A Rhino Grasshopper Plugin for Spectral Daylight Simulation & Analysis in Controlled Environment Agriculture

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Abstract

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Controlled environment agriculture (CEA) requires stable and accurate light for consistent photosynthetic plant production, with consideration given to both duration and quality. In agricultural lighting, light quantity is the most significant metric in plant production since it directly correlates to the photosynthetic activity necessary for plant growth. However, light quality, which describes the relevance of light in a given spectrum as it relates to the specific needs of a plant's growth stage, is also important and has been shown to impact many other variables aside from growth, including flowering, fruiting, flavor, and color. CEA has experienced rapid growth and large-scale adoption over the last decade, standardizing the presence of artificial lighting and making lighting the greatest energy consumer within this sector. While lighting technology has seen increases in efficiency, including the ability to tune lights to specific spectra most suitable for plant production, attempts to build agricultural operations that rely solely on electric lighting have shown to be not economically viable and sustainable. Greenhouses, a form of controlled environment agriculture, utilize solar radiation as the primary light source for plant growth, relying on supplemental electric lighting only during reduced photoperiods of available daylight, such as during winter. Combining daylight with spectrally tunable LED lights offers the most promising area of energy reduction within CEA. However, most research is currently focused on the spectra of LED lights, with little consideration given to the spectra of daylight, which changes throughout the day. By accurately simulating the quality of light at the plant canopy from natural daylight and supplemental light sources, a hybrid model may be developed that offers deeper insights into not just quantity but quality. This project develops a modeling tool allowing daylight and electric light sources in a given controlled environment to be assessed for spectral qualities related to the region, climate, weather, building envelope, and surrounding context. By providing greater color accuracy of daylight at the plant canopy level, supplemental lighting for controlled environment greenhouses could shift from static to dynamic light output, reducing light in non-relevant spectra for a given plant phase and supplementing only specific spectra when necessary.

MSDT Thesis
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Specularia

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Bryant Callahan

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Preface

Plants, People, and PAR

Plants, People, and PAR

I came into architecture from another career, reasonably ignorant about what the practice of architecture actually looked like, but also open-minded to what it could be. Computational design caught me by surprise, and I was hooked. The first time I used Grasshopper and the first time I used data as a design tool coincided in the same class on computational daylighting taught by Mehlika Inanici. I signed up for the course as the first elective of my first year, and while we were all locked down at home, watching the world get ravaged by the Covid pandemic, I found solace in taking on the challenge of learning Grasshopper. One of the briefs for that class was to design a flower shop with three daylight zones for different groups of flowers. My friend Nathan and I thought it would be hilarious to design a flower shop that looked like an actual flower since we were also in the throes of the mandatory history and theory courses at the time. Venturi's every-building-is-a-duck-or—a-shed was like low-hanging fruit. I didn't realize how much lighting design would become a significant part of my life and, even more so, how much computational design would shape my future career. Fast forward to now, three years later, and it feels fitting that the conclusion of my academic course of study is centered around plants and Grasshopper, but also about using design tools not as blunt instruments that magically do your work for you, but as refined implements which, as so eloquently observed by Achim Menges, can actually extend our intellect. Computational thinking has allowed me to do better, but most importantly, focus on what matters most: finding meaning in everything I do.

Anyone who's ever had the opportunity (or misfortune, depending on their tolerance for uncertainty) of working with me knows not knowing how to do something has never been a reason to not do something. Thanks to the work this thesis represents, I feel now more than ever that problems in the world will require bold leaps forward into uncertainty to address. While computational design isn't the only tool in my toolbox, it's essential. I'm forever grateful for the faculty, especially the input of my thesis committee, who stuck it out with me through not just one but two thesis projects and helped me find a way forward into architecture that was uniquely mine.

But enough about me, now let's talk about lighting.

I. Introduction

Daylight Simulation for Controlled Environment Agriculture

Research Question

What is the role of daylight spectra & intensity in controlled environment agriculture?

Chapter 1: Introduction

1.1 Daylight Modeling for Controlled Environment Agriculture

Buildings account for half the world's primary energy consumption (DOE, 2010), while agriculture consumes an additional 13-15% of total energy in developed countries (UCEEE, 2007). Controlled environment agriculture (CEA) is a central component of global food supply and security, especially in high-latitude regions where year-round growing conditions would otherwise be impossible. As populations increasingly shift towards urban areas, CEA offers increased spatial efficiency, proximity to the consumer, and reliable climate controls (Eaton, 2021).

Climate control within these built environments is a complex and nonlinear process that balances the many environmental factors related to plant growth, including temperature, humidity, light, and CO2. Of these factors, lighting is the most important factor in plant production (Mahdavian, 2017). Insufficient solar radiation, especially in northern regions where greenhouses are a commonly used application of CEA, requires supplemental lighting during winter months to maintain the consistent production requirements of a commercial operation (Hao, 2018). Supplemental lighting accounts for approximately 20-30% of energy consumption within all CEA (Singh 2015), the highest single source. Studies demonstrate that when paired with spectral analysis, actively tuning supplement lighting can significantly reduce energy use without negatively impacting plant production (Hernandez, 2020). Using an RGB controller to dynamically tune supplemental lighting based on daylight spectra has shown a 20-30% reduction in the amount of supplemental light needed, with no impact on crop yield or quality (Institut für Gartenbau et al., 2016; Jiang, 2020). Given that daylight spectra play a significant role in decreasing supplementary lighting needs, a tool such as the one proposed would offer long-term benefits for buildings that incorporate controlled agriculture since the daylight spectra could be more accurately modeled in the design phase in spaces that don't conform to traditional greenhouse forms or locations and thus have fewer data to indicate future performance.

Developing a tool that can accurately simulate the impact of daylight spectra on plant growth can provide more accurate data for hybrid agricultural environments such as vertical farms or integrated greenhouses while also supporting the refinement of hybrid lighting systems, allowing supplemental lighting to be finely tuned to fill in missing gaps across the spectrum. Since lighting is the largest energy consumer within CEA, this creates a significant potential for reducing energy consumption and operating costs, a benefit to both growers and the environment. This is especially true of the increasing number of CEA operations in urban environments, which often consist of building integrated agriculture (BIA) such as rooftop greenhouses, where factors such as overshading and envelope material add additional parameters to consider when assessing the availability of daylight to the space.

Environmental Shift

Why agriculture, and why now?

Fig. 1.1 : Changes to Agriculture

1.2 Agricultural Lighting in the Built Environment

There is currently no tool readily accessible to built environment professionals which offer a reliable method for assessing the feasibility of agriculture in a building. Many commonly integrated typologies within urban agriculture, including integrated rooftop greenhouses (iRTG) and vertical farms, are constructed in non-typical spaces for agricultural practice and thus do not benefit from traditional tools used to assess standard, ground-based greenhouse designs.

A tool that allows architects and designers a chance to offer valuable feedback on the feasibility of their building designs early on in the design phase will provide a better understanding of how and when it is appropriate to incorporate controlled environment agriculture into a project and, if so, set realistic expectations about what the growth performance of that space might be from a lighting standpoint. Architects already provide extensive daylight analysis regarding human occupants, so expanding the consideration to how spaces perform plants is a natural move and necessary for an integrated design approach for controlled agriculture (Toboso-Chavero, 2021).

Specularia

The first greenhouses ever recorded were simple framed structures covered in sheets of transparent stone such as mica or lapis. Called specularia, the Romans used these proto-greenhouses to grow melons and other crops in the cooler months by providing a place to diffuse solar radiation and protect from frost (Paris et al. 2008). Since then, the power of harvesting for the production of food and cultivation of plants has moved along an evolutionary trajectory parallel to that of ground-based agriculture, and with the advent of computational design platforms such as Grasshopper, the ability to simulate daylight on controlled agriculture is an area of research rich with potential for more efficient farming operations and new insights into how plants utilize light spectra for growth.

Specularia is largely based on another open-source multi-spectral lighting plugin, Lark (V.1 Inanici et al., 2015; V.2 Gkaintatzi-Masouti et al., 2022), a multispectral daylight simulation plugin built to assess the impact of daylight on human circadian rhythms. Though plants lack melanin or cortisol, they are still impacted by circadian rhythms, a trait observable in all living organisms (Shabaev & Romanovets, 2021). For plants, this is related to shifts in daylight spectra over time which trigger unique stages of plant growth, including flowering, fruiting, and leaf density. Plants also primarily absorb light in a certain range of wavelengths known as Photosynthetically Active Radiation, or PAR,, making the spectral composition of daylight especially important for predicting plant growth.

1.3 Goals, Objectives, & Deliverables

Goal: This project aims to develop an open-source, parametric tool that allows designers to assess the spectra and intensity of light in a space as it relates to plant needs. There are two objectives related to the outcome of this goal:

Objectives: The first objective is an in-depth literature review of the current state of agricultural lighting, including controlled agriculture and any research on plant growth and lighting. This review contextualizes the needs of Specularia, ensuring that the plugin development is fulfill-

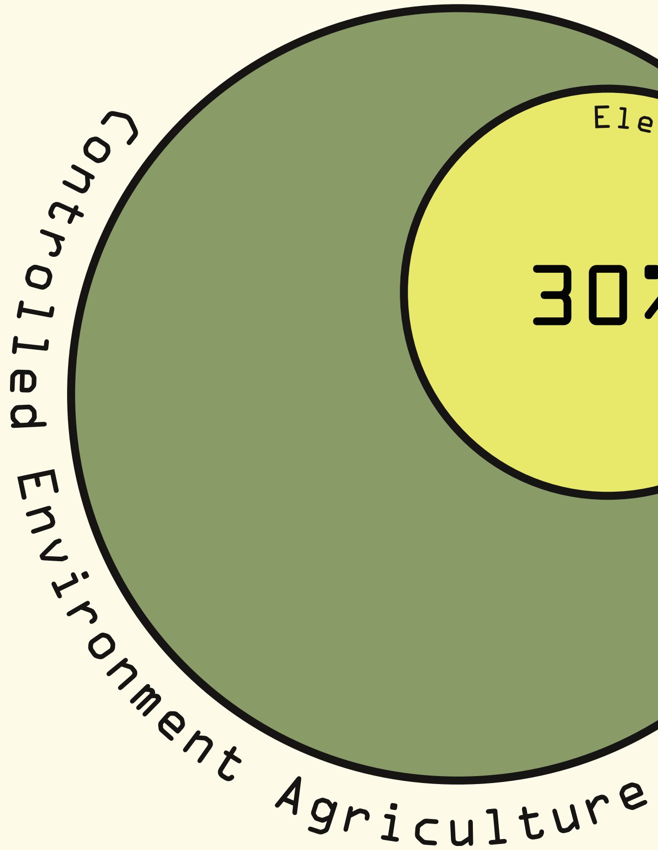


Fig. 1.2 : Lighting Consumption in CEA

ing a gap in the currently available tools while representing the most current research on daylight simulation for plants.

The second objective is to build the tool itself, accomplished through the development of a Rhino Grasshopper plugin, scripted in Python, that uses the Radiance Simulation and a selection of components from another plugin, Ladybug/Honeybee, to convert the geometry to objects for simulation of daylight in the space. The result of these simulations provides two critical metrics for understanding the fitness of a given plant species in space: Photosynthetic Active Radiation, or PAR, which examines both intensity and spectra, as well as Daily Light Integral, a metric describing how much light a given square meter of space receives as it relates to plant needs.

Deliverables:

A Rhino Grasshopper plugin, built on the frame work and code of Lark Multispectral Lighting, and packaged into a new tool capable of assessing both PAR and DLI from daylight and electric light sources.

The thesis document containing an introduction, literature review, methodology (including a tutorial and description on how to set up and use the plugin), results, and discussion.

1.4 Outcomes

It is not enough to simply reduce energy consumption. To sustainably integrate agriculture into the built environment, buildings need to take advantage of the abundance of solar radiation available for plant production. To place things in context, on a typically clear day, illuminance can be in excess of 100,000 lux. By comparison, an overcast day can see as low as 5000 lux. To put this in perspective, the typical office light fixture only produces 350-500 lux. This translates to the worst day of natural light still 10x better than an artificial light. And plants require light for a majority of the day, everyday, in order to maintain consistent growth.

Using a tool like Specularia to make intelligent design decisions about agriculture in built environments isn’t only about resource reduction or smart design. It’s an opportunity to look at spaces that utilize the abundance of energy available to them via solar radiation in the best way possible, and design those spaces to accommodate a range of occupants, plants and people alike.

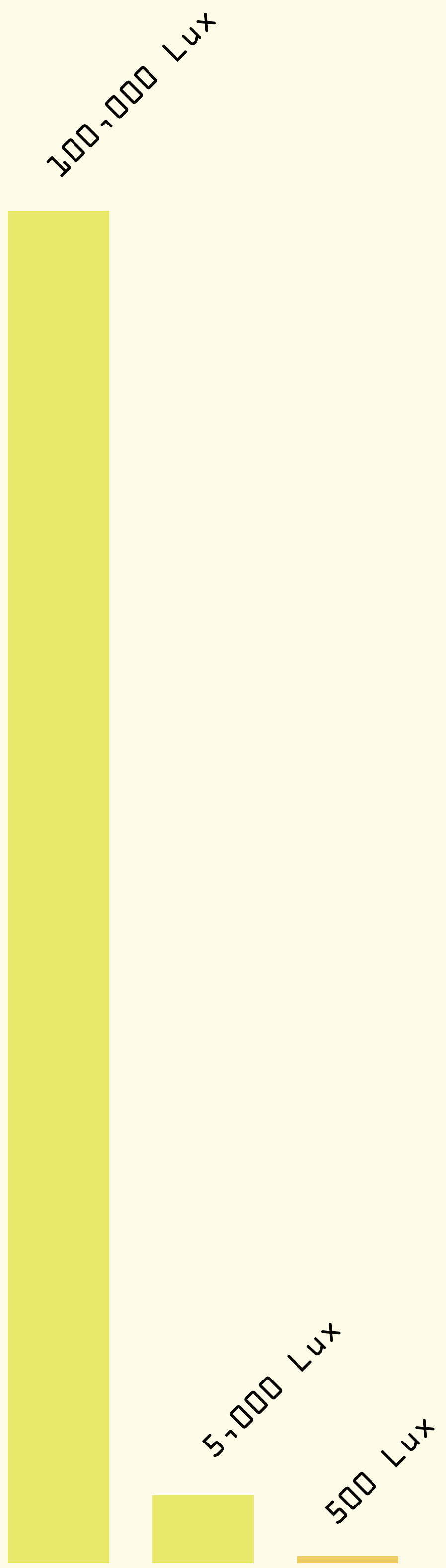


Fig. 1.3 : Solar Fortunes

1.5 Project Timeline

A few notes about the timeline of this project. This work represents completing my Master of Science in Architecture (Design Technology) degree. However, it is also a continuation of my previous thesis, which was finished as a requirement for my Master of Architecture degree. That work, entitled MicroArcologies: A Design Framework for Building-Integrated Greenhouses, provided a foundation for this project by allowing me to examine various forms of greenhouse integration to determine how they might share symbiotic resource flows with their host building. One of the most significant insights from that project was the need for better design tools related to greenhouse integration.

Most of the current offerings are either too generic to serve as a data-driven design tool or to niche to another industry and, aside from the investment of extensive training and resources, beyond the reach of most people working in AEC. Greenhouses need to be understood not as stand-alone structures but as components that offer an opportunity to extend building performance to include plant considerations. Thanks to the support of my thesis committee, I was able to establish a link between that work and this project, allowing me to take my MArch thesis after it was finished and move it one step further, from the proposal of a design framework to the development of a specific tool, which is what this project delivers.

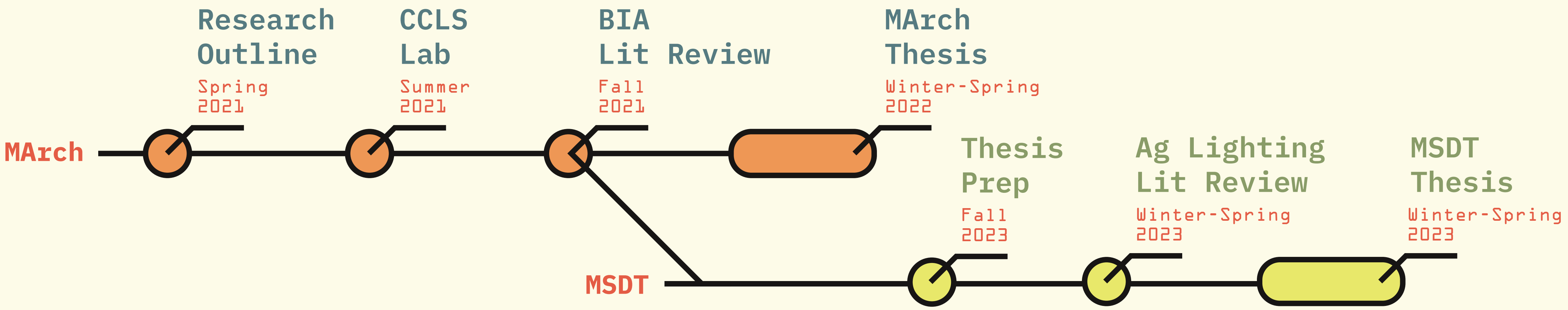


Fig. 1.4 : Project Timeline

II. Literature Review

Agricultural Lighting in Controlled Environments

Chapter 2: Literature Review

Introduction to Agricultural Lighting Topics

Research in lighting for controlled environment agriculture (CEA) is an active and evolving field aimed at optimizing plant growth and productivity. Current trends in research are heavily weighted toward LED lighting technology, which has seen large jumps in efficiency, lifespan, and performance over the last decade. In addition to exploring new ways of designing and implementing LED technology, much work goes into looking at tuned curves which tailor light spectra for specific plant responses, which is particularly useful for intensive controlled agriculture where flowering or fruiting require precise spectral shifts to trigger shifts in a plant's growth stage.

