CROP STEERING

THE INTERSECTION OF PLANT SCIENCE AND HORTICULTURE

Cannabis cultivation is at a very exciting point today. Easing of prohibition laws worldwide have opened the floodgates to investigate the science of cannabis cultivation in a way that has never been possible before. While ushering in this new age of cannabis research, we can draw on well-established research and best practices from other horticultural crops. Cannabis also offers exciting opportunities for advancing all horticultural science because it is such a high-value crop that allows growers to use technologies and experiment with new techniques that would be economically unfeasible for almost any other crop.

Growers today have the unique opportunity and responsibility to develop and optimize best practices for commercial cannabis cultivation. While navigating this uncharted territory, we will make the most progress by using whatever maps we have available from established horticultural science and plant biology. “Crop steering” is a technique that draws from these disciplines and is currently underutilized in commercial cannabis cultivation.

CANNABIS ALSO OFFERS EXCITING OPPORTUNITIES FOR ADVANCING ALL HORTICULTURAL SCIENCE BECAUSE IT IS SUCH A HIGH-VALUE CROP THAT ALLOWS GROWERS TO USE TECHNOLOGIES AND EXPERIMENT WITH NEW TECHNIQUES THAT WOULD BE ECONOMICALLY UNFEASIBLE FOR ALMOST ANY OTHER CROP.

Crop steering is a data-driven form of precision agriculture which uses subtle environmental cues and irrigation techniques to "steer" crop growth and development to meet grower objectives and it has been widely used in important horticultural crops for decades [1]. Traditions from legacy growing also calls for making changes to environment and irrigation at prescribed points in the growth cycle. Vetting and fine-tuning these traditional practices through the lens of well-established horticultural science offers a new level of control and precision for commercial cannabis growers. Indeed, early adopters of crop steering in the cannabis industry are reporting record yields and unprecedented control over their crops. The precision of crop steering is ideal for continuous improvements to plant performance and profit margins based on quantifiable goals and outcomes. Crop steering offers an exciting opportunity to revolutionize the way cannabis is grown on a commercial scale.

EARLY ADOPTERS OF CROP STEERING IN THE CANNABIS INDUSTRY ARE REPORTING RECORD YIELDS AND UNPRECEDENTED CONTROL OVER THEIR CROPS.

Because crop steering is based on changes to the environment and irrigation strategies, it does not require any additional inputs beyond irrigation and environmental control systems. It is much more effective, however, with irrigation and environmental systems that offer both good control and the ability to monitor data, as well as the knowledge to interpret and act on data. After suitable control systems are in place, practicing crop steering costs virtually nothing and can greatly increase yields and cannabinoid production.

AFTER SUITABLE CONTROL SYSTEMS ARE IN PLACE, PRACTICING CROP STEERING COSTS VIRTUALLY NOTHING AND CAN GREATLY INCREASE YIELDS AND CANNABINOID PRODUCTION.

This paper offers a tour of crop steering and how it can be applied to commercial cannabis cultivation, best crop steering practices based on the latest research on cannabis and other crops, and an overview of how environmental and irrigation control systems can be optimized, integrated, and automated for the most effective crop steering.

WHY CROP STEERING FOR CANNABIS?

Cannabis and crop steering make an excellent match for a variety of reasons: biological, technical, and economic. Using crop steering, commercial production goals can be reached by coaxing natural plant growth and development one way or the other. The way commercial cannabis is typically grown is particularly well suited to these techniques but first, it is important to understand the lifecycle of cannabis and the forces that drive it. Cannabis is a short-day flowering, annual crop grown for its female inflorescences (commonly called flower or bud). This means cannabis is biologically programmed to complete its entire lifecycle in one season and is triggered to start the reproductive phase of its life when hours of daylight get shorter, and hours of darkness get longer. Additionally, stress pushes cannabis toward reproductive growth to ensure it can complete its lifecycle and reproduce before conditions become too stressful to survive.

The cannabis lifecycle is important to keep in mind when discussing cannabis cultivation and crop steering, particularly the forces that are driving reproductive growth. While these natural forces should be considered, there are some important differences between cannabis in nature and commercial production. First, cannabis plants in the wild are extremely different from cultivars used in commercial production. Natural selection has driven wild plants to adapt to grow and reproduce in their natural environments. In contrast, cultivars grown commercially have been bred and selected to accentuate traits we value like yield, cannabinoid production, growth habit, disease resistance, etc. Next, the goals of growers are similar to, but not the same as, the forces that drive a wild cannabis plant. We are trying to produce the largest yield of the highest quality flower whereas the wild plant is trying to produce the most seeds as quickly as possible. While the priorities of cultivars have been shifted from those of their wild relatives, the drive to reproduce remains inherent in all. Lastly, we should not be aiming to emulate the natural settings or lifecycle of cannabis, but rather to optimize elements of the environment and direct the lifecycle to meet our goals as producers.

