues, temperature/humidity problems, etc. Growers tend to focus on the nutrient solution as the potential source and cure to all plant problems but the key is often in the environment and crop management more than within the actual nutrient solution. Even when the cause is the nutrient solution growers often misdiagnose the problem and increase or decrease nutrient concentrations, more often than not making the problem worse.

Due to the above it is not surprising that few hydroponic growers find tissue analysis very useful. While in soil crops tissue analysis is usually used to manage fertilization and soil amendments in hydroponics the environment and solution are so controlled that the problems become much more difficult to diagnose and the solutions are often not what you would consider intuitive. It certainly requires a lot of reading and

experience to properly interpret leaf tissue analysis and tackle the causal factors that are causing issues in hydroponic crops. However with enough experience or guidance leaf tissue analysis can be a great tool to know what your plant is taking, what it’s not and how these issues can be fixed.