There is also a significant body of recent work on the spectral effects of light on plant physiology. Studies investigating how specific wavelengths, such as blue, red, far-red, and beyond, influence plant growth, development, and photosynthetic production (Zhen et. al, 2020). Researchers are also investigating the impact of supplemental light on plant growth and production (Yakovtseva et al., 2017; Weaver et al., 2020).

Dynamic lighting strategies (DLS) are an emergent topic, driven largely by more accessible computational design algorithms that seek to optimize plant production by varying light intensity, duration, and spectra throughout the day (or stage of growth) in order to mimic natural lighting conditions (Pinho, 2015). While research around DLS explores benefits related to crop performance, nutrient content, and plant stress response (Mosharafian 2021), it also overlaps with work on sustainability, which looks for innovative ways to lower the carbon footprint of controlled agriculture through intelligent systems that actively tune lights to fill gaps in available daylight (Hao et al., 2018).

Integrated lighting investigates the interaction between lighting and other environmental parameters in order to developing integrated control strategies (Kuijperset at., 2020). It also considers the relationship of lighting with other environmental factors in CEA, such as temperature, thermal gain, and structural arrangement (Fang et al., 2019) in order to develop a holistic and optimized approach toward ideal growing conditions.

Light recipes and crop-specific lighting involves tailoring light spectra to the unique requirements of different plant species. Researchers are developing specific light recipes that optimize growth, yield, and quality characteristics for various crops (Anpo et al., 2018). This includes determining the optimal ratios of red to blue light, incorporating specific wavelengths for desired plant responses, and considering the influence of lighting on photomorphogenesis (Lanoue et al., 2022).

Energy Efficiency and Sustainability: As CEA systems aim for greater energy efficiency and sustainability, research focuses on reducing energy consumption and maximizing the use of renewable energy sources. Studies investigate energy-efficient lighting designs (Singh et al., 2015), optimization of light distribution within the growing area, and evaluating the economic impacts of lighting technologies and strategies (Nelson et al., 2014).

Mathematical modeling and simulation are used to predict and optimize lighting conditions in CEA systems, including indoor farms with no daylight access (Eaton et al., 2021). This work also includes models for better explaining the impact of daylight and solar radiation in agriculture (Shabaev et al., 2021). These models help in designing efficient lighting layouts, determining lighting requirements for specific crops, and evaluating the effects of lighting on plant performance (Xu et. al., 2020).

2.2 Plant Conditions

Environmental factors require careful control and optimized in order to maintain ideal growing conditions for plants in CEA.

Water: Water is essential for plant growth, and its availability and quality are crucial in CEA. Proper irrigation management ensures plants receive adequate water while avoiding waterlogging or drought stress. Factors such as water source, irrigation frequency, and irrigation method need to be considered. Monitoring soil moisture levels, using water sensors, and implementing irrigation systems with precise control can help maintain optimal water conditions for plant growth.

Temperature and Humidity: Temperature and humidity levels significantly influence plant growth and development. Different crops have specific temperature requirements, including optimal day and night temperatures. Maintaining proper temperature ranges helps regulate physiological processes and influences crop phenology. Humidity control is also essential to prevent excessive moisture or high humidity conditions that can lead to disease development. Proper ventilation, heating, cooling, and humidity management systems are necessary to maintain optimal temperature and humidity conditions within the growing environment (Villagrán, 2019).

Nutrients: Plants require a balanced supply of essential nutrients for healthy growth. In CEA, nutrient management is typically achieved through hydroponic or fertigation systems, where nutrients are dissolved in water and provided directly to the plants' root systems.

CO2: Increasing CO2 levels in the growing environment can enhance photosynthetic rates and plant growth (Ruijs, 2020). Supplemental CO2 is often added to CEA systems to maintain elevated CO2 concentrations, typically around 1000-1200 parts per million (ppm). Monitoring and controlling CO2 levels through injection systems or CO2 enrichment techniques can help optimize plant productivity and maximize photosynthetic efficiency.

Light: In CEA, both natural and supplemental lighting are used to provide adequate light intensity and spectral quality. Natural light can be optimized by selecting the appropriate greenhouse location, orientation, and shading strategies. Supplemental lighting, such as LED systems, can be used to ensure consistent light levels, extend photoperiods, and fine-tune the light spectrum for specific growth stages. Monitoring and adjusting light levels, photoperiods, and spectral composition are essential for promoting healthy plant growth and optimizing yield. Careful management and control of these environmental factors in CEA systems contribute to optimal plant

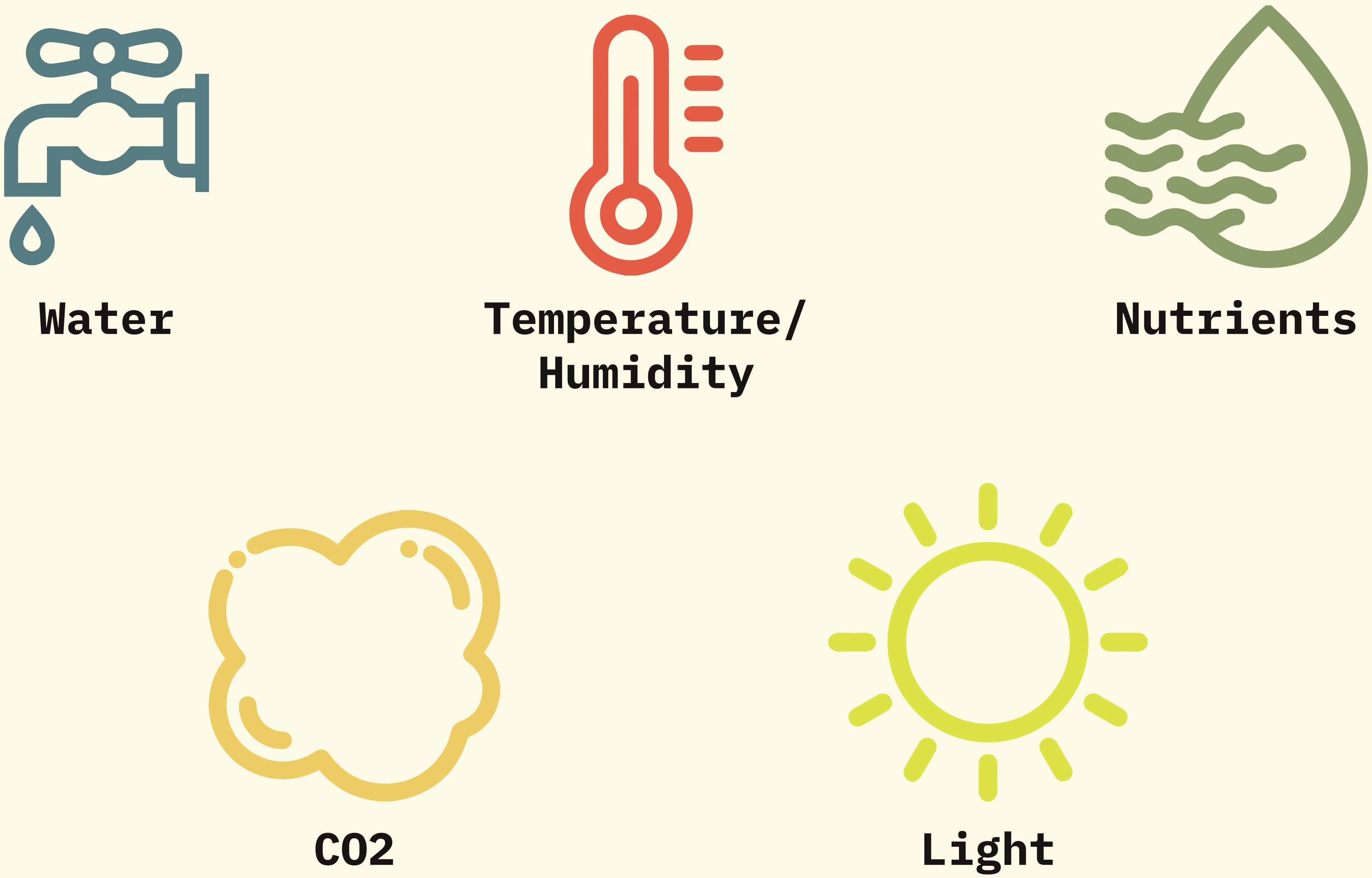


Fig. 2.1 : Plant Requirements

growth, development, and overall crop production. Monitoring systems, sensors, and automation technologies can help maintain precise control and ensure that plants receive the optimal environmental conditions throughout their growth cycle.

2.3 Lighting Metrics

Light is defined by three main characteristics: light quantity (intensity), light quality (spectral distribution), and light duration (photoperiod). Light quantity, also referred to as intensity, has the strongest correlation to photosynthesis and is typically the primary metric for assessing agricultural lighting, while light quality relates to the color and amount of light at each wavelength and has a direct impact on the shape of the plant, overall development, and transition between growth stages. PAR is related to both light intensity and spectra. Finally, light duration describes the amount of energy over time and impacts the flowering stage in plants (Singh. 2015). Most of the metrics used to quantify light, especially those related to the built environment, measure photopic light, which is light visible to the human eye; however, plants only use a specific range of light in the 400-700 nm range referred to as photosynthetic active radiation, or PAR (Torres, 2012). Because of this, the primary metrics used for assessing agricultural lighting are directly related to photosynthetic production, with photosynthetic flux (PPFD) used to measure intensity, photosynthetic active radiation (PAR) for spectral distribution, and daily light integral (DLI) used to define light duration.

PAR vs Photopic Curves

PAR (Photosynthetically Active Radiation) and the photopic curve are both related to the measurement and characterization of light, but they differ in their specific purposes and the spectral range they focus on. Photosynthetically Active Radiation) (PAR): PAR refers to the spectral range of light necessary for plants to engage in photosynthesis. The PAR range traditionally spans from 400 to 700 nanometers (McCree, 1972), covering the violet, blue, green, yellow, and red regions of the electromagnetic spectrum. 4-6% of the received solar radiation is metabolized into chemical energy by the plant (Zhu et al. 2010). The McCree curve was later revised by Sager (1988), who extended the range to the 300-800 nm wavelength and smoothing the steps on either end to better accommodate the radiant environment's impact on plant growth. PAR is used in horticulture, agriculture, and other plant-related studies as it provides a measure of the light energy available for plants to carry out photosynthesis effectively. PAR measurements are usually expressed in units of micromoles per square meter per second (µmol/m^2/s), or PPFD) and are used to quantify the intensity of light and spectra that plants receive for optimal growth and development.

Photopic Curve: The photopic curve, also known as the luminosity function, represents the sensitivity of the human eye to different wavelengths of light under well-lit conditions. It describes the average spectral response of the human eye to light stimuli and is used to calculate photopic luminous efficiency. The photopic curve is derived from psychophysical experiments, where human observers were asked to compare the brightness of different monochromatic lights (CIE 1932; Guilford, 1964). The results of these experiments formed the basis for the photopic curve, which indicates that the human eye is most sensitive to greenish-yellow light, peaking around 555 nm. The photopic curve covers a broader range of wavelengths than PAR, extending from around 380 to

Illuminance

Quantity

Photosynthetic Photon Flux Density (PPFD)
µmol•m2•s

Human Equivalent: Lux

Radiant Power

Quality

Photosynthetic Active Radiation (PAR)
400-700nm

Human Equivalent: Lumens

Photoperiod

Duration

Daily Light Integral (DLI)
mol•m2•day

Fig. 2.2 : Lighting Metrics

780 nm, encompassing the entire visible spectrum. The photopic curve is essential in lighting design, as it helps determine the appropriate distribution and intensity of light for different applications. By weighting the spectral power distribution of a light source with the photopic curve, one can calculate the luminous efficacy and evaluate how efficiently the light source appears to the human eye.

Photosynthetic Active Radiation

The quantum yield for a given light-dependent process is defined as the rate at which the measured event occurs relative to the system's capacity for photon absorption (Skillman, 2008); in the case of plant production, this is called photosynthetic quantum yield and describes the energetic efficiency for photoautotrophy. In commercial agriculture, only light within the active photosynthetic range is desired, limiting wavelengths between 400-700 nanometers.

This range, called PAR (photosynthetic active radiation), defines a well-supported curve for calculating the wavelengths viable for plants for photosynthetic action (McCree, 1971). Light occurring across these wavelengths is utilized by plants to perform the metabolic process of photosynthesis, although the rate at which light is available for absorption differs based on where it falls in the spectral range and is defined by the McCree curve (McCree, 1971).

While PAR is widely accepted and supported, new research suggests that as living organisms, plants require full spectrum daylight to thrive (Pazuki, 2017). By using calibrated LEDs to measure the photosynthetic response of plants, recent findings support an emergent model that demonstrates the range of useful radiation is wider than initially thought. Most recently, the introduction of ePAR, or extended PAR, which widens the original PAR range, demonstrates that plants are more receptive to light occurring in the far-red (701-750 nm) range than initially thought (Zhen et al., 2020; Zhen et al. 2021) and capable of utilizing light across the entire spectrum depending on the intensity (Wu et al. 2019), further evidence that plants utilize daylight in more complex processes than initially thought (Wu et al. 2019).

Additionally, when measuring the impact of light on photosynthesis, plant production is only one metric. Whole-plant photosynthesis should be considered since the spectral quality of light has also been found to impact other factors, such as secondary metabolites and anti-oxidants, causing certain plants to increase production and reduce the amount in other plants (Hao, 2018). Though advancements in LED technology have prompted a move towards plant factories, which exclude daylight entirely to rely solely on artificial light (Eaton, 2021), daylight remains the ideal source for plant growth, providing a continuous perfect spectrum for photosynthesis at zero cost (Mahdavian, 2017).

For the purpose of this plugin, PAR will be calculated using the Sager curve (1988), a modified version of the original McCree (1972) curve, which refines the original data to better take into consideration the radiant environment's impact on plant growth. Since the greenhouse envelope diffuses incoming light across the entire growing area, this curve is especially suitable for modeling light in a building or enclosed area.

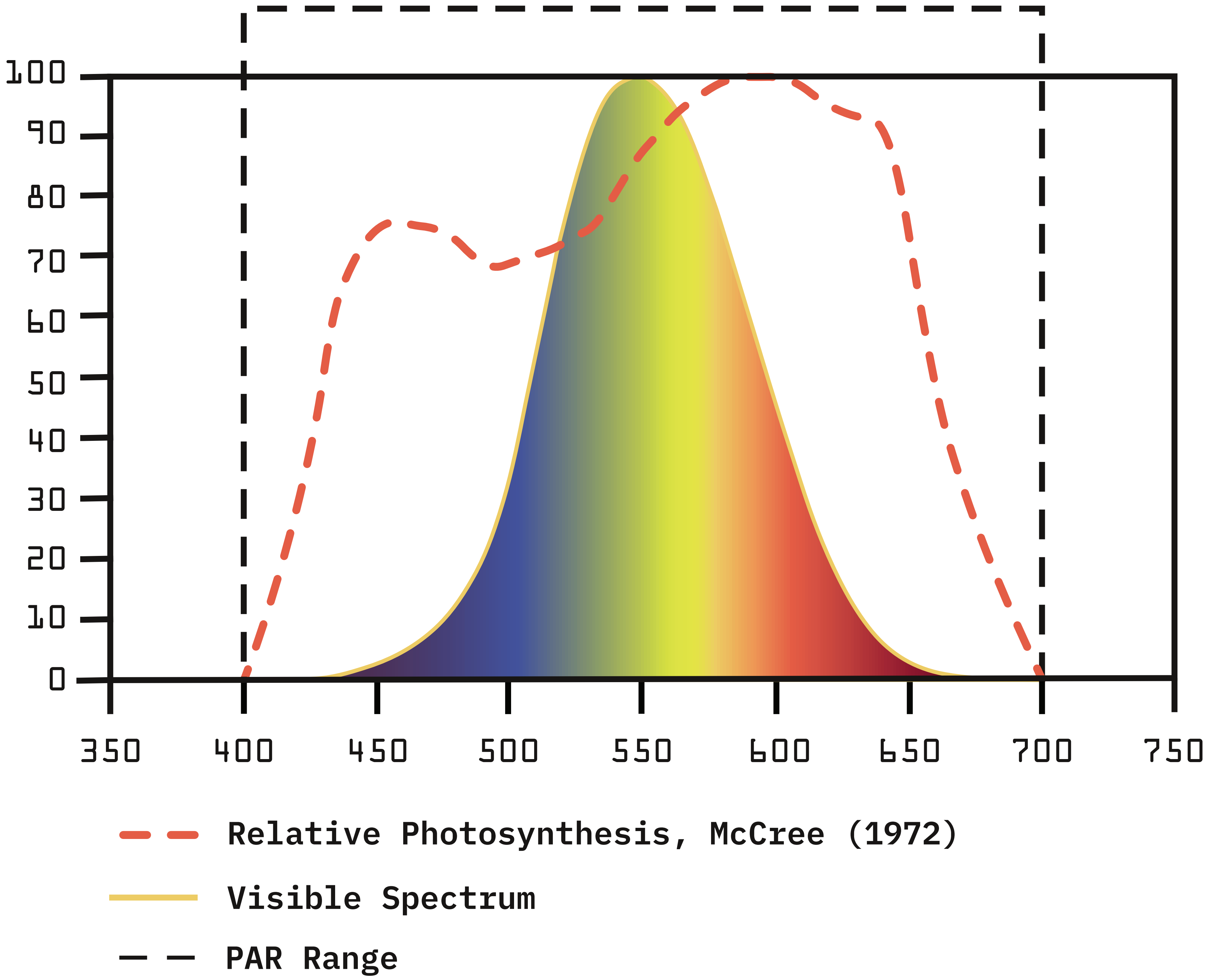


Fig. 2.3 : PAR vs Photopic Curve

Daily Light Integral

Although PAR defines the spectral response range of plants, the wavelength of light is only one component of photosynthetic action. Daily Light Integral is the total amount of PAR received each day as a function of light intensity over duration and is expressed as mol per m2 per day, representing the cumulative amount of photons reaching a plant in a given twenty-four-hour photoperiod (Torres & Lopez, 2012).
DLI is typically used in agricultural lighting to determine the amount of supplemental lighting necessary for sustained plant production in controlled environments, especially when growing cycles require photosynthetic needs beyond the daily photoperiod of available daylight (Benis, 2017).