Using environmental cues to drive the growth and development of plants is at the heart of crop steering. Crop steering is most effective in highly controlled environments and cannabis is such a high value crop that the investment in sophisticated environmental and irrigation control systems are justified. Most cannabis grows already have some degree of control and automation over the environment and irrigation. Any level of control can be a starting point for crop steering and any improvements on controls benefit crop steering as well as other parts of cultivation like disease prevention and resource use efficiency.

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CROP STEERING IS MOST EFFECTIVE IN HIGHLY CONTROLLED ENVIRONMENTS AND CANNABIS IS SUCH A HIGH VALUE CROP THAT THE INVESTMENT IN SOPHISTICATED ENVIRONMENTAL AND IRRIGATION CONTROL SYSTEMS ARE JUSTIFIED.

Cannabis is a high input crop. It has been shown to have a particularly large appetite for light [2] which must be balanced with a greater consumption of water and nutrients. Because crop steering is based in precision and data, it allows growers to closely match these inputs with exactly what the crop requires, avoiding waste from applying materials in excess of what is needed. Also, after the proper infrastructure is in place, crop steering does not require any additional input, but rather manages the application of inputs that are needed anyway. As such a high input crop in such a competitive market, growers will need to implement strategies like crop steering that minimize inputs and synergize the infrastructure that is already required.

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IN SUCH A COMPETITIVE MARKET, GROWERS WILL NEED TO IMPLEMENT STRATEGIES LIKE CROP STEERING THAT MINIMIZE INPUTS AND SYNERGIZE THE INFRASTRUCTURE THAT IS ALREADY REQUIRED.

CROP STEERING BASICS: VEGETATIVE AND GENERATIVE STEERING

Crop steering has been used for decades and has been fine tuned for a variety of fruiting and flowering crops, particularly tomatoes and ornamental flowers [1]. Unlike cannabis, greenhouse tomatoes are not photoperiod-sensitive, so they are grown to produce and be harvested over the course of many months. To maximize production, tomato growers must modulate between vegetative and generative growth. The growth of new shoots and leaves is promoted by vegetative growth and allows the plant to generate energy (see our paper on metabolisms for more information on sink-source relations), whereas steering toward generative growth prompts the plants to channel energy and resources to flower and fruit production. By balancing energy production (vegetative steering) with energy use (generative steering), tomato growers perpetuate harvest for months on end.

In many ways, cannabis has more similarities with ornamental flowering crops than fruiting crops like tomatoes. While the goal for vegetable crops is to have perpetual production from the same plants for many months, ornamentals and cannabis are both triggered to flower, allowed to mature for a certain amount of time, and are harvested or sent to market when they are at the proper stage of maturity. For cannabis and ornamentals, we need to modulate the trajectory toward generative growth, which is already mostly driven by another, stronger trigger (photoperiod, temperature, etc.) rather than balancing between vegetative and generative growth to maintain production over time. In cannabis, the path that the photoperiod sets toward generative growth cannot be reversed, so there is really only one chance to steer each cannabis crop. Steering tomatoes is like piloting a plane at cruising altitude; steering cannabis is like landing that plane.

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THE KEY TO CROP STEERING IS TO APPLY STRESS THAT WILL PROMOTE GENERATIVE GROWTH WHILE NOT SACRIFICING YIELD OR CANNABINOID PRODUCTION.

Cannabis is steered toward generative growth with the controlled application of stress. As we saw earlier, plants are triggered to reproduce when they experience stress to ensure they have a chance to perpetuate and preserve their genetics. The controlled application of stress to improve production has been proven to work on a variety of horticultural crops. Moreover, there is a growing body of scientific evidence to support the efficacy of some legacy cannabis cultivation practices that apply stress to increase yields and improve quality [3]. The key to crop steering is to apply stress that will promote generative growth while not sacrificing yield or cannabinoid production. Too much stress can interfere with the biological processes needed to grow and produce properly. Generally, stress is applied to stimulate generative growth by intensifying the growing environment and simulating scarcity for the plant. Conversely, vegetative growth is promoted by eliminating stresses by creating a mild, abundant environment.

HOW TO STEER CROPS: IRRIGATION

Water potential is a key principle in crop steering because it is used to simulate water scarcity without inflicting any drought stress. Water potential is a measure of how easy or difficult it is for water to move. In the context of roots, it can be understood as how hard the plant needs to pull to draw water out of the root zone. When talking about water moving from growing media into roots, water potential is broken down further into matric potential (how tightly media holds onto water) and osmotic potential (how EC influences water movement). Both matric and osmotic potentials increase as media dries out, making it more difficult for water to be absorbed by the roots. Osmotic potential, specifically, is raised by irrigating with a higher EC. In crop steering, the main goal of irrigation is to manage the water content (WC) and electrical conductivity (EC) in the root zone to change the water potential in the root zone. Both factors affect the water potential in the growing media and, so, can be used to drive either vegetative or generative growth.