Every plant species has a specific DLI, and exceeding that requirement produces no additional benefits. This metric becomes extremely important in controlled environments that rely on supplemental lighting since providing light in excess of the crop's DLI results in unnecessary energy consumption that does not impact production (Lanoue, 2022). This metric is not as important for daylit greenhouses since sunlight is free. Thus, the primary risks of exceeding the DLI are the side effects of too much solar radiation, including excess heat or sunburn. However, the intensity of solar radiation is far greater than energy produced by electric lighting, so even shading crops during hot summer months still allows adequate DLI for sustained growth.

Photosynthetic Photon Flux Density

PPFD (Photosynthetic Photon Flux Density) is a primary measurement used in CEA to quantify the intensity of light that plants receive for photosynthesis. PPFD is expressed in units of micromoles per square meter per second ($\mu mol/m^2/s$), indicating the number of photons (in the PAR range) that reach one square meter area per second (Runkle & Runkle, 2019). Per the Stark-Einstein law, every photon, regardless of wavelength, is assumed to excite one electron, meaning that energy reaching the plant will contribute equally to the photosynthetic process but the plant will only utilize wavelengths between 400-700nm (Ashdown, 2015). In CEA, where plants are grown indoors or in environments with artificial lighting, PPFD is a key parameter to optimize plant growth and productivity. It provides a quantitative assessment of the light energy available for photosynthesis, which is crucial for plant development, leaf expansion, flowering, and overall yield.

PPFD is typically measured using a specialized device called a quantum sensor (or PAR meter), which contains a photovoltaic cell sensitive to light in the PAR range and capable of providing readings in greenhouses for calculating the amount of light plants are receiving. Higher PPFD values indicate more intense light, which can have positive effects on plant growth. However, it's important to note that different plant species have varying light requirements, and excessive PPFD levels can cause photodamage or stress to plants. By carefully monitoring and adjusting PPFD levels in CEA systems, growers can ensure that plants receive optimal light for photosynthesis and growth. This involves strategically positioning light sources, adjusting light intensity, and maintaining appropriate light distribution across the crop canopy to promote uniform growth and productivity.

2.4 Supplemental Lighting

Supplemental lighting plays an important role in CEA by

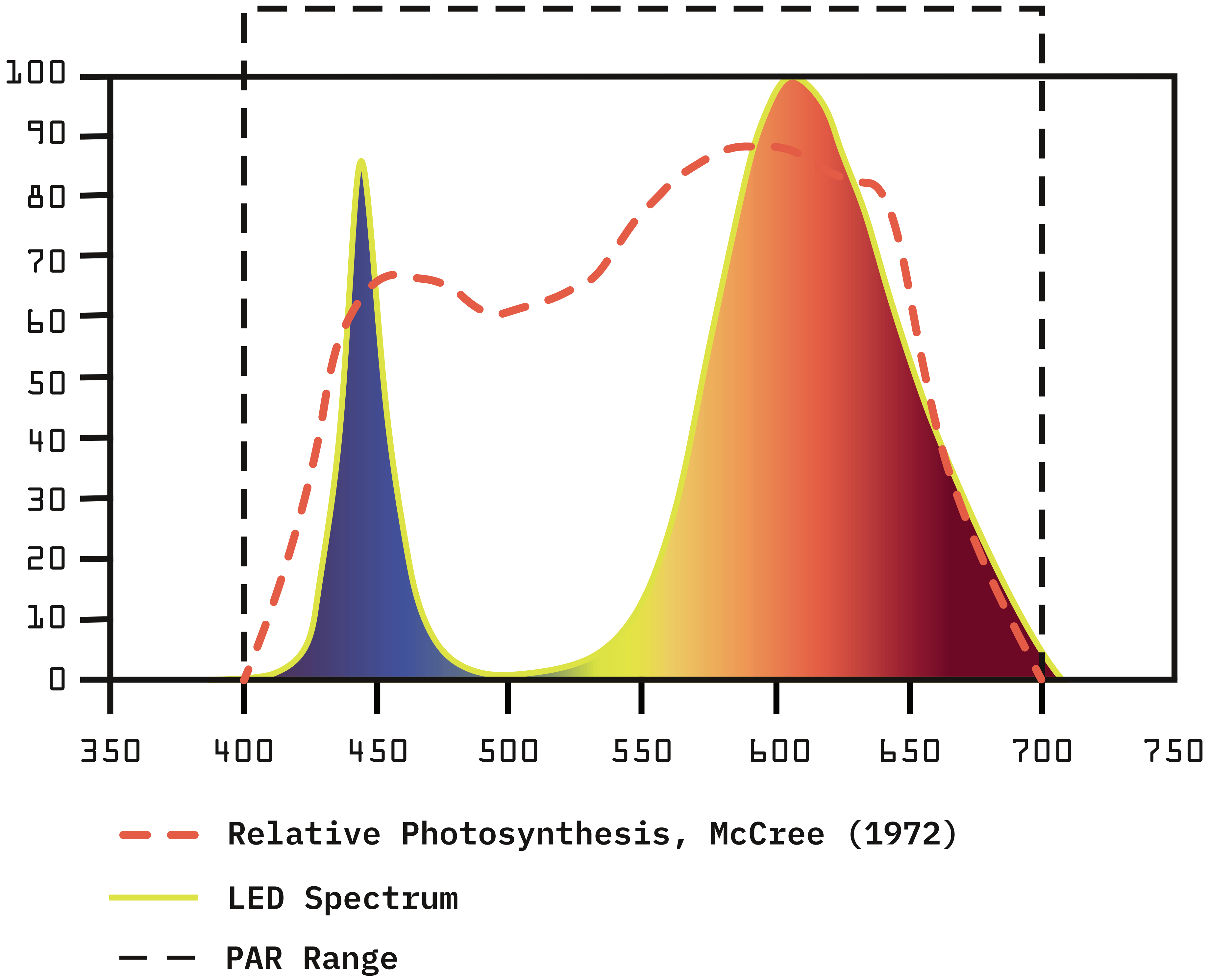
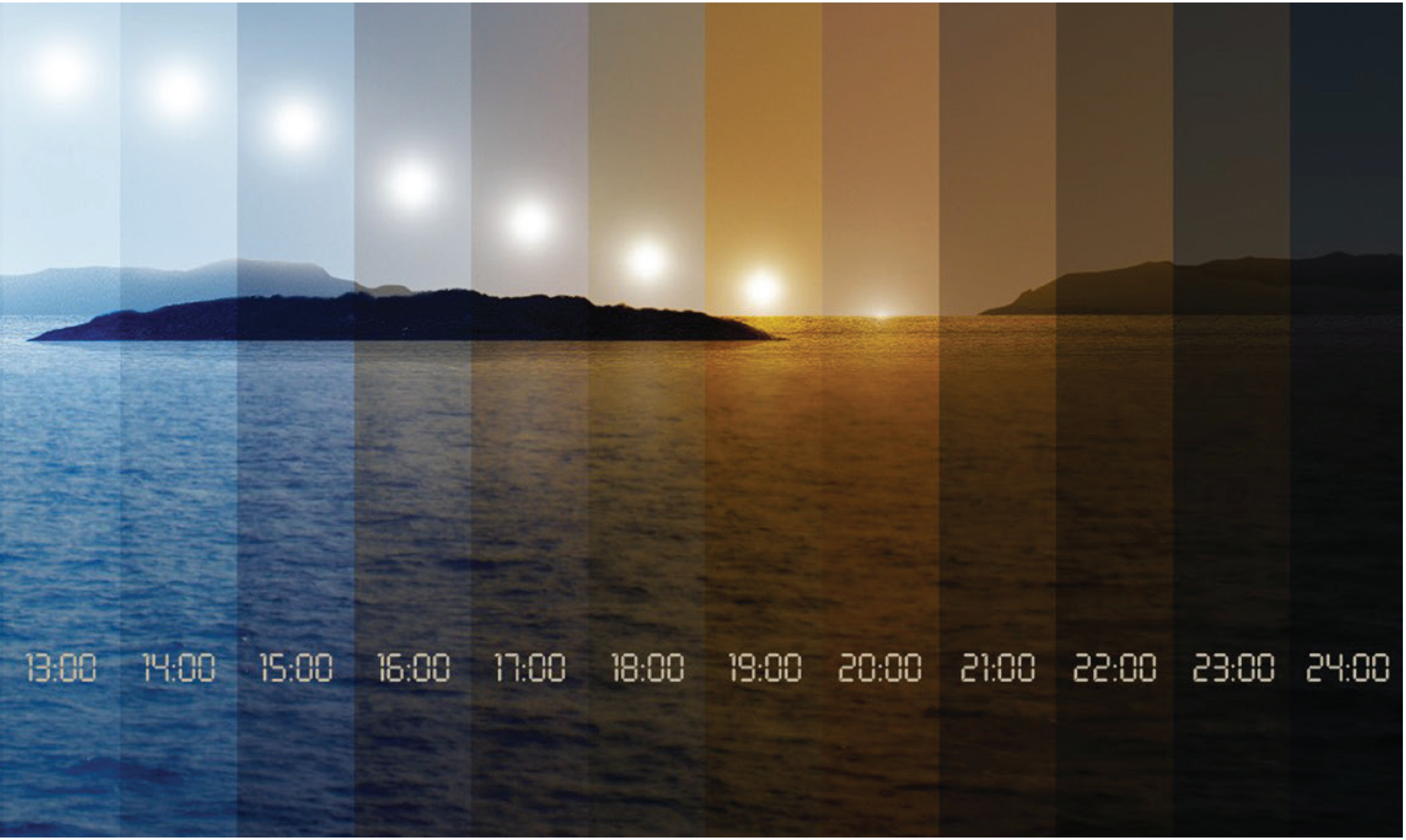


Fig. 2.4 : Electric Lighting

Fig. 2.5 : Daylight Color Temperature



6500K

9000K

providing artificial light to plants when the available solar radiation drops below acceptable levels, such as during winter months when the daily photoperiod is shorter, ensuring stable lighting conditions for consistent plant growth. With supplemental lighting, the ability to precisely tune the light spectrum has enabled more detailed control of growing conditions, including triggering growth stages brought on by shifts in spectra. For example, the ratio of red to blue light is related to vegetative growth versus flowering, respectively (Yakovtseva et al., 2017).

Adequate and well-designed supplemental lighting systems can significantly increase crop productivity and yield in CEA. By providing optimal light conditions, plants can photosynthesize efficiently, produce more biomass, and generate higher-quality fruits or vegetables. Supplemental lighting can also enhance crop uniformity and reduce variations in growth rates. Advances in lighting technologies (especially LED lighting) have improved energy efficiency in CEA, showing up to a 70% increase in efficiency compared to sources such as high-pressure sodium (HPS) lamps (Singh et al, 2015).

It's worth noting that the selection and design of a supplemental lighting system should be based on the specific requirements of the crops being grown, cost-effectiveness, energy efficiency, and overall sustainability goals. Careful planning, light distribution optimization, and monitoring of light levels are crucial to maximizing the benefits of supplemental lighting in controlled environment agriculture. Recent attempts to build indoor farms which rely entirely on supplemental lighting have proved inherently unsustainable (Reynolds, 2022), reinforcing the need more than ever to accurately understand the quality of daylight entering a space and supplement accordingly, rather than designing a growing space inherently dependent on artificial lighting.

2.5 Lighting Considerations in Controlled Environment Agriculture

Controlled environment agriculture within a built environment means the application, control, and distribution of lighting necessary for photosynthesis represents a significant factor in the design of the building or structure, especially in regard to solar radiation (Nadal et al. 2017). The structure's envelope, which diffuses solar radiation into the interior growing spaces, is typically semi-opaque to fully transparent in order to allow the greatest amount of available light into a space.

In certain locations, it may be necessary to reduce solar radiation by using methods such as shading screens, especially when excess heat from solar radiation gain causes other factors, such as temperature or humidity, to shift outside of the acceptable ranges (Shamshiri et al., 2018). Light intensity is important, as excess light does not result in increased plant growth but can increase heat, resulting in additional cooling costs or, in the case of artificial lighting, increased energy costs with no additional return on value (Torres et al., 2012).

External Factors

Being primarily performance-based buildings, external factors may have a significant impact on the effectiveness of natural light in CEA, including overshading from nearby buildings, sky conditions, solar incidence and orientation, and dust accumulation on the greenhouse envelope.

Overshading: The presence of tall buildings or structures near the greenhouse can cause shadows and reduce the

Fig. 2.6 : External Factors

amount of direct sunlight reaching the crops. Overshading can lead to uneven light distribution within the growing area and potentially limit the overall light intensity. Because of this, it's important to consider the surrounding context of a greenhouse, especially in an urban setting where taller buildings may present a significant challenge for maximizing solar exposure.

Sky Conditions: The variability in sky conditions throughout the day and across seasons should be taken into account when designing the greenhouse and planning supplemental lighting strategies to ensure consistent and optimal light levels for crop growth. A typical clear day can produce in excess of 100,000 lux, while an overcast sky may receive as low as 5000 lux, a wide range which can significantly impact both the quality and quantity of light reaching the plants in a built environment. The variability of spectra in daylight also need to be taken into account, since a number of factors impact the spectral composition (Hernández-Andrés et al., 2001). These factors include solar radiation intensity, sun altitude, atmospheric aerosol content, cloud type, and ground albedo (Inanici et al., 2022).

Solar Incidence and Orientation: The angle at which sunlight hits the greenhouse affects the intensity and distribution of light inside (Elsner, 2000). The solar incidence angle changes throughout the day and varies with seasonal changes. Proper orientation of the greenhouse relative to the sun's path can optimize light penetration and distribution. For example, aligning the greenhouse lengthwise in the east-west direction allows for maximum exposure to sunlight during the day, while minimizing shading caused by the greenhouse structure itself.

Dust: Dust accumulation on the greenhouse envelope can reduce the amount of light transmitted into the growing area. Dust particles on the surface scatter and absorb light, diminishing its quality and intensity. Because of this, greenhouses require regular cleaning and maintenance of the envelope to minimize dust accumulation and maximize light transmission, and poorly maintained greenhouses (Tantau et al. 2012).

Internal Factors

Internal factors related to CEA lighting are those directly relate to the design and configuration of the growing environment, including planting density, envelope material, structural configuration, and orientation of the planting area (Mosharafian et al, 2021).

Planting density: This refers to the spacing and arrangement of plants within the growing area. It affects the penetration and distribution of light within the crop canopy. Higher planting densities can result in greater shading between plants, reducing the amount of light reaching the lower leaves. Conversely, lower planting densities can promote better light distribution and penetration. The choice of planting density should be based on the specific crop's light requirements and growth characteristics to ensure efficient light capture and uniform plant development.

Envelope Transmissivity: The transmissivity of the greenhouse envelope material determines the amount of light able to pass through it. Different materials, such as glass or various types of plastics, have varying degrees of light transmittance, thus the ability to set material parameters in a simulation plugin is imperative for accurate modeling. Clear materials with high transmissivity allow more light to enter the greenhouse, while materials with lower trans-

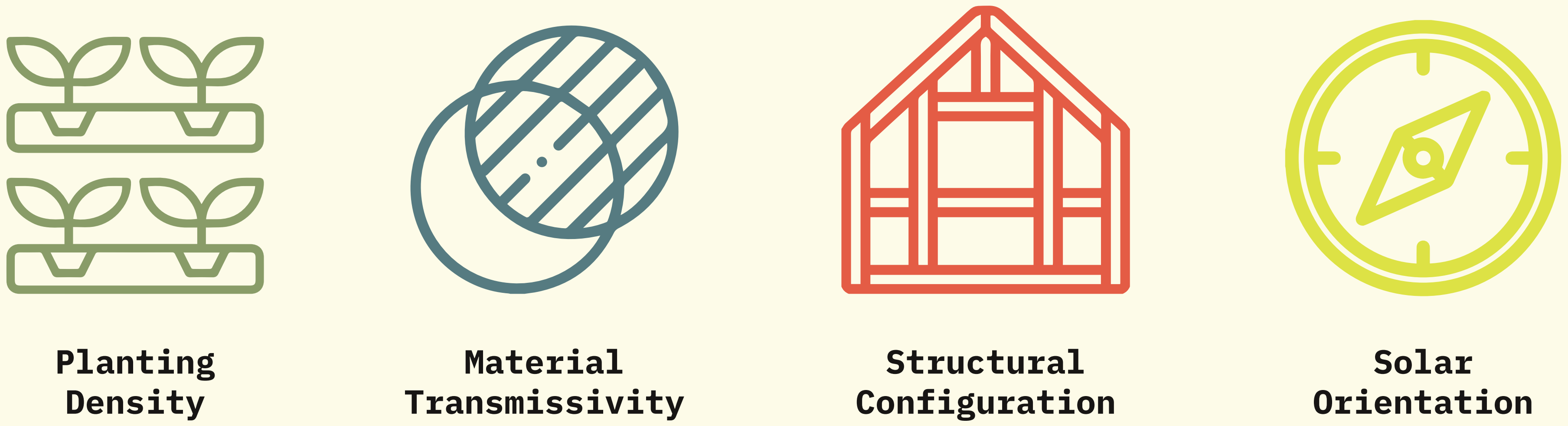


Fig. 2.7 : Internal Variables

missivity, such as diffusing or colored films, can influence light distribution and quality. Selecting greenhouse materials with optimal transmissivity for the desired crop can maximize light capture and utilization.

Structural Configuration: The structural configuration of the greenhouse, including its height, shape, and internal structures, can influence light distribution (Golddammer, 2021). Tall greenhouses allow for more light penetration and distribution within the crop canopy. Greenhouses with peaked or curved roofs can enhance light capture compared to flat roofs. The presence of internal shading structures, such as trellising or support wires, can affect light distribution within the canopy and should be carefully planned to minimize shading and ensure adequate light exposure for all plants.

Planting area orientation: The orientation of the planting area within the greenhouse can impact the amount and quality of light received by the plants. Proper orientation aligns the rows or beds in a way that maximizes exposure to sunlight. The planting area's orientation should consider the angle of incidence of sunlight and the positioning of the greenhouse relative to the sun's path. Optimal orientation ensures that plants receive uniform light distribution throughout the day and avoids excessive shading caused by neighboring plants or structural elements.

By carefully managing these internal factors, growers can optimize daylight simulation in CEA and enhance the efficiency of natural light utilization. Balancing planting density, selecting appropriate envelope materials, designing an efficient greenhouse structure, and aligning the planting area orientation contribute to uniform light distribution, optimal light capture, and improved plant growth and productivity. Regular monitoring and adjustments may be necessary to maintain the desired light conditions as plants grow and develop within the controlled environment.

2.6 Trends in Agricultural Lighting

Dynamic Lighting Control (DLC): When paired with spectral color analysis, active tuning of supplemental lighting though dynamic lighting control algorithms can significantly reduce energy consumption with no negative impact to plant production (Hao et al., 2018). Additionally, both top lighting and interlighting methods were found to benefit from dynamic lighting control, with reduced energy consumption across multiple lighting arrangements (Wang et al. 2018).

Extended Spectra: The traditionally defined PAR range of 400-700 nm is wider than initially thought, with recent studies demonstrating plants utilize as near as 380 and up to 750nm wavelengths (Zhen et al. 2020; Zhen et al. 2021), with other research looking at expanding PAR further to include far-red (FR), UV-B, UV-A, and infrared (IR) wavelengths (Pazuki et al. 2017), although the utilization of light in the UV region should be done with caution as it has harmful effects on humans.

Daylight Access: There is mounting evidence that plants, as complex living organisms, require full spectrum light to thrive. Plants are responsive to the circadian rhythm (Shabaev & Romanovets. 2021), which is responsible for triggering different stages of growth, flowering, and fruiting as changes to spectra and intensity shift. Additionally, plant metabolic cycles responsible for photosynthesis are also regulated by circadian rhythms (Kim et al., 2017).

Fig. 2.8 : Indoor Farming

III. Simulation Tools

Simulated States

Chapter 3: Simulation Tools

3.1 Lighting Simulation Tools

Daylighting simulation in controlled agriculture represents a central topic in the work being done around agricultural lighting. However, many of the tools used to perform these simulations are industry-specific to either agriculture or lighting, and a tool for assessing plant metrics that is easily accessible to architects and designers is lacking.

Simulating daylight spectra in controlled environment agriculture requires the ability to specify a range of parameters for controlling the light spectra, material properties, and simulation area, including geometry. Based on the current range of tools discussed in the literature or readily accessible to built environment professionals, there is a noticeable gap in the functionality for daylight simulation that allows spectral data to be used to model daylight for plant metrics, especially PPFD, which looks at the intensity of PAR, and DLI.

In order to develop a tool that effectively fills this gap, an assessment of the tools currently available was made. Tools were assessed based on their ability to provide the following three categories:

Plant-based Lighting Metrics: As a minimum, in order for a tool to be effective in must provide both PAR and DLI. While other lighting metrics exist, the ability to accurately simulate these provides data on both the contribution of supplemental lighting (PAR, measured as PPFD) and daylight autonomy (via DLI), which looks at the fitness of a space over a given photoperiod based on the necessary range of a plant or plant species.

Geometry & Solar Orientation: Many basic simulation tools used to calculate greenhouse performance rely on the use of standardized, predetermined building models. Given the increase of building-integrated and how a tool for agricultural daylight simulation would liked be used to inform design decisions, the capacity to model geometry which matches the proposed building is essential.

Spectral Properties: Because PAR defines a limited spectral range, running accurate daylighting simulations requires the ability to set custom spectral power distribution curves for both electric and sky light sources, as well as defining material properties. Spectral properties related to surface reflection or transmission must be defined, along with the specific type of reflection or diffusion (diffuse, direct, or directional diffuse).

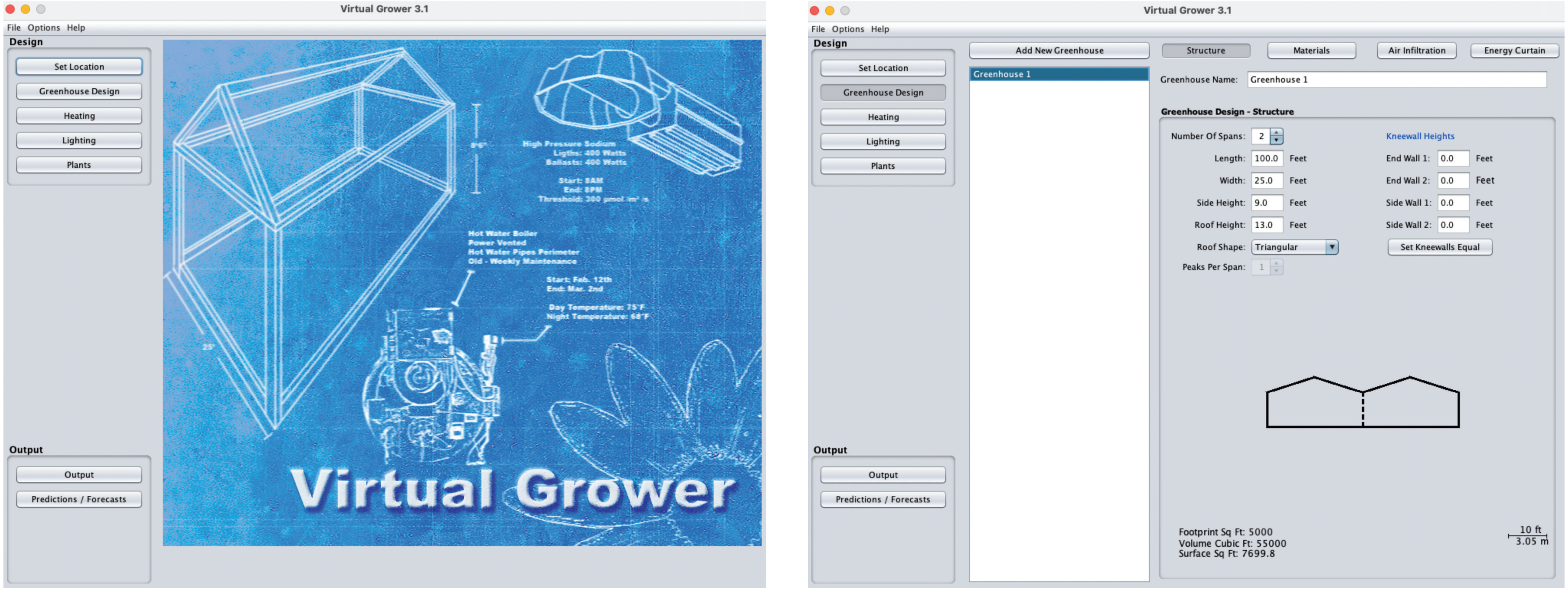
Multi-channel Light Analysis: Finally, being able to set up more complex simulations using multiple channels (beyond the standard 3-channel RGB one would expect to find) is important to agricultural lighting, since the spectral distribution curves found in electric light sources are typically tuned for PAR output or with peaks in certain red and blue wavelengths meant to trigger plant stages and assesses light in 8 or more channels (Hegemann, 2022).

3.2 Tools

USDA Virtual Grower 3 Model

The USDA Virtual Grower 3 (Virtual Grower (USDA ARS, 2011) is a software tool that allows growers to simulate and evaluate the performance of different crops in controlled environment conditions. It incorporates a range of environmental factors, including light, temperature, and humidity. While Virtual Grower 3 is not specifically focused on daylight simulation, it enables users to assess lighting scenarios and their impact on crop growth by adjusting parameters such as light intensity and photoperiod.

The software is designed to help potential farmers simulate the cost of greenhouse operations and estimate production capacity for a given geographical location. The tool is limited, requiring a selection of standardized inputs that expect a traditional greenhouse structure, does not provide consideration for the orientation of the greenhouse, and are helpful more for developing a general guideline for plant production in a specific climate than as a discreet performance tool.



Greenhouse Name: Greenhouse 1

Number Of Spans: 2
Length: 100.0 Feet
Width: 25.0 Feet
Side Height: 9.0 Feet
Roof Height: 13.0 Feet
Roof Shape: Triangular
Peaks Per Span: 1

End Wall 1: 0.0 Feet
End Wall 2: 0.0 Feet
Side Wall 1: 0.0 Feet
Side Wall 2: 0.0 Feet

Footprint Sq Ft: 5000
Volume Cubic Ft: 55000
Surface Sq Ft: 7699.8

Fig. 3.1 : USDA Virtual Grower 3 Software

AiPlantCare

While numerous tools are available for simulating daylight related to human comfort and building performance within the built environment, none specifically simulate plant response. Currently, only AiPlantCare (AiPlantCare, 2022) is the only Grasshopper plugin currently offering PAR as an output for daylight simulation.

However, AiPlantCare, despite running a three-channel radiance simulation, only requires reflectance or transmittance for the material property, which dictates they run the data only in a single channel which rejects all color information. Despite offering the ability to input material data as simulation parameters, using a single-channel model does not apply these parameters, leading to a simulation model which can seem misleading.

Additionally, daylight simulations are still run using Radiance, with Ladybug/Honeybee required as a plugin dependency, but simulation data itself is sent and called via an API to the AiPlantCare servers, which offer no transparency as to how the data is being processed. These issues, combined with the lack of multi-channel spectral analysis, make the plugin unsuitable for research. However, they offer a solid range of analysis tools including annual PAR exceeded (APE), plant sunburn risk, which looks at DLI in excess of a given range, and spatial daylight PAR autonomy, none of which are offered by any other tool covered in this assessment.

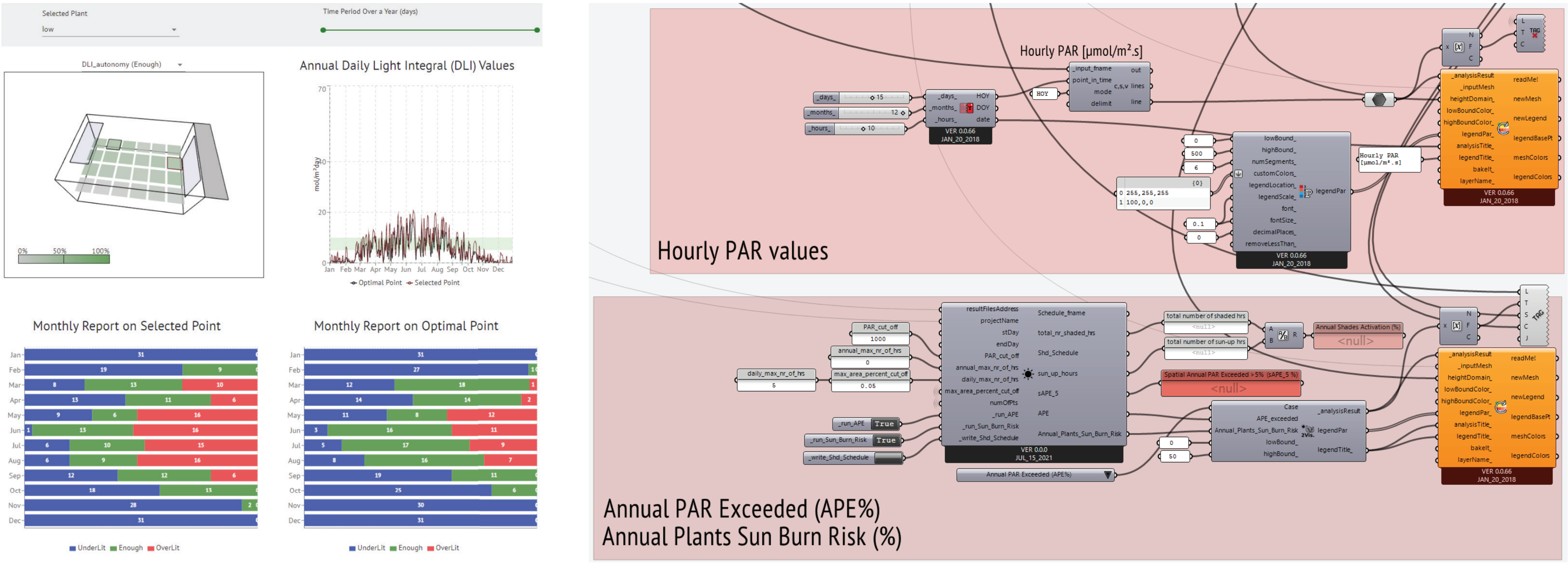


Fig. 3.2 : AiPlantCare

MIT/UMI Harvest

The Harvest plugin is a component of the Urban Modeling Interface (UMI) developed by MIT is a simulation tool that combines building energy analysis and urban agriculture modeling (Benis et al., 2017). The Harvest plugin enables users to assess the potential for urban agriculture within specific buildings or urban areas. It considers factors such as sunlight availability and shading analysis to determine the suitability of spaces for different types of crops.

Harvest can accept PAR as an input, using it to calculate the PPFD necessary to maintain stable growth for an urban farm. This application is well-documented but is useful only after PAR is known, and not able to model PAR for a building or space.