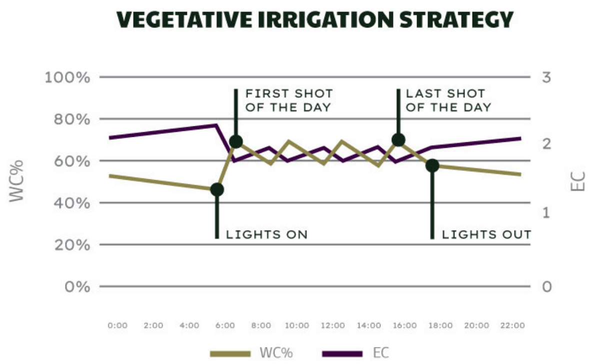
WC is typically expressed as a percentage of the volume of water a container can hold when saturated. As soon as a plant is irrigated, The WC of the root zone begins to drop due to runoff, evaporation, and absorption by the roots. This water loss is called dry down. As dry down progresses, water exits larger pores first and the remaining water is left in smaller pores which hold water more tightly due to a higher matric potential. Drying down also raises the EC in the remaining water. Dry down is influenced by the composition and volume of the growing medium, the environment, and the plant itself. Media will lose water to runoff and evaporation at different rates depending on pore sizes in the growing media. Pore sizes in media similarly determine how tightly media holds on to water. Larger, more vigorous plants, smaller root zones, warmer air temperatures, lower relative humidity, and brighter lights will also speed up dry down.

Along with WC, EC is the other primary factor used to steer crops from the root zone. EC is an easy and reliable measure of the concentration of total salts in solution. A higher EC in the root zone has a higher osmotic potential, making it more difficult for roots to absorb the water and driving generative growth. EC is also influenced by media type dry down and the plant. Popular hydroponic media, such as peat, coir and rockwool, do not have a large impact on EC themselves, but the varying dry down speed of these media can have a big influence. For example, rockwool dries more quickly than peat or coir, so it can cause rapid spikes in EC if it dries too quickly.

Irrigation is typically split up into multiple shots, or irrigation events throughout the day. Each shot is used to manage the WC and EC in the root zone and must be in tune with the rate of dry down at any given time. The rate of dry down will change throughout the day and throughout stages of growth. In most cases, dry down is driven by water taken up by plants. Plants drink the most when lights are on, so dry down slows down when lights are off.

To match this daily cycle, a crop steering irrigation strategy typically calls for a prolonged dry down at night, rehydration

FIGURE 1



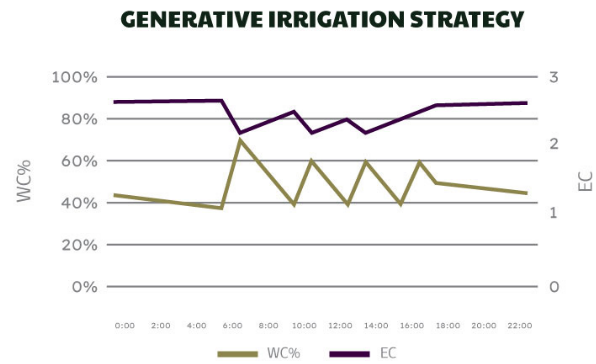


FIGURE 1 Example irrigation strategies for vegetative and generative steering with target media water content (WC%) and electrical conductivity (EC). Vegetative steering targets higher WC% and lower EC with more frequent irrigation shots, whereas generative steering targets larger dry downs and higher EC with less frequent irrigation shots.

after lights turn on, and smaller shots throughout the day. The dry down at night is determined by the timing of the final shot before lights go out and the first shot after lights turn on. Because the first shot of the day is typically timed to coincide with plants beginning to drink in the morning, the final shot of the day is the main way to control dry down. The first shot of the day is used to rehydrate the root zone following the long dry down of the night and reset the EC. The smaller shots throughout the day are used to maintain a target WC (Figure 1).

To drive vegetative growth from the root zone, irrigation should be more frequent, and each shot should be longer to maintain a higher WC. The EC in the root zone should be lower and the temperature should be warmer. These root zone factors will allow water to enter the roots more easily. Conversely, A higher EC and less frequent irrigation makes water in the root zone more difficult to absorb into the roots and drive generative growth. Water is critical to all biological processes in plants so crop steering must not go too far, otherwise the stress will begin to limit the plant's production of biomass and cannabinoids.

WATER IS CRITICAL TO ALL BIOLOGICAL PROCESSES IN PLANTS SO CROP STEERING MUST NOT GO TOO FAR, OTHERWISE THE STRESS WILL BEGIN TO LIMIT THE PLANT'S PRODUCTION OF BIOMASS AND CANNABINOIDS.

With this understanding of the complex factors that influence dry down, we can see that dry down is more of a passive process whereas rehydration is a simple, active process. The WC of a media can be quickly raised by irrigating, but only time will lower it again. Because of this, crop steering is much easier in systems with naturally fast dry downs. Media that retains more water and dries down more slowly offers an advantage of being less at risk to irrigation failures but is much easier to tightly control the WC of media with a faster dry down. The same is true for other factors that increase dry down speed - crops grown under higher light intensity, at higher temperatures and lower RH are less buffered against system failures but can be steered with more precision. Crop

FIGURE 2

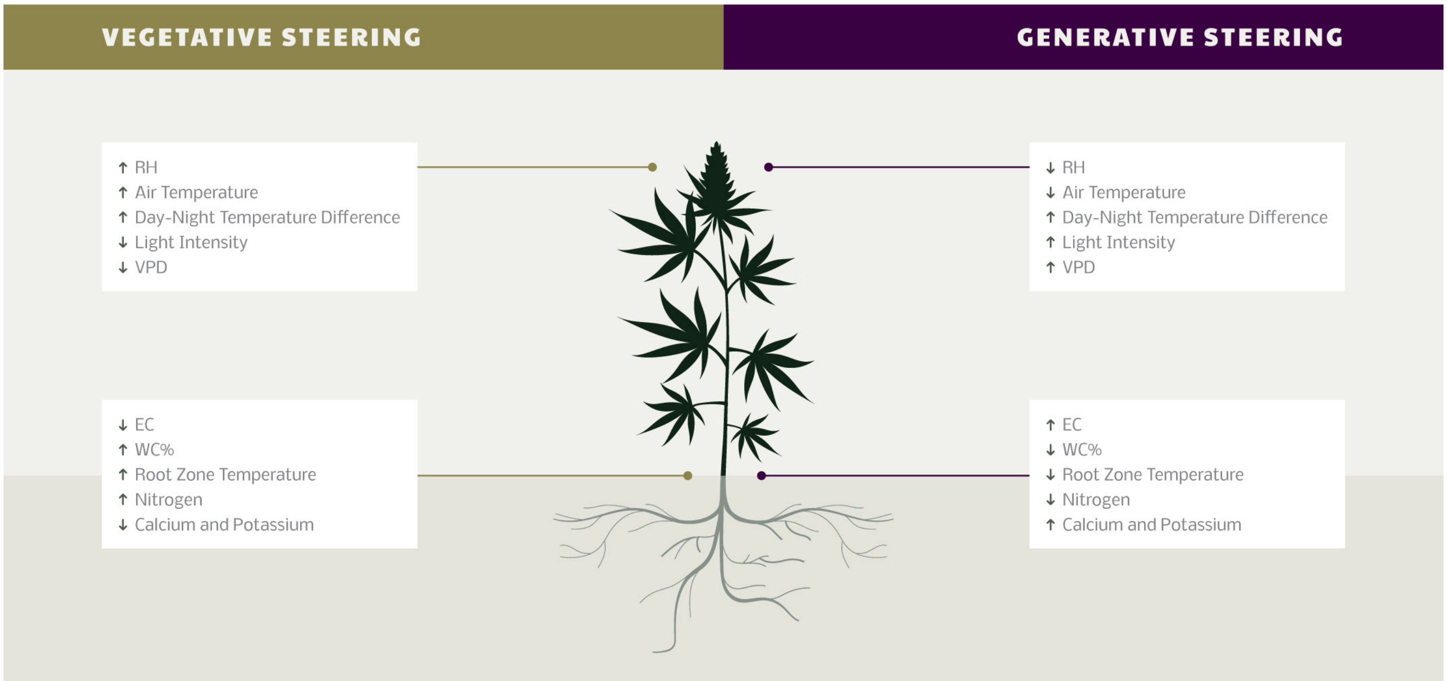


FIGURE 2 Factors driving vegetative and generative growth both with above-ground plant parts and in the root zone.

steering is possible in systems that do not dry down quickly, or systems that do not dry at all, like deep water culture or nutrient film technique. Crops in these systems can be steered with cues from the environment and by tightly controlling EC but are limited by not being able to control WC.

HOW TO STEER CROPS: ENVIRONMENT

Along with precise irrigation, crop steering requires proper, balanced environmental set points that modulate mild stress. The environment can be used to manipulate the availability of water, leading plants to perceive either an abundance or scarcity of water or can be used to directly steer crops (Figure 2).

Air temperature and relative humidity are the biggest factors influencing how fast water exits plants. Together, temperature and relative humidity are used to calculate vapor pressure deficit (VPD), which can more directly be used to predict water loss from plants (this is discussed in more detail in our plant-water relations paper). Higher temperatures raise VPD and higher RH lowers VPD and vice versa (Figure 3).

To drive vegetative growth, the environment should be milder; less light intensity, lower VPD and lower root zone temperature. All these factors will allow water to enter the roots more easily and slow water exiting the plant. By slowing the water leaving the plant and minimizing barriers to enter the plant, plants steered toward vegetative growth always have an abundance of water. Overall, the goal of vegetative steering is to remove all barriers from growth. Conversely, generative growth is stimulated by a more intense environment where the plant perceives a scarcity of water. By increasing light intensity and increasing VPD, water exits the plant more quickly.