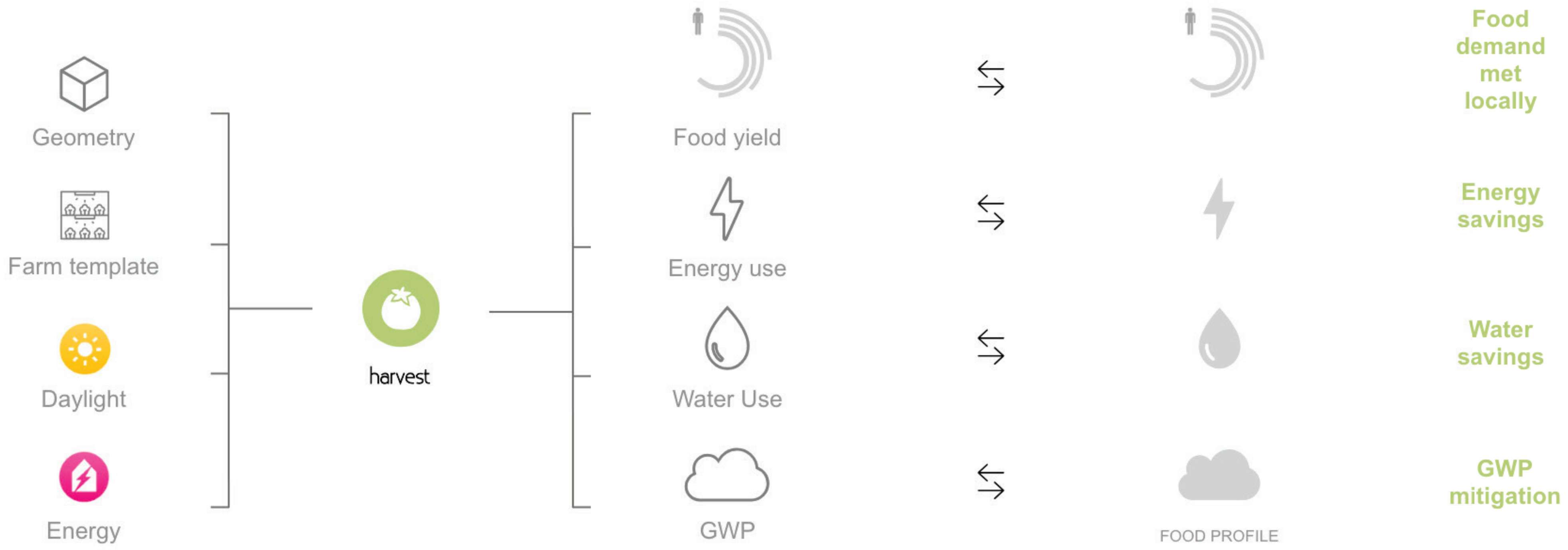


Fig. 3.3 : Harvest

Ladybug/Honeybee

Ladybug and Honeybee (Ladybug Tools, 2022) are plugins for the Grasshopper visual programming platform, widely used for environmental analysis in architecture and urban design. Ladybug focuses on solar and daylight analysis, while Honeybee focuses on energy modeling. Together, they enable users to perform complex daylight simulations, analyze sun exposure, and assess shading effects on buildings or urban agriculture systems. These tools can help designers and growers optimize daylight conditions and make informed decisions regarding building orientation, glazing design, and urban agriculture layout.

While not specific to agricultural lighting, the plugins include a range of components that act as a graphical user interface with the Radiance engine. Both Radiance, as well as Honeybee/Grasshopper have been extensively validated, with research supporting the accuracy of daylight modeling in these plugins (Kharvari, 2020). The radiance engine uses a hybrid model for ray tracking, combining deterministic ray tracing with the Monte Carlo method and using backtracking, which traces a ray of light back to the source (Kharvari, 2020), allowing for relatively rapid but accurate simulations.

While Ladybug/Honeybee is accurate, it is intended for daylight analysis in humans; thus the visualizations and outputs are provided in photopic Lux. However, because all the data is still present, utilizing the Ladybug/Honeybee component libraries as a dependency for Specularia provides a valid source for obtaining Radiance data within Grasshopper.

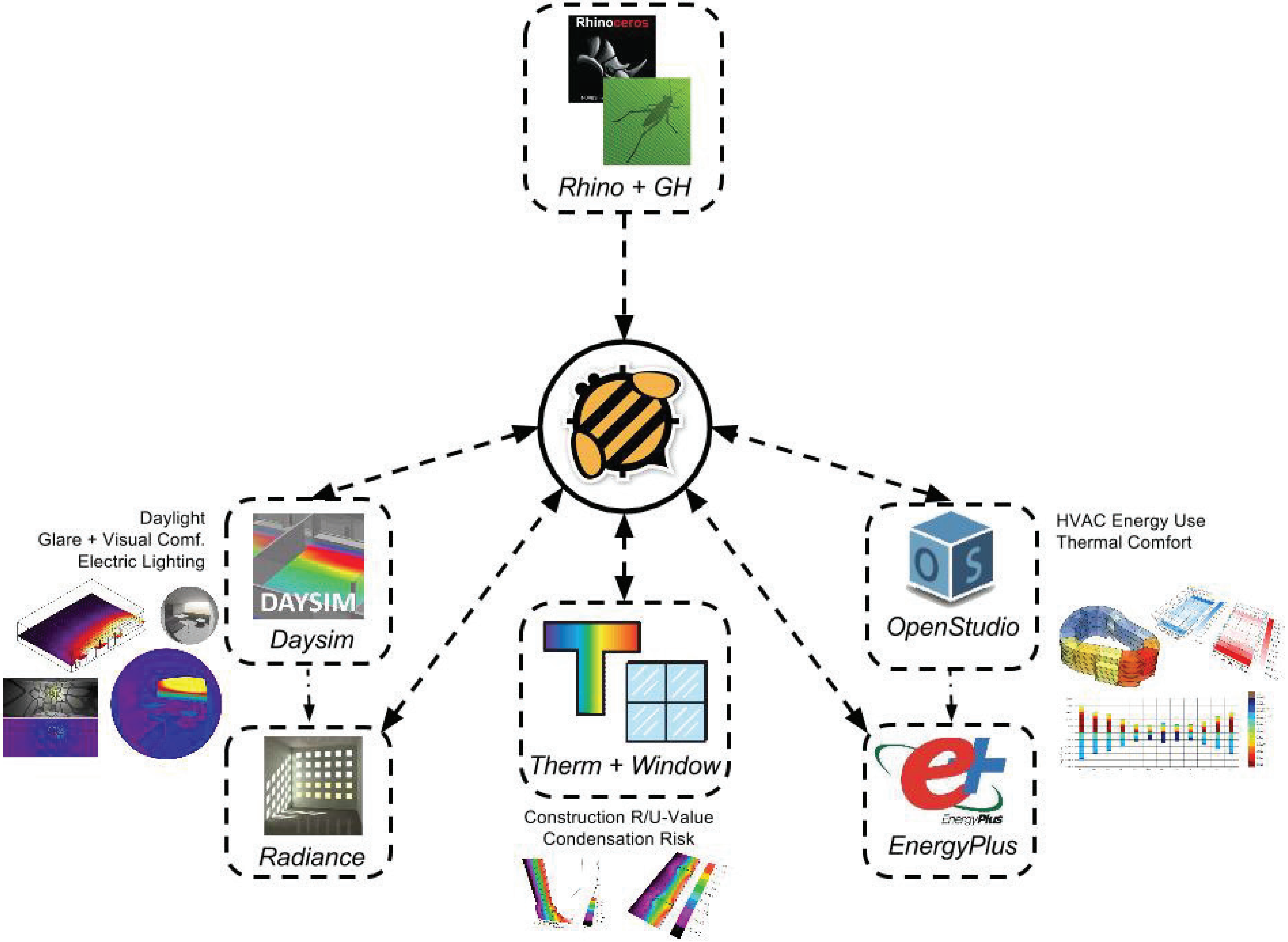


Fig. 3.4 : Ladybug/Honeybee

3.3 Development Objectives

Based on the assessment of the following tools, a series of development objectives was established to serve as a guideline for Specularia, ensuring that the tool is not replicating existing software and preventing feature creep during the development process. These objectives were informed by the literature review and the current tool assessment, and are in no way meant to be comprehensive, but rather serve as a minimum collection of functions necessary for accurate simulation.

Specularia is designed to fill two missing links in current daylight simulation tools: multi-spectral daylight simulation for plants, and custom geometry and material parameters. Because this tool is tailored for architects and designers, it fundamentally necessitates taking geometry which matches the building being designed, rather than approximating a typical greenhouse in similar conditions. Additionally, there is need for an open-source tool which is both accessible and capable of being modified and expanded upon. Specularia itself exists because of Lark, another open-source tool generously made accessible by the original authors. The need for an agricultural simulation tool presents a new opportunity to create a transparent and free tool for people to engage and utilize.

While Specularia is meant to act as a design tool, the ability to finely tune additional parameters such as sky spectra means that in addition to simulating the impact of potential design choices, it could also serve as a digital twin for an existing, sensor-equipped building. Digital twins are a simulated environment that mirrors an actual physical space, and are finding use in CEA to monitor and assess projected performance with actual, real-life performance (Jans-Singh et al., 2020).

Based on the initial assessment categories, the development objectives for Specularia were refined as specific action items for the software development phase:

PAR: Provide PAR as PPFD, which may be used to then calculate supplemental lighting needs or DLI

DLI: Provide the total light in a 24-hour photoperiod by simulating, at a minimum, hourly PAR for every hour of illuminance in a given day.

Custom Geometry: Include the ability to specify custom geometry which accurately represents the physical space at the desired scale of complexity.

Solar Orientation: Ability to define both the orientation of the building and the grow spaces as they relate to the position of the sun.

Material Properties: Specify custom spectral power distribution (SPD) curves for materials, both opaque and transparent, used on the building.

Electric Lighting: Ability to define the location, candle power distribution (.ies file format) and spectral content for electric lighting, as well as utilize them for either the primary light source or as a supplement to daylight.

Daylight Spectra: Ability to model any sky luminance distributions (Perez all-weather skies), and set any sky spectra based on measurements.

Multi-spectral light simulation: The option for nine-channel simulations, which consider spectral information relevant to plant response on the PAR curve in greater specificity at the cost of increased computing time.

	PAR	DLI	Custom Geometry	Solar Orientation	Material Properties	Electric Lighting	Daylight Spectra	Multi-Channel Light Analysis
Ladybug/Honeybee			X	X	X	X	X	X
USDA Virtual Grower 3				X		X		
AiPlantCare	X	X	X			X		
MIT UMI Harvest			X	X				

Fig. 3.5 : Existing Tools Matrix

IV. Methodology

Specularia Development

Chapter 4: Methodology

4.1 Plugin Development

When looking at potential platforms suitable for running a tool that could handle the complex task of simulating specific building geometry with parameters for setting the spectral properties of both materials and sky, Rhinoceros 7.0 (McNeel, 2021), a 3D modeling program was a logical fit. This is largely due to the ability to leverage Grasshopper, an algorithmic component for parametric modeling and simulation inside the Rhino environment. Grasshopper is already a familiar part of architectural design and simulation workflows and offers a stable and well-supported development environment for extending the functionality of an existing platform, providing an opportunity to develop a specific tool such as agricultural daylight simulation and analysis.

Rhino is already widely used in architectural design, and Grasshopper currently provides various environmental lighting analyses via third-party plugins such as Climate Studio (Solemma, 2022) and Honeybee/Ladybug (Ladybug, 2022), which offer a convenient front-end interface for parametric simulation using building geometry using the Radiance daylighting simulation engine. Furthermore, thanks to the Honeybee/Ladybug suite of plugins, Radiance-based simulations can be run and the data parsed out to additional components for additional post processing. This makes efficient use of computing time, since once the initial building is set up inside a Grasshopper definition, the data from a single simulation or series of simulations can be parsed to other components for assessing additional metrics, including PAR and DLI.

Specularia's core repositories and framework are built upon Lark MultiSpectral Lighting, including components from v1.0 (Inanici et al., 2015) and v2.0 (Gkaintatzi-Masouti et al., 2022). Lark is an open-source Grasshopper plugin that models circadian and non-visual light in the built environment. Lark provided a valuable repository of libraries relevant to this project and served as the foundation for the development of Specularia. Since plants respond to light differently than humans, computing spectra is useful as the spectra can be processed with plant action curves that inform how effective the light reaching them is as being used for photosynthesis.

Specularia aims to provide actionable data for aiding design feasibility studies on projects with a building-integrated agricultural component. As with other grid-based Radiance simulations, Specularia works by setting a grid of regularly spaced upward-facing sensors at the top surface of the desired plant canopy. Using the Radiance engine, daylight illumination values for each sensor point for each hour of the year are generated, and those radiance values are then converted to PPFD in the PAR range, a workflow that is validated by other research, including the MIT UMI Harvest plugin (Benis et al., 2017).

4.2 Simulation Workflow

Daylighting simulations in Grasshopper are divided into three primary phases: 1) Preprocessing, 2) Simulation, and 3) Post-processing. Additionally, in order to run, Specularia requires both the Radiance daylighting engine as well the Ladybug & Honeybee Grasshopper plugins installed. The plugin files include a readme file outlining the installation and set up process for both of these dependencies.

Phase 1 - Preprocessing: The preprocessing phase sets up the simulation by defining parameters and creating the sky and building models.

Phase 1A: Sky Model

a. .epw File: Import a .epw file, which contains TMY3 weather data for the desired location, providing information about solar radiation, temperature, and other climatic conditions.
b. Time and Date: Time and Date: Set the specific time and date for the simulation to represent the desired daylight conditions. For point-in-time simulations, the specified time will be used; for DLI, the date is used, and the time is computed hourly for each hour of illuminance.
c. Sky Spectra: Define the sky spectra parameters, which can be selected from a range of standard sky conditions or customized via an SPD curve and wavelength range.

This data is combined and, using components from Ladybug tools, a sky dome is generated representing the distribution of light sources in the sky. That sky some is then converted into a sky matrix suitable for Radiance-based simulations by capturing the distribution of light from different directions.

Phase 1B: Building Model

a. Define Building Geometry: Create or import the 3D geometry of the controlled environment agriculture structure within Rhino Grasshopper.
b. Assign Material Properties: Specify the material properties of the building surfaces, including spectral data, reflectance, transmittance, as well as specularity and roughness for opaque materials. These properties may be found in the Spectral Materials Database (Jakubiec, 2022) for opaque materials and Optics6 (LBNL, 2019) for transparent material definitions.
c. Set Electric Light Sources: Placing points inside the Rhino model, as well as importing .ies and SPD files, which define the light source distribution.

Phase 2 - Simulation:

The simulation phase generates a Radiance-based simulation using the building and sky models. In order to run, the following parameters must be specified:

a. Radiance Parameters: Configure the simulation settings in Honeybee to define the desired accuracy, calculation grid, and other simulation parameters.
b. Generate Radiance Scene: Combine the sky model and building model to create a Radiance scene. This scene represents the interaction of light with the building surfaces and the surrounding environment.
c. Run Simulation: Using Honeybee components, a Radiance-based simulation is initialized, computing the distribution of daylight within the defined space.

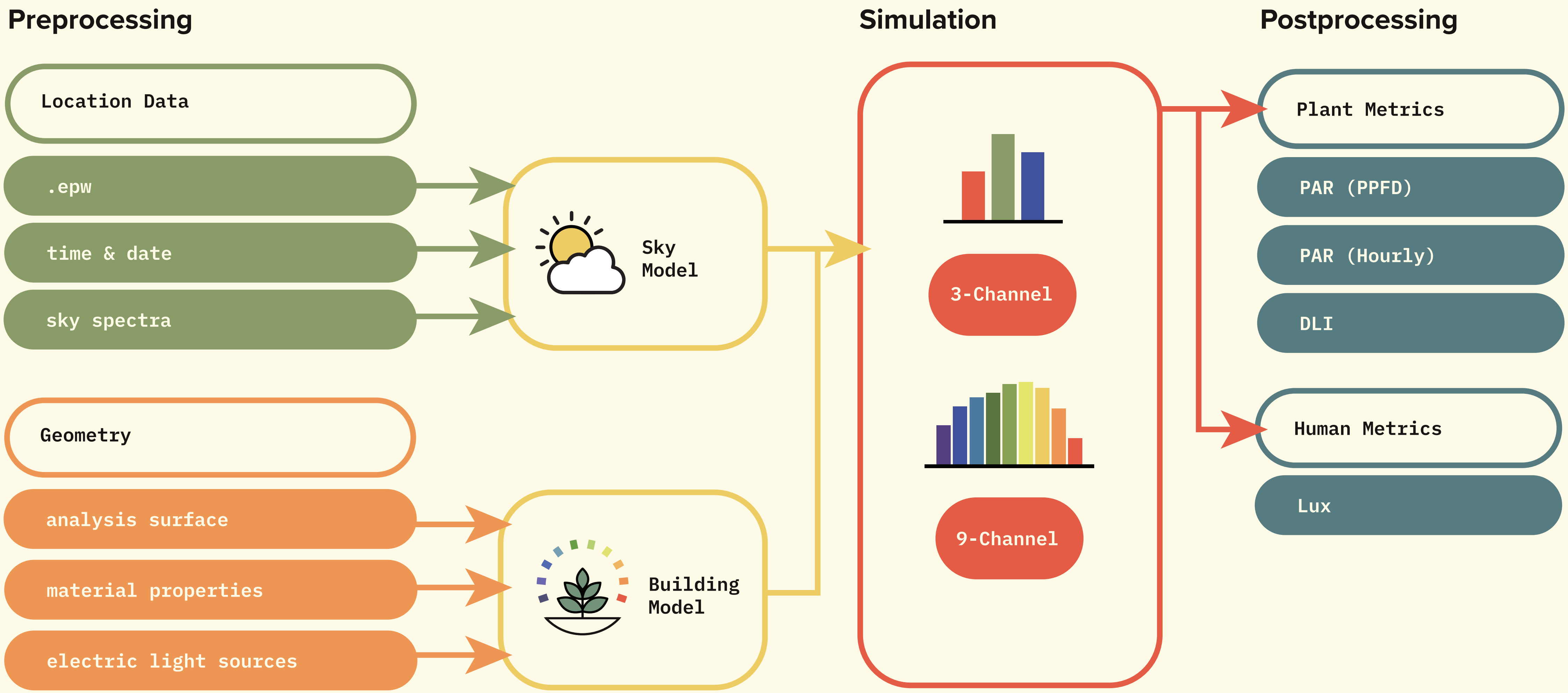


Fig. 4.1 : Simulation Model

Post-processing: This phase involves parsing the simulation output using components from Specularia to extract key metrics for analysis and visualization. Depending on the simulation type, either PAR or DLI or both are output and using Ladybug or other Grasshopper components, visualized or parsed further. The results are also written to a text file and stored locally.

4.3 Specularia Components

Specularia components, scripted in Python as custom Grasshopper objects, enable the simulation workflow outlined in the previous section to generate a multispectral Radiance simulation. Multispectral simulations are a computational process for modeling the distribution of light across different wavelengths (spectra) in a given environment. These simulations are capable of providing valuable insight and analysis for how light interacts with surfaces and objects at various wavelengths, making them ideal candidates for agricultural daylighting simulations, which rely heavily on the distribution of spectra due to the limited PAR range.

In order to run a multispectral radiance simulation, a mathematical model such as Radiance is used to calculate the radiance values for a range of wavelengths, taking into account the light sources, geometry, material properties, and layout of the environment. Ladybug/Honeybee plugin provides the core components necessary for base simulations, however the output is delivered as lux, which is not useful for planting analysis, and the simulations are limited to three channels. Lark Multispectral Lighting offers the ability to run 9-channel simulations via a component which subdivides a standard 3 channel simulation in three separate simulations, providing 3 channels each for red, green, and blue. Lark also provides the components necessary for creating the spectral material and sky definitions. These components were adapted to provide the same functionality to Specularia. However, the wavelength ranges were changed as follows in order to optimize for the PAR curve:

3 channel
R 587 780
B 499 587
B 380 499

9 channel
R1 700 780
R2 643 700
R3 587 643
G1 558 587
G2 529 558
G3 499 529
B1 449 499
B2 399 449
B3 380 399

Spectral Materials Component: The spectral materials component provides functionality to define and assign spectral properties to materials used in the lighting scene for both 3- and 9-channel simulations. It allows users to specify the spectral reflectance and transmittance characteristics by taking the arguments defined below:

- spd_input: filepath to spectral power distribution .txt file.
- source_interval: wavelengh increment from spd_input
- excel_daylight_series_cal: Boolean toggle True if data is derived from the Rochester Institute of Technology Excel Daylight Series Cal-

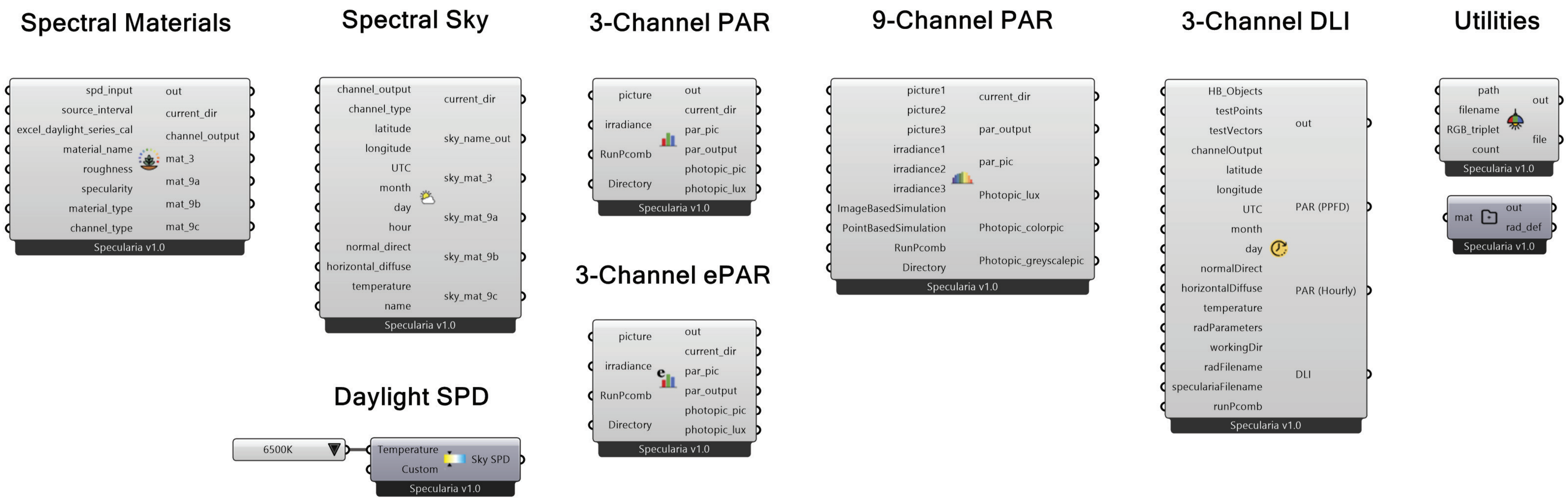


Fig. 4.2 : Specularia Components

culator
- material_name: name for Radiance material
- roughness: float 0-1
- specularity: float 0-1
- material_type: [0 = glass] [1 = plastic] [2 = sky] [3 = electriclight]
- channel_type: [0 = 3 channel] [1 = 9 channel] 3 channel is RGB/ 9 channel is b1,b2,b3,g1,g2,g3,r1,r2,r3

The component returns the following output:

- current_dir: working folder
- channel_output: average reflectance or transmissivity per channel [0-1]
- mat_3: 3-channel Radiance material definition [r,g,b]
- mat_9a: 9-channel Radiance material definition [b1,b2,b3]
- mat_9b: 9-channel Radiance material definition [g1,g2,g3]
- mat_9c: 9-channel Radiance material definition [r1,r2,r3]

Spectral Sky Component: Similar to the spectral materials component, the sky component allows users to define and assign spectral properties to a sky model. The component takes the following arguments:

- channel_output: use the Specularia Spectral Materials component to write 3 or 9 spectral channels
- channel_type: Choose [0 = 3 channel] [1 = 9 channel]
- latitude: north of the equator is positive
- longitude: west of the Prime Meridian is positive
- UTC: Coordinated Universal Time
- month: integer 1-12
- day: integer 1-31
- hour:float 1-24
- normal_direct: normal direct irradiance
- horizontal_diffuse: float radiation from .epw file
- temperature: dew point temperature
- name: optional name for sky spectrum

The spectral sky component returns the following arguments:

- current_dir: working folder
- sky_name_out: Radiance sky definition name
- sky_mat_3: filepath for 3 channel sky definition
- sky_mat_9a: filepath for 9a channel sky definition
- sky_mat_9b: filepath for 9b channel sky definition
- sky_mat_9c: filepath for 9c channel sky definition

3-Channel PAR Component: The 3-channel PAR component takes the illuminance output from the Radiance simulaton, multiplies each channel by the area under the corresponding segment of the PAR curve, and then converts those values from lux to PPFD. The component is available for both the standard PAR curve, as well as ePAR, which expands the spectral range from 380 to 750 to reflect new research on the photosynthetic action. The component takes the following arguments:

- picture: filepath to 3-channel image [RGB]
- irradiance: filepath to 3-channel irradiance out-

put (example .dat, .res)
- RunPcomb: Set Boolean to True to run simulation
- Directory: optional subfolder name (default folder is C:\specularia)

After successfully running, the component will produce the following outputs:

- current_dir: current working folder
- par_pic: filepath to PAR picture
- par_output: Photosynthetically Active Radiation (PAR) output [McCree-Sager curve]
- photopic_pic: filepath to photopic luminance picture
- photopic_lux: list of photopic illuminance

9-Channel PAR Component: Like the 3-channel PAR, this component takes a similar range of inputs, except in place a of a single irradiance filepath, there are three inputs, one for each of the 3-channel simulations. Due to running three back-to-back simulations, the 9-channel component is best suited for simulations involving electric lighting, since there is not a significant difference between the two curves when daylight is the only light source. The component takes the following arguments:

- picture1: filepath to 3-channel image (blue wavelength bin)
- picture2: filepath to 3-channel image (green wavelength bin)
- picture3: filepath to 3-channel image (red wavelength bin)
- irradiance1: simulated RGB values (blue wavelength bin)
- irradiance2: simulated RGB values (green wavelength bin)
- irradiance3: simulated RGB values (red wavelength bin)
- ImageBasedSimulation: set Boolean to True if Grasshopper template includes imageBased-Simulation recipe and the outputs will be HDR images
- PointBasedSimulation: set Boolean to True if Grasshopper template includes gridBased-Simulation recipe and the outputs will be RGB values
- RunPcomb: set Boolean to True to run simulation
- Directory: optional subfolder name (default folder is C:\specularia)

Daily Light Integral (DLI) Component: The DLI component is a modified PAR component which does not create a point-in-time simulation, but looks at the day specified in the inputs, then runs a series of simulations at the start of each hour of the day between 7:00 and 20:00 to look at the total light for that day. The plugin takes the following arguments from both the spectral materials, spectral sky, and a few additional inputs from the standard 3-channel simulation:

- HB_Objects: list of objects from spectral materials components.
- testPoints: points from analysis surface
- testVectors: vector from analysis surface
- channelOutput: file from sky spectra
- workingDir: current working folder
- radFilename: optional file name
- speculariaFilename: optional file name
- runPcomb: set Boolean to True to run

Create Colored Luminaire: A post-processing component that updates the luminaire in an electric light simulation to the color provided in the SPD. It takes the following arguments, and puts out a single radiance file:

- path: folder path of the existing luminaire rad file
- filename: filename to existing luminaire rad file
- RGB_triplet: 9 values describing the SPD
- count: 0: blue (first 3 of the 9 spectral values), 1: green part of the spectrum (second 3 of the 9 spectral values), 2: red part of the spectrum (last 3 of the 9 spectral values)

4.1 Calculating PAR & DLI

The original McCree curve for relative quantum yield was a continuous function from 350 to 725 nm, determined by the leaf absorbency of incident radiation and measured as photon flux (McCree, 1971). Sager (1982) modified this curve, extending the range to the 300-800 nm wavelength and smoothing the steps on either end to better accommodate the radiant environment's impact on plant growth, which is ideal for assessing PAR in built structures. A second, more experimental curve based on extended PAR (ePAR) was also calculated and included as an option for daylight modeling, extending the far-red portion to 750 nm before tapering off. This extended curve reflects more recent research proposing an extended far-red sensitivity that demonstrates plants utilize much more light in the 701-750 nm wavelength range than initially thought (Zhen et al., 2020, 2021). The ability to choose between a standard PAR or the ePAR curve allows the user to compare data from both models since ePAR is promising but still relatively new. For the purposes of this plugin, the Sager curve was used for calculating PAR, however in an effort to support the most relevant research, a second Grasshopper component with the extended PAR curve was also built and included in the v1.0 release of Specularia.

Three-Channel PAR: The three-channel PAR component takes the irradiance reading from Radiance, multiplies each channel by the correlating coefficient of the curve area based on standard Radiance color space, then converts from irradiance values to PPFD. Channels were parsed based on PAR curve optimization using the following bins:
R 587 780 / B 499 587 /B 380 499

The coefficients were then calculated based on RGB intervals (default RGB) in Radiance color space:

$$[(0.4141 * R) + (0.2963 * G) + (0.2896 * B)] * 2.02$$
$$= \mu moles\text{-}m2\text{-}s$$

The conversion of Lux (W-m2) to PAR (µmoles-m2-s) is based on the standard conversation for Lux to pyranometers is 1 W m-2 = 4.57 µmol m-2 s-1 (Thimijan & Heins, 1983), however since PAR assumes that only energy in the 400-700 nm range is usable by plants, it ignores total solar radiation, using only 45% of the value (the approximate percentage of usable wavelengths in full spectrum daylight) to create a conversation value of 2.02 (Mavi & Tupper, 2004).

Nine-Channel PAR: To calculate PAR in nine channels, a three-channel Radiance simulation is run three separate times, breaking a single channel into three subchannels for more accurate color modeling. Wavelengths were parsed into the following channels wavelengths into the

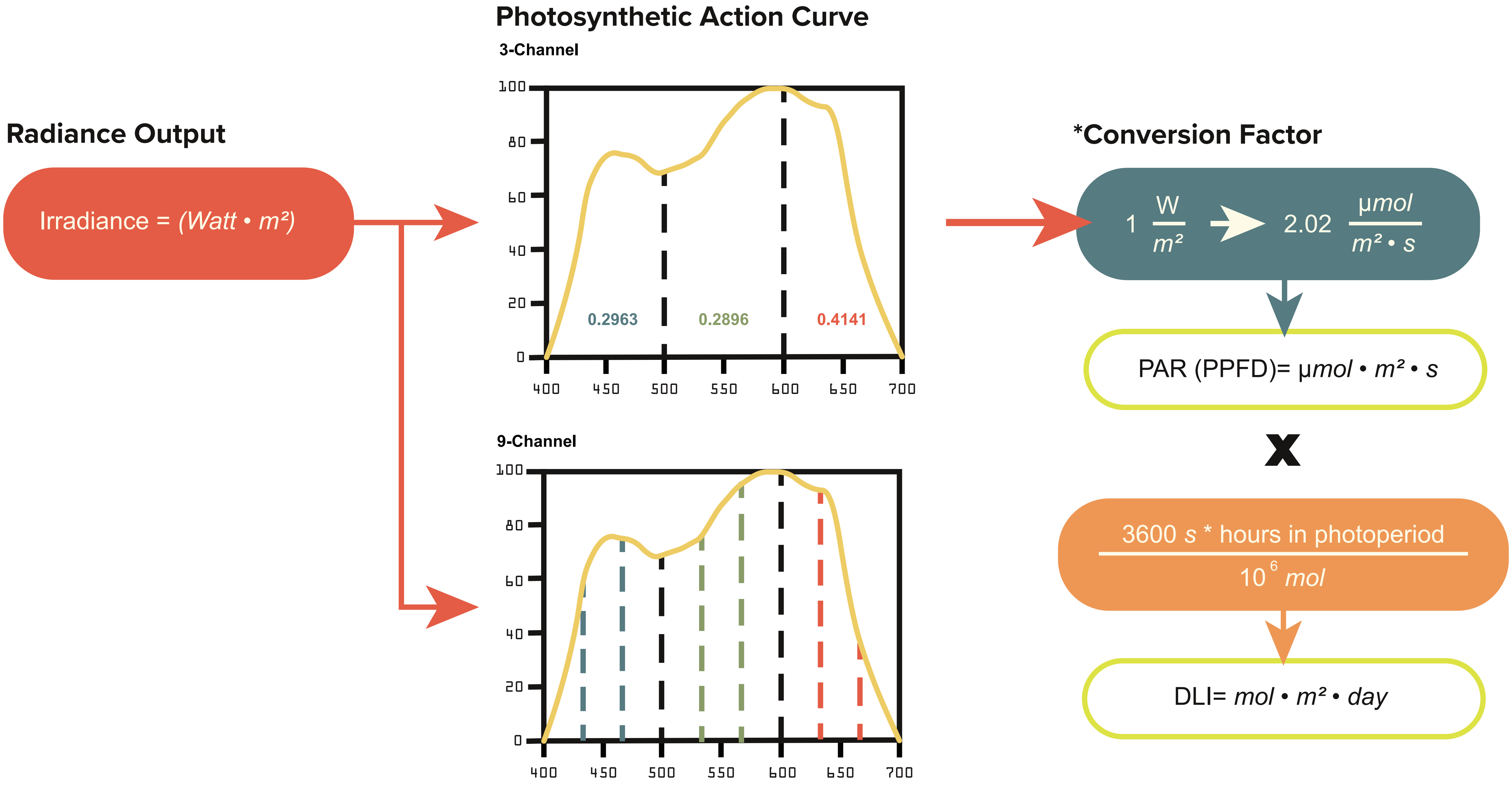


Fig. 4.3 : PAR/DLI Calculations

following channels to optimize the PAR curve:

R1 700 780 / R2 643 700 / R3 587 643
G1 558 587 / G2 529 558 / G3 499 529
B1 449 499 / B2 399 449 / B3 380 399

The coefficients derived from those channels are then used to calculate PAR in nine channels:

$$[(0.1426 * B1) + (0.147 * B2) + (0.0 * B3) + (0.1105 * G1) + (0.0976 * G2) + (0.0882 * G3) + (0.0 * R1) + (0.1898 * R2) + (0.2243 * R3)] * 2.02 = \mu mol\text{-}m2\text{-}s$$

Daily Light Integral (DLI): Modeling DLI is a complex task, since daylight spectra change hourly and simulations require significant time and computing resources. However, DLI may be approximated by setting a color temperature for the sky or setting individual CCTs for each hour of the day via an input parameter, then calculating the hours of a given day which receive illuminance through the global horizontal illuminance measured at a local meteorological station or documented in the TMY3 dataset. Hourly PAR is then multiplied by the number of daylight hours for that photoperiod, providing a baseline DLI that considers overshading, geographic location, and typical weather data (Runkle & Runkle, 2019).

4.2 Model Validation

Once the plugin components were built, work moved from development into beta testing. Since the both the 9-channel PAR and DLI components are more complex versions that depend on the base 3-channel PAR, a validation model was created in order to test them on a simple greenhouse.