Environmental and irrigation factors must

FIGURE 3

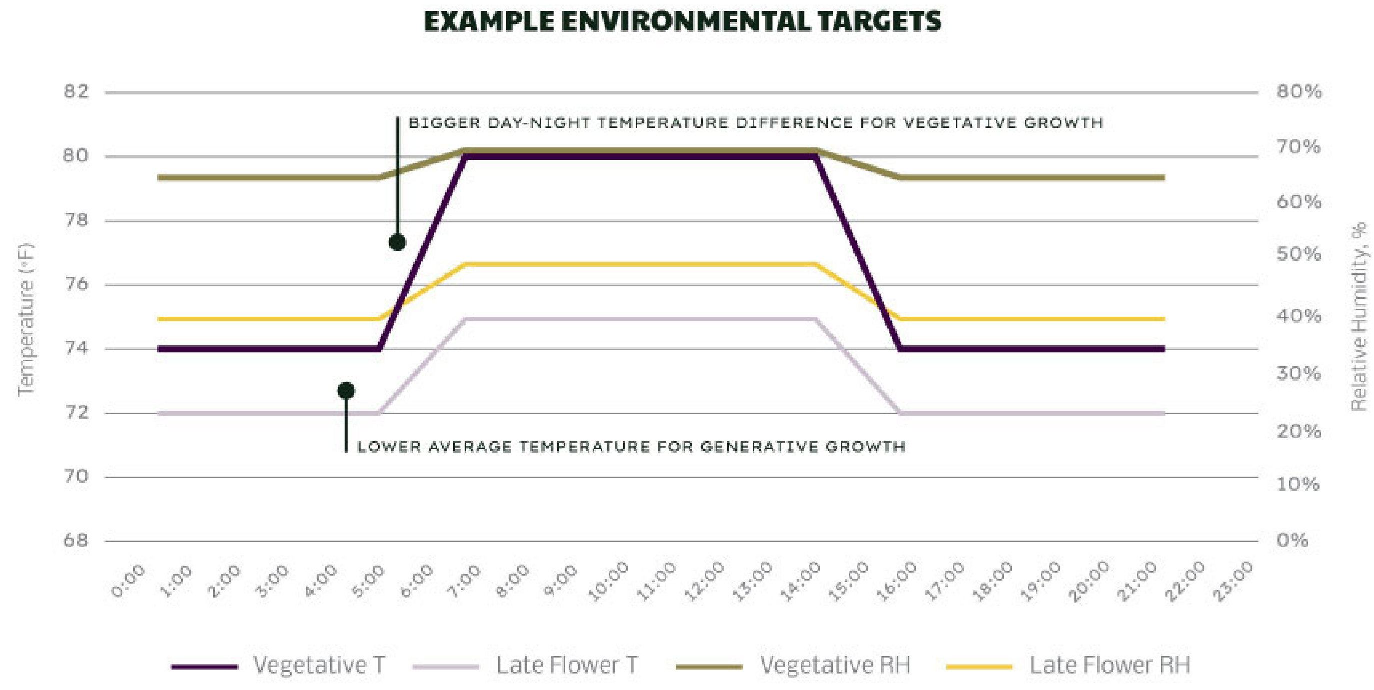


FIGURE 3 Example environmental set points for driving vegetative (left) growth and generative (right) growth.

all be in balance to achieve the goals of crop steering. Everything in a grow is linked together with water - this is an important principle to keep in mind with environmental setpoints. Each change to the environment or irrigation schedule changes the movement of water from the root zone, through the plant, and into the air.

MANAGING THE GROWING ENVIRONMENT: CONTROLS, SENSORS & MONITORING

Crop management, in general, is easiest with consistent growing environments. Consistency is important spatially (throughout the growing space) and temporally (over time). This is especially true for crop steering because it is based on using the environment to influence plant growth and development. Microclimates within the growing space or large fluctuations throughout the day work against what the

FIGURE 4

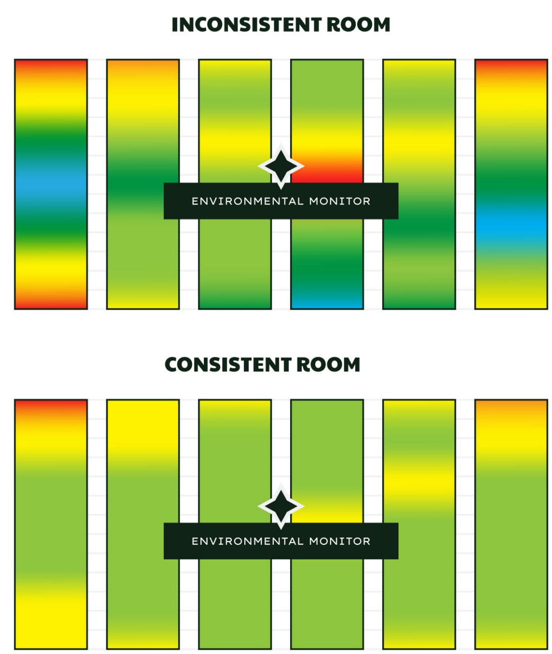


FIGURE 4 Heat maps of cultivation room floor plans with inconsistent (above) and consistent (below) environments. Blue represents values far below the set point, red represents values far above the set point, and green represents values close to the set point.

grower is trying to achieve with crop steering. Because crop steering is based on using subtle environmental cues, inconsistencies in the environment increases the risk of portions of the room being far enough from the environmental set point to either harm the crop, or not achieve the crop steering goal (Figure 4).