Using two spectral material components, one for the ground and one for the envelope, a basic simulation was run inside Grasshopper in order to validate the output. As a reference check, a second simulation was run with the AiPlantCare components using the same model. This process required converting the spectral material definitions from Specularia into single channel reflectance or transmission values, since AiPlantCare does not offer multispectral simulations and uses Daysim and with a daylight coefficient that does not contain spectral data. Both simulations were run using a standard D6500K sky color on June 21, 12:00 with a Seattle-Tacoma.epw weather file.

A second reference check was then calculated using the raw illuminance output from the Radiance Simulation, and the lux was manually multiplied by the corresponding channel coefficient and then converted to PPFD. After some debugging of the components and Grasshopper definition, the data coming from Specularia matched the manual validation and was within a small margin of the

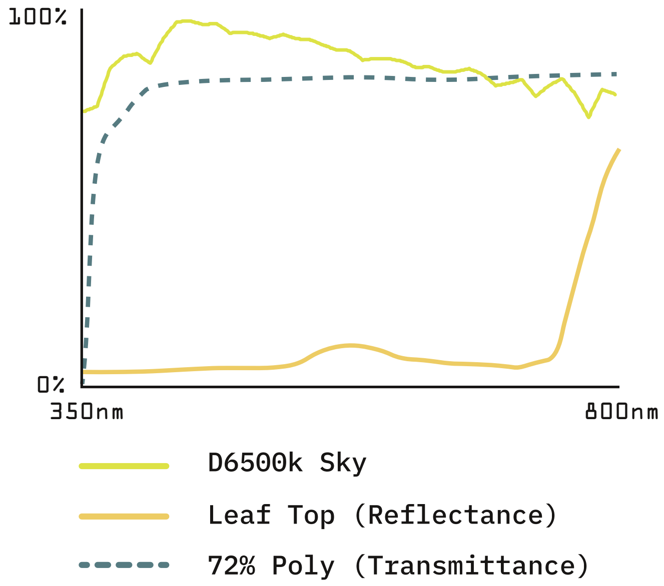


Fig. 4.4 : Spectral Profile

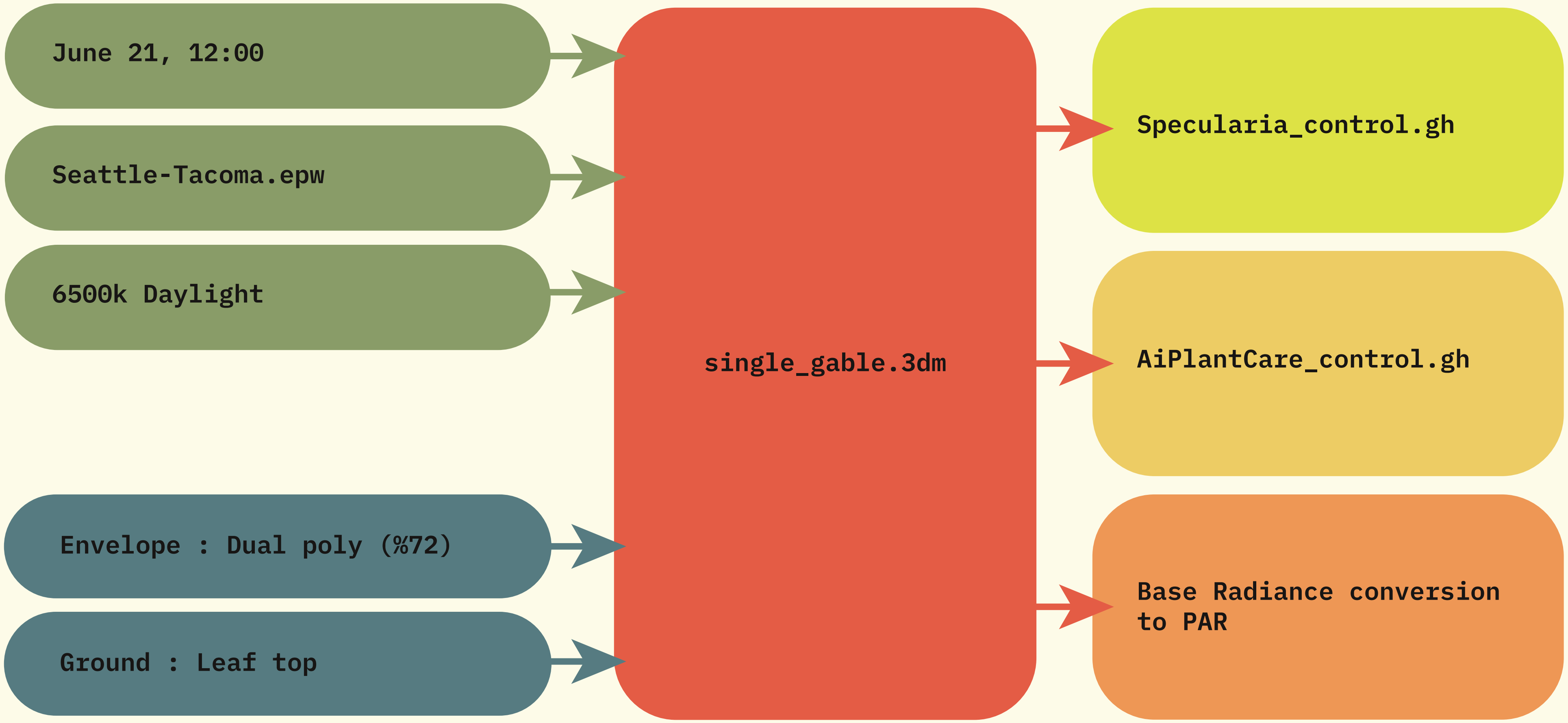


Fig. 4.5 : Model Validation

AiPlantCare data, confirming the component was working and the simulation workflow was a success.

Specularia also includes a lux output, which it passes from the Radiance file, and while this is useful for comparing human daylight metrics to plant metrics in the same component, it also proved invaluable as a quick reference check when a simulation was complete. While many designers have a general idea of what to expect for lux values when looking at simulation data or visualizations, plant metrics, especially PAR, are often not well known. The ability to read the lux in parallel with PPFD from the component output helped flag any outlying data and identify issues with testing when the models became more complex.

4.4 3-Channel Definition

Due to the number of components required to run a multispectral simulation in Grasshopper, Specularia v1.0 ships with two predefined templates that include simulation workflows already set up and annotated to aid in the process of getting started. Releasing plugins with a corresponding definition is common practice, but Lark has an exceptional series of templates that include all the necessary dependencies in a layout that is simple to follow. In addition to the core python scripts, Specularia also borrowed heavily from these starter templates, adapting them to for daylight simulation in controlled agriculture.

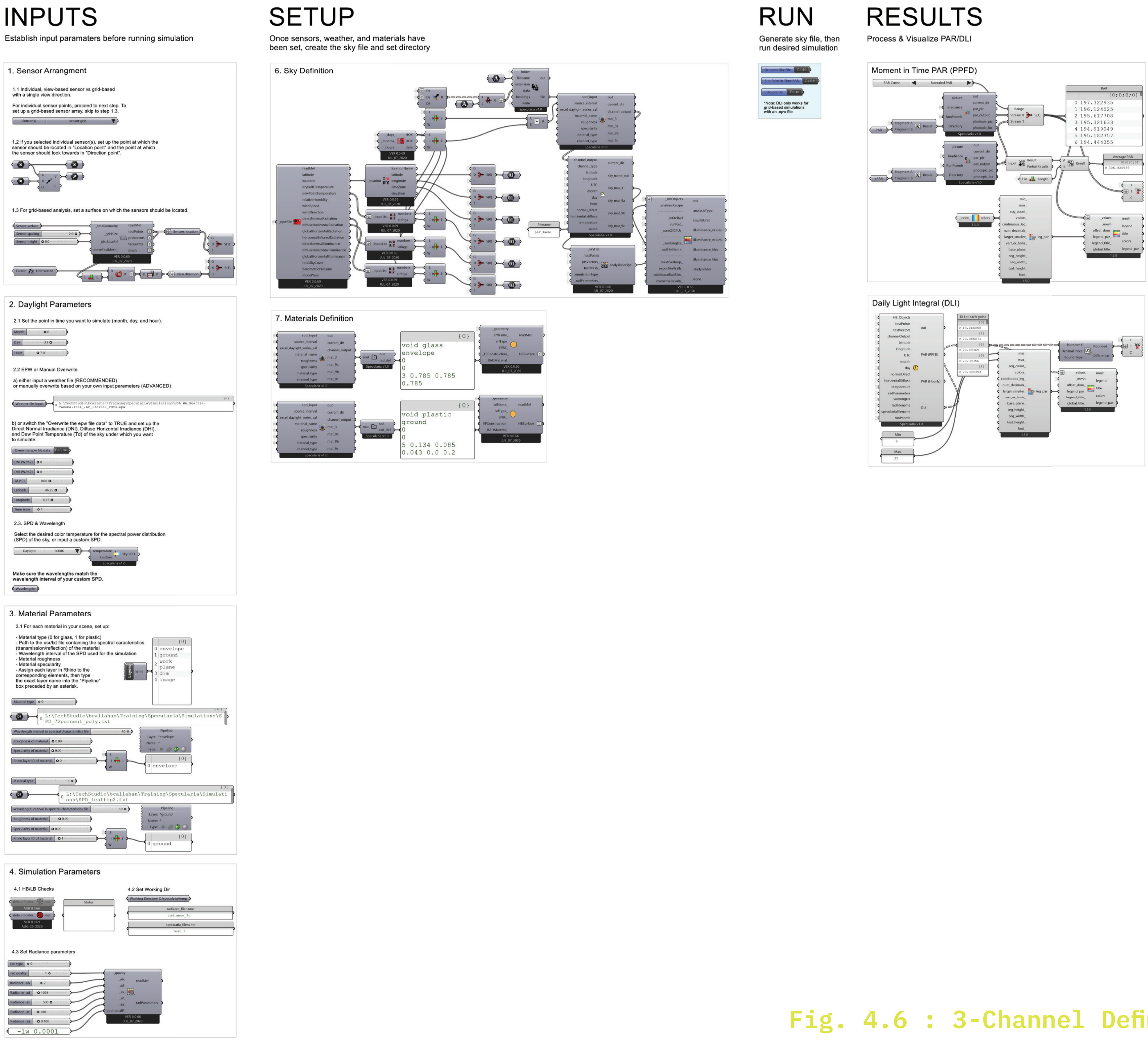
The first template is the 3-Channel PAR/DLI template, which combines the spectral materials, spectral sky, 3-channel PAR, and DLI components into a single definition along with the necessary Honeybee/Ladybug objects for running Radiance. While the 3-channel does provide the higher resolution data that the 9-channel offers, initial testing demonstrated that there was no significant variation in the PAR output between 3- and 9-channels when daylight was the only light source. Once electric lights are introduced, the more specific spectral bands offer more accurate data for tuned agricultural lighting curves.

The 3-Channel PAR/DLI template was set up to provide a general assessment of daylight available to plants in a specific space, with the option to run either a single point-in-time PAR simulation, which produces PPFD for spot checking areas of a space, or for calculating DLI, which runs a sequence of 3-channel simulations corresponding from the hours of 07:00 to 20:00 on the specified day. The results are compiled and converted to a daily light integral, which ranges from 0 to approximately 25 depending on the space, available light, location, and time of year. Just as the photopic_lux output on the PAR component provides a rapid reference correlating to the PAR range, the ability to quickly run a single PAR simulation is recommended prior to running a DLI simulation. Simulating a complex model can take time, and using the point-in-time PAR will help flag any errors before computing time is used to run a much longer DLI simulation.

Components are divided into four main sections: inputs, setup, and run, results. The required inputs are necessary for the simulation to successfully complete, while the optional input are predefined and offer the ability to fine tune the simulation parameters if needed.

Required Inputs:

- Selecting between single point or grid-based
- Setting the analysis surface
- Setting the date and time and importing .epw
- Importing SPD files and setting material properties.



INPUTS

Establish input paramaters before running simulation

1. Sensor Arrangment

1.1 Individual, view-based sensor vs grid-based with a single view direction.

For individual sensor points, proceed to next step. To set up a grid-based sensor array, skip to step 1.3.

Sensor(s): sensor grid

1.2 If you selected individual sensor(s), set up the point at which the sensor should be located in "Location point" and the point at which the sensor should look towards in "Direction point".

1.3 For grid-based analysis, set a surface on which the sensors should be located.

Sensor spacing 2.0

Sensor height 0.0

2. Daylight Parameters

2.1 Set the point in time you want to simulate (month, day, and hour).

Month 6

Day 21

Hour 7.0

2.2 EPW or Manual Overwrite

a) either input a weather file (RECOMMENDED)
or manually overwrite based on your own input parameters (ADVANCED)

```
L:\TechStudio\bcallahan\Training\Specularia\Simulations\USA_WA_Seattle-Tacoma.Intl_.AP_.727930_TMY3.epw
```

b) or switch the "Overwrite the epw file data" to TRUE and set up the Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and Dew Point Temperature (Td) of the sky under which you want to simulate.

Overwrite epw file data False

DNI (W/m2) 0

DHI (W/m2) 0

Td (°C) 0.00

Latitude 46.25

Longitude 6.13

Time zone 1

2.3. SPD & Wavelength

Select the desired color temperature for the spectral power distribution (SPD) of the sky, or input a custom SPD.

Daylight 5000K

Make sure the wavelengths match the wavelength interval of your custom SPD.

3. Material Parameters

3.1 For each material in your scene, set up:

- Material type (0 for glass, 1 for plastic)
- Path to the usr/txt file containing the spectral caracteristics (transmission/reflection) of the material
- Wavelength interval of the SPD used for the simulation
- Material roughness
- Material specularity
- Assign each layer in Rhino to the corresponding elements, then type the exact layer name into the "Pipeline" box preceded by an asterisk.

```
0 envelope
1 ground
2 work plane
3 dim
4 image
```

Material type 0

```
L:\TechStudio\bcallahan\Training\Specularia\Simulations\SPD_72percent_poly.txt
```

Wavelength interval in spectral characteristics file 10

Roughness of material 0.00

Specularity of material 0.00

Rhino layer ID of material 0

Pipeline Layer: *envelope Name: *

0 envelope

Material type 1

```
L:\TechStudio\bcallahan\Training\Specularia\Simulations\SPD_leaftop2.txt
```

Wavelength interval in spectral characteristics file 10

Roughness of material 0.20

Specularity of material 0.00

Rhino layer ID of material 1

Pipeline Layer: *ground Name: *

0 ground

4. Simulation Parameters

4.1 HB/LB Checks

4.2 Set Working Dir

Working Directory C:/specularia/temp

radiance_filename: radiance_3c

specularia_filename: test_3

4.3 Set Radiance parameters

sim type 0

rad quality 1

Radiance -ab 2

Radiance -ad 1024

Radiance -as 500

Radiance -ar 100

Radiance -aa 0.100

-lw 0.0001

SETUP

Once sensors, weather, and materials have been set, create the sky file and set directory

6. Sky Definition

filename: par_base

7. Materials Definition

```
void glass
envelope
0
0
3 0.785 0.785
0.785
```

```
void plastic
ground
0
0
5 0.134 0.085
0.043 0.0 0.2
```

RUN

Generate sky file, then run desired simulation

Generate Sky File True

Run Point in Time PAR True

Calcuate DLI True

*Note: DLI only works for grid-based simulations with an .epw file

RESULTS

Process & Visualize PAR/DLI

Moment in Time PAR (PPFD)

```
PAR
{0;0;0;0}
0 197.322935
1 196.124525
2 195.617708
3 195.321633
4 194.919049
5 195.182357
6 194.444355
```

```
Average PAR
{0;0;0;0}
0 306.020639
```

Daily Light Integral (DLI)

Fig. 4.6 : 3-Channel Definition

Optional Inputs:

- Sky Spectra and wavelength interval
- Radiance settings
- Custom location data

Once the inputs are loaded, the setup will take those inputs and generate a Radiance scene with both the building and sky. Setting Run to true will generate the sky. To run either simulation, simply set the corresponding toggle to true and wait for the results, which will automatically be passed to the final section for reading or visualization.

4.5 9-Channel PAR/Electric Lighting Definition

The 9-Channel PAR definition is setup in the same format as the 3-Channel, with four main sections: inputs, setup, run, and results. As in the previous definition, the required inputs are necessary for the simulation to successfully complete, while the optional inputs are predefined and offer the ability to fine tune the simulation parameters if needed. This allows users who may be unfamiliar with daylighting simulations to begin testing design decisions, while at the same time still affording advanced users or researchers the ability to have complete control over the simulation parameters.

Due to the amount of time it takes to run a DLI simulation in 3-channels, the decision was made to not offer a 9-channel DLI component, since it would triple the amount of time in an already lengthy process. As mentioned previously, only supplemental electric lighting benefits from 9-channel simulation. The suggested workflow if DLI is needed is to perform an initial 3-channel simulation and find the DLI of a space for a range of dates, then using them same Rhino model, open the 9-channel template and test the light output of the desired luminaries and SPD curves. The light output will be consistent, so it can be extrapolated to find how much supplemental lighting would be needed based on the DLI ranges taken from the 3-channel.