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CONSISTENCY IS ACHIEVED THROUGH GOOD DESIGN AND MANAGEMENT OF GROWING SPACES AND ENVIRONMENTAL CONTROLS.

Consistency is achieved through good design and management of growing spaces and environmental controls. The best designs consider how a growing space will change throughout the growing cycle, and particularly how plants influence the environment. For example, a typical flower room will start with smaller, vegetative plants which put less moisture into the air but require high RH, and will progress to have larger flowering plants which produce more moisture and require a lower RH setpoint. HVAC systems must be sized to handle the heat load and dehumidification of the room filled with full-grown plants and lights at a full intensity. In a grow room, plants have a huge impact on the environment, so the HVAC needs of a grow room are quite different from other indoor spaces. When lights are on, plants are constantly putting water vapor into the air through transpiration that must be removed by the HVAC system. Furthermore, plants are approximately 90% water by weight, so a room full of large flowering plants is a room full of water. Because water has a high specific heat, all the water in a room of mature plants offers a bit of a temperature buffer. Conversely, a freshly loaded room with smaller plants has less plant and water mass to act as a thermal buffer, so it is more vulnerable to temperature swings.

Lighting also has a big impact on the HVAC load. The two most popular lighting choices, high pressure sodium (HPS) and light emitting diode (LED) offer unique challenges for environmental controls. HPS lamps generate a significant amount of heat, so they require a greater cooling capacity. HPS lights can also create large swings in temperature and RH when they turn on and off. Because LED generate less heat and require less energy to run, they can be run at a higher light intensity using the same amount of energy. Higher light intensity increases plant transpiration and the dehumidification requirements.

With all this in mind, an HVAC system must be extremely adaptable - able to moderate temperature swings in early flower, handle the large moisture load later in flower and temperature swings when lights turn on and off. Also, growing with more intense settings offers more control of crop steering, but puts crops more at risk of system failures.

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IT IS IMPORTANT TO HAVE ENVIRONMENTAL CONTROLS AND IRRIGATION WITH ROBUST SAFETY CHECKS, REDUNDANCY, AND ALARMS.

It is important to have environmental controls and irrigation with robust safety checks, redundancy, and alarms. Having set procedures in place in the event of a system failure is a good way to reduce risk. For example, if the automated irrigation control system loses its connection to the irrigation components, is there a good way to manually run the irrigation system? If the power goes out, is there a generator to keep critical systems afloat? Often, HVAC systems in cannabis cultivation sites are modeled after other indoor spaces but require more fine-tuned controls and more monitoring capabilities than other systems.

CONTROLS

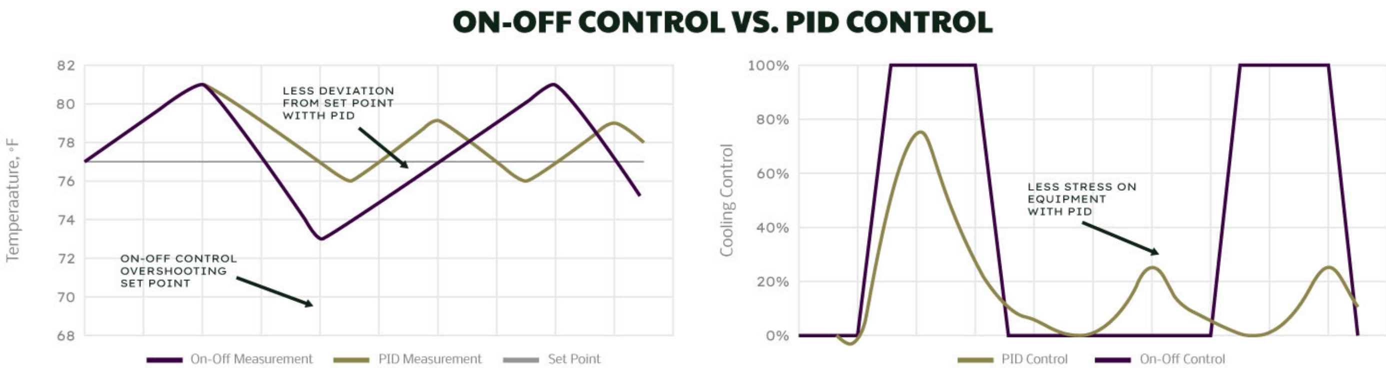
There is a huge spectrum of controls a grower can use to manage irrigation and the environment. On one end of the spectrum is completely manual control. On the other end of the spectrum are fully automated controls that are orchestrated by complex computer programs to work together to create a consistent environment. Crop steering is most effective with fully integrated systems that use continuous monitoring to automate controls. The simplest and least expensive form of automation is timers. Timers can be as simple as a dial that gets plugged into the wall and as complicated as a computer program with daily and weekly schedules. Timers are most used on the commercial scale for controls that only have on and off settings, like photoperiod lights and irrigation. The best timers are linked to computer systems that can program timer schedules per day and per week. While timer systems are most common for irrigation controls, irrigation can also be controlled with various inputs such as WC, and light monitors.

For environmental factors that require more dynamic settings, like temperature and humidity, an integrated environmental control system is a better choice. There are many producers of environmental control systems that have been designing controls for greenhouses and other controlled environments for decades. There are also several newer companies that have created control systems tailor made for the specific needs of cannabis cultivation. A good environmental control program will be able to integrate all components of an environmental control system (dehumidification, cooling, heating, irrigation etc.) to work together to consistently create the desired environment.

Systems that use "proportional integral derivatives" (PID) offer the best control of environments (Figure 5). Rather than just turning system components on and off to reach set point, PID controls will incrementally adjust system components to reach set points without overshooting by slowing corrections as they get closer to the set point. For example, a system without PID controls, if the temperature is above the

FIGURE 5 On-off controls vs PID controls. Above depicts how the measured temperature responded to each control. Below shows the percentage of cooling control from off (0%) to fully on (100%).

FIGURE 5



setpoint, it will turn on the cooling until the setpoint is reach, then turn it off. This sort of on-off control causes often overshoots setpoints, leading to a system that is always working to correct itself and causing spikes in the environment. In the same situation, a PID control will turn on the cooling but will incrementally close the cooling valve as the temperature gets closer to the set point. In this way, PID controls smooth out the environment and put less strain on the system.

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SYSTEMS THAT USE “PROPORTIONAL INTEGRAL DERIVATIVES” (PID) OFFER THE BEST CONTROL OF ENVIRONMENTS .

SENSORS

Much like how a grower observes their crop and takes note of changes in the growing environment throughout the day or from day to day to make decisions, environmental sensors are central in the decision-making process of environmental control systems. Crop steering is a data-driven system and sensors are the source of the data. It is important to keep in mind, however, that a control system is only as good as the information it is receiving. Sensors must be both accurate, and representative of the growing environment. Ideally, sensors should experience the same environment as the plants. Temperature, relative humidity, and CO_2 sensors should be close to the canopy and away from outlier areas. Maintaining a consistent environment helps with getting representative measurements.
Ensuring a representative measurement from the growing environment requires some preparation and planning but will make a control system much more manageable and predictable in the future. A good representative measure should be close to the median of the growing space rather than a localized extreme. While every growing space has its own microclimates, a sensor should be placed to reflect the environment of most of the room.

To understand where to place sensors to get the best representative samples, a grower must understand the variability of their growing space. To get a good picture of this variability, measurements should be taken throughout the growing space and over time to determine where variability occurs and where sensors can get the most representative data (Figure 4). Handheld sensors are useful for measuring variability in temperature, RH, CO_2, and light intensity. Placing several root zone probes that log temperature, EC, and water content throughout the room provides another useful measure of variability. Comparing the dry down of rootzones throughout the room offers excellent insights into both temporal and spatial variability in the room.

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SENSORS MUST BE BOTH ACCURATE, AND REPRESENTATIVE OF THE GROWING ENVIRONMENT.

Spatial variability is often most apparent toward the edges of the crop. Indeed, “the edge effect” is well known to growers, and in most cases can be mitigated but not entirely avoided. Plants on the edge of growing tables tend to grow at different rates and have different irrigation requirements to those in the center of the canopy due to differences in light intensity, temperature, relative humidity, and air flow. The location of HVAC intakes/ outlets and fan placement are also common sources of spatial variability.

Temporal variability often takes the form of large swings in temperature and humidity throughout the crop cycle and throughout the day. This kind of variability can be especially troublesome for crop steering because a sensor may be measuring the correct average over time while the plants are experiencing extremes most of the day.

Some of the newest technology in cultivation sensors combines optics [4] and artificial intelligence [5] to monitor crop health and development. This technology has been used in agronomic field crops for a few decades and has been used to automate post-harvest quality control for various horticultural commodity crops. The idea behind this technology is artificial intelligence can be trained to detect pests, diseases or physiological problems in crops by using color and shape data collected from cameras. With each new development in automation the role of the grower may be called into question, but whether irrigation is automated or intelligent machines begin assisting with scouting, there is no replacement for experienced, knowledgeable growers.

MONITORING

As with controllers, there is a wide spectrum of technology for monitoring the grow from completely manual pen-and-paper measurements and records to fully automated systems that track data points every couple of minutes. Crop steering is a data driven approach to growing so the more data that can be gathered, the better. This data is useful for:

- Verifying systems are working properly
- Diagnosing issues with systems
- Tracking how changes to environmental factors affect each other (e.g., how does raising the temperature affect dry down?)
- Tracking how changes to environmental factors affect growth factors (yield, quality, etc.)