Required Inputs:

- Selecting between single point or grid-based
- Selecting the light source as either daylight, electric light, or mixed
- Setting the analysis surface
- importing an .epw file
- Setting the date and time
- Importing SPD files and setting the material properties and geometry. This includes an additional section not present in the 3-channel that is responsible for setting the layer inside Rhino containing the points for the luminaries, along places to import both the .ies and SPD files.

Optional Inputs:

- Sky Spectra and wavelength interval
- Radiance settings
- Custom location data

In order to run the simulation, set the sky to true, then set the simulation run to true.

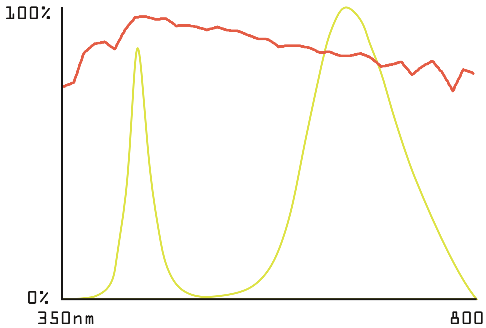
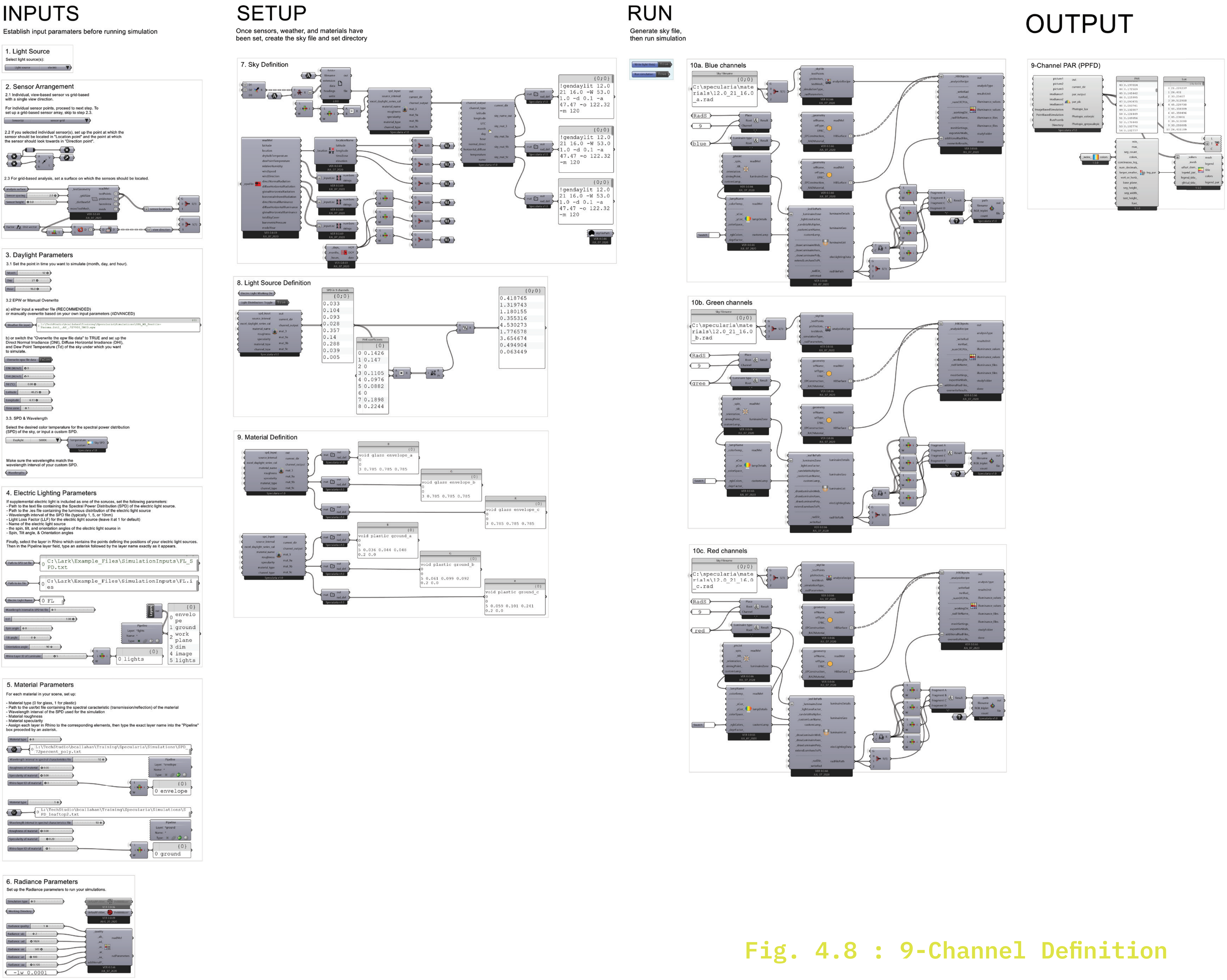


Fig. 4.7 : Electric vs Daylight SPD



INPUTS

Establish input paramaters before running simulation

1. Light Source

Select light source(s):

Light source: electric

2. Sensor Arrangement

2.1 Individual, view-based sensor vs grid-based with a single view direction.

For individual sensor points, proceed to next step. To set up a grid-based sensor array, skip to step 2.3.

Sensor(s): sensor grid

2.2 If you selected individual sensor(s), set up the point at which the sensor should be located in "Location point" and the point at which the sensor should look towards in "Direction point".

2.3 For grid-based analysis, set a surface on which the sensors should be located.

Sensor spacing: 2.0

Sensor height: 0.0

3. Daylight Parameters

3.1 Set the point in time you want to simulate (month, day, and hour).

Month: 12

Day: 21

Hour: 16.0

3.2 EPW or Manual Overwrite

a) either input a weather file (RECOMMENDED)
or manually overwrite based on your own input parameters (ADVANCED)

Weather file (epw): L:\TechStudio\bcallahan\Training\Specularia\Simulations\USA_WA_Seattle-Tacoma.Intl_.AP_.727930_TMY3.epw

b) or switch the "Overwrite the epw file data" to TRUE and set up the Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and Dew Point Temperature (Td) of the sky under which you want to simulate.

Overwrite epw file data: False

DNI (W/m2): 0

DHI (W/m2): 0

Td (°C): 0.00

Latitude: 46.25

Longitude: 6.13

Time zone: 1

3.3. SPD & Wavelength

Select the desired color temperature for the spectral power distribution (SPD) of the sky, or input a custom SPD.

Daylight: 5000K

Make sure the wavelengths match the wavelength interval of your custom SPD.

4. Electric Lighting Parameters

If supplemental electric light is included as one of the soruces, set the following parameters:
- Path to the text file containing the Spectral Power Distribution (SPD) of the electric light source.
- Path to the .ies file containing the luminous distribution of the electric light source
- Wavelength interval of the SPD file (typically 1, 5, or 10nm)
- Light Loss Factor (LLF) for the electric light source (leave it at 1 for default)
- Name of the electric light source
- the spin, tilt, and orientation angles of the electric light source in
- Spin, Tilt angle, & Orientation angles

Finally, select the layer in Rhino which contains the points defining the positions of your electric light sources. Then in the Pipeline layer field, type an asterisk followed by the layer name exactly as it appears.

Path to SPD txt file: C:\Lark\Example_Files\SimulationInputs\FL_SPD.txt

Path to ies file: C:\Lark\Example_Files\SimulationInputs\FL.ies

Electric Light Name: FL

Wavelength interval in SPD txt file: 1

LLF: 1.00

Spin angle: 0

Tilt angle: 0

Orientation angle: 90

Rhino Layer ID of Luminaire: 5

Pipeline Layer: *lights

```
{0}
0 envelope
1 ground
2 work plane
3 dim
4 image
5 lights
```

```
{0}
0 lights
```

5. Material Parameters

For each material in your scene, set up:

- Material type (0 for glass, 1 for plastic)
- Path to the usr/txt file containing the spectral caracteristic (transmission/reflection) of the material
- Wavelength interval of the SPD used for the simulation
- Material roughness
- Material specularity
- Assign each layer in Rhino to the corresponding elements, then type the exact layer name into the "Pipeline" box preceded by an asterisk.

Material type: 0

L:\TechStudio\bcallahan\Training\Specularia\Simulations\SPD_72percent_poly.txt

Wavelength interval in spectral characteristics file: 10

Roughness of material: 0.00

Specularity of material: 0.00

Rhino layer ID of material: 0

Pipeline Layer: *envelope

```
{0}
0 envelope
```

Material type: 1

L:\TechStudio\bcallahan\Training\Specularia\Simulations\SPD_leaftop2.txt

Wavelength interval in spectral characteristics file: 10

Roughness of material: 0.00

Specularity of material: 0.20

Rhino layer ID of material: 1

Pipeline Layer: *ground

```
{0}
0 ground
```

6. Radiance Parameters

Set up the Radiance parameters to run your simulations.

Simulation type: 0

Radiance quality: 1

Radiance -ab: 2

Radiance -ad: 1024

Radiance -as: 500

Radiance -ar: 100

Radiance -aa: 0.100

-lw 0.0001

SETUP

Once sensors, weather, and materials have been set, create the sky file and set directory

7. Sky Definition

```
{0;0}
!gendaylit 12.0 21 16.0 -W 53.0 1.0 -d 0.1 -a 47.47 -o 122.32 -m 120
```

```
{0;0}
!gendaylit 12.0 21 16.0 -W 53.0 1.0 -d 0.1 -a 47.47 -o 122.32 -m 120
```

```
{0;0}
!gendaylit 12.0 21 16.0 -W 53.0 1.0 -d 0.1 -a 47.47 -o 122.32 -m 120
```

8. Light Source Definition

Light Distribution: Toggle: True

```
SPD in 9 channels
{0;0}
0.033
0.104
0.093
0.028
0.357
0.14
0.288
0.039
0.005
```

```
PAR coefficients
{0}
0 0.1426
1 0.147
2 0
3 0.1105
4 0.0976
5 0.0882
6 0
7 0.1898
8 0.2244
```

```
{0;0}
0.418765
1.319743
1.180155
0.355316
4.530273
1.776578
3.654674
0.494904
0.063449
```

9. Material Definition

```
B
{0}
void glass envelope_a
0
0
3 0.785 0.785 0.785
```

```
G
{0}
void glass envelope_b
0
0
3 0.785 0.785 0.785
```

```
R
{0}
void glass envelope_c
0
0
3 0.785 0.785 0.785
```

```
B
{0}
void plastic ground_a
0
0
5 0.036 0.044 0.048
0.2 0.0
```

```
G
{0}
void plastic ground_b
0
0
5 0.061 0.099 0.092
0.2 0.0
```

```
R
{0}
void plastic ground_c
0
0
5 0.059 0.101 0.241
0.2 0.0
```

RUN

Generate sky file, then run simulation

Write light file(s): True

Run simulation: True

10a. Blue channels

Sky Filename: C:\specularia\materials\12.0_21_16.0_a.rad

RadS

9

blue

10b. Green channels

Sky Filename: C:\specularia\materials\12.0_21_16.0_b.rad

RadS

9

gree

10c. Red channels

Sky Filename: C:\specularia\materials\12.0_21_16.0_c.rad

RadS

9

red

OUTPUT

9-Channel PAR (PPFD)

```
PAR
43 0.197814
44 0.172519
45 0.145442
46 0.115995
47 0.093475
48 0.083741
49 0.102887
50 0.126449
51 0.149056
52 0.170448
53 0.182776
54 0.182777
```

```
Lux
{0;0;0}
0 21.224237
1 26.401
2 33.25607
3 39.512918
4 45.229738
5 48.350389
6 48.350496
7 45.23001
8 39.513088
9 33.255885
10 26.401189
```

Fig. 4.8 : 9-Channel Definition

V. Application

Daylight Simulations in Specularia

Chapter 5: Application

5.1 Sample Simulations

What good is a tool if you never get a opportunity to use it? While a significant amount of resources and the bulk of time devoted to this project went into the development of Specularia, it would be a missed chance to launch the tool without some appropriate testing. This chapter covers the application of Specularia, providing some baseline results, examples of how the tool might be used, and some visualizations demonstrating some typical simulation results. As with any Grasshopper plugin, the components included in v1.0 have the capacity to interface with a wide range of other plugins, and the data may be post-processed to the user's needs.

5.2 Sample Vignettes

While the ability to set reference geometry from the design workflow and assign material properties directly within the plugin interface is a main advantage of using Rhino, developing a preset geometry selection is an accessible entry point while providing baseline data for plugin testing. To accomplish this, a series of vignettes were developed based on common typologies within controlled-environment agriculture, emphasizing building-integrated types found in hybrid projects that frequently share space with human occupants. In order to test how the application of Specularia looked across a range of diverse spaces, a series of design vignettes was modeled in Rhino with the purpose of simulating the same parameters across different spaces. These design vignettes were simple closed polysurfaces, limited to a material palette of four materials (ground, wall, glazing, and 72% dual wall polycarbonate). Their intended purpose was not to accurately represent a physical space, but to show the impact of spatial orientation on daylight performance as it related to plant needs. These typologies are founded in my prior thesis, MicroAcrcologies, which examined building-integrated agriculture through an integrated theoretical framework. Each typology represents a unique approach and design strategy for incorporating plants or an agricultural element into a building design.

Single-Span (Gable) Style Greenhouse: This vignette represents a standard small-scale commercial greenhouse with a typical 24’ single-span gable roof. The footprint is 24’ x 100’ on a concrete slab, with walls 14’ high. The roof ridge line runs N-S for increased solar gain, and slope is set at 32 degrees. The gabled roof typology represents a balance between flat, low-technology roof types and curved or more complex shapes, such as the Venlo style, making it a great candidate for a baseline simulation test in a form factor that many users will find familiar.

Multi-Span Venlo Style Rooftop Greenhouse (RTG): Venlo greenhouses are common in commercial rooftop agricultural operations due to their increased span width and additional ridge line ventilation. This vignette models a 30’ span with two peaks per span, arranged in a multi-span configuration for a total footprint of 60’ x 60’ and 16’ side walls. Context buildings are included for testing overshading, and may be turned off to compare the difference in PAR when they are present versus a control simulation if the same greenhouse were on the ground in an open area.

Building-Integrated Vertical Farm: Vertical greenhouses are often found in urban areas where rooftop space is not available and there opportunity for a south-facing addition to the building that harvests sunlight along the face rather than the top surface of a building. The vertical farm vignette consists of a two-story massing with a 10’ glazed structure extending out from it. The structure is oriented so the wall faces south, and the ground plane is modeled out 10’ beyond the greenhouse enclosure. Since the facade is glazing instead of semi-transparent polycarbonate cladding, this enables lighting bouncing off the ground to reflect back into the growing space near the bottom of the structure.

Interior Atrium Growing Space: Freestanding hydroponic tower gardens are often placed in open atrium spaces that are daylit by overhead skylights, such as in an academic building, a library, or a shopping center. To test this typology, a simulation surface was set on the ground floor of a two story building. The walls and skylights were set as a standard LowE double glazing.

Results: After running a series of initial simulations on each of the four vignettes, it quickly became clear that the true benefit of Specularia was in modeling complex geometry types. With the exception of the atrium and one simulation in the rooftop greenhouse space, all the other simulations produced essentially a flat range of light. While the decision was made to avoid modeling any structural elements to conserve computing time, daylight is dynamic and as a collection of flat, transparent surfaces, the results indicate nothing more than a dip in DLI and PAR due to light loss through the envelope. The simulations all looked generally the same, so rather than continue modeling and getting the same data, a new greenhouse was modeled. This second iteration contained structural elements more detail, and as an example space better demonstrated the potential of plant daylight simulation in a built environment.

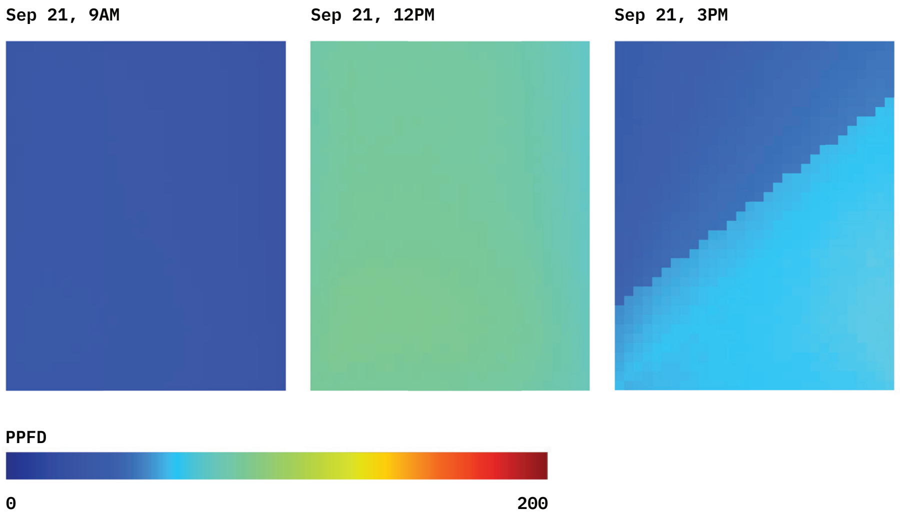


Fig. 5.1 : Initial Simulations