While irrigation systems typically log data within the system like the pH, EC and volume of water delivered, it does not always track data after the water delivered to the crop. Data from the root zone and runoff brings the precision with which a grower can steer their crop to a new level. As discussed above, the WC and EC of the root zone are some of the primary data points used in crop steering, so being able to monitor them directly offers growers the ability to fine tune their steering. Various root zone monitors are available that integrate with other systems to varying degrees. Some only give a snapshot of root zone conditions in real time while others can be fully integrated with irrigation and environmental control systems [6].

Integrated environmental control systems and high-quality irrigation automation systems typically use the same sensors they use for controls to log various data points. For most, users can even customize which data points are logged. Sophisticated environmental control systems can also monitor and log the activity of all the components of the system down to specific valves.

The ability to log and track data from control systems is only a start. This data does little unless it is interpreted and applied to

“ DATA FROM THE ROOT ZONE AND RUNOFF BRINGS THE PRECISION WITH WHICH A GROWER CAN STEER THEIR CROP TO A NEW LEVEL.

management decisions by a skilled grower. Automation can aid in gathering data and presenting is in useful ways, but it is still up to the grower to decide how this data is used.

KEY TAKEAWAYS

- Crop steering strategies offers cannabis cultivators the ability to use environmental and irrigation control systems to achieve production goals by manipulation the forces that naturally affect plant growth and development.

- The better control a grower has over their environment and irrigation, the better positioned they are to profit from crop steering. The benefits of crop steering should be taken into account when considering retrofits to existing control systems or designing new systems.

- All growth factors must be in balance to achieve optimum results. This balance can be achieved manually, but there is well established technology that can automate all aspects of irrigation and environmental controls.

- Crop steering can be done more precisely with more dynamic, intense systems that have smaller buffers and can be riskier. Well-designed systems with automation, redundancies and safeguards reduce the risk of using such systems.

- Controls, sensors, and monitoring are all used together to continuously optimize crop steering. These facets of can be integrated with the use of technology but still require knowledgeable and skilled growers to make decisions.

- For a more in-depth look at the biology and latest research surrounding the concepts of crop steering, read our whitepapers covering Plant-Water Relations, Plant Metabolisms, The Root Zone and Fertilizers

CROP STEERING GLOSSARY

Dry Down
The period between irrigation events in which WC decreases. Many factors influence the speed of dry down.

Electrical Conductivity (EC)
An indirect measure of dissolved salts in a solution. Indicates the "strength" of fertilizer, runoff etc.

Generative Steering
The use of environment and irrigation to steer plants toward reproductive growth (flowers, fruits, seeds). In annual crops like cannabis, it also marks the start of end of its lifecycle.

Heating, Ventilation and Air Conditioning (HVAC)
Systems and technology used to control the environment.

Matric Potential
How tightly a medium holds on to water. The matric potential decreases as a medium dries, making it more difficult for roots to absorb water.

Osmotic Potential
How tightly dissolved material in water holds on to it. The osmotic potential decreases as EC increases.

Photoperiod
The hours of light or darkness plants experience in a 24-hour period. Photoperiod-sensitive plants, like cannabis are triggered to flower with short or long nights.

Pore Size
The size, or distribution of sizes of pores in a medium thatcan be filled with either air or water.

Proportional Integral Derivative (PID)
A type of control that proportionally scales back control as a measured value approaches a set point (as opposed to an on-off control).

Relative Humidity (RH)
Air humidity expressed as a percentage of the maximum water that can be held by air at a given temperature.

Set Point
A value that a control system is set to achieve.

Short Day Flowering
Plants, like cannabis that flower when nights become longer. In commercial cannabis production, plants are typically triggered to flower with 12-hour nights.

Vapor Pressure Deficit (VPD)
A value based on the difference between the relative humidity and the maximum water that can be held by air at a given temperature. VPD almost directly correlated with plant transpiration.

Vegetative Steering
The use of environment and irrigation to steer plants toward vegetative growth (building of structure, leaf, shoot and root growth).

Water Content (WC)
The volume of water held by media expressed as a percentage of the maximum volume the media can hold when fully saturated.

Water Potential
The ease at which water moves across a gradient. Water tends to flow from a higher potential to a lower potential.

ABOUT THE AUTHOR

Jack Lamont is a horticulturist, plant scientist, and commercial cannabis grower. He is on a mission to stamp out myths and misconceptions in cannabis cultivation using established plant science and emerging cannabis research. With more than a decade of experience in horticulture, he has led cultivation departments of cannabis production facilities in Canada and The United States. He has also authored numerous scientific and trade journal articles, served on various scientific committees, and recently founded a biodynamic vegetable, herb, and poultry farm with his family in Keene, New Hampshire.

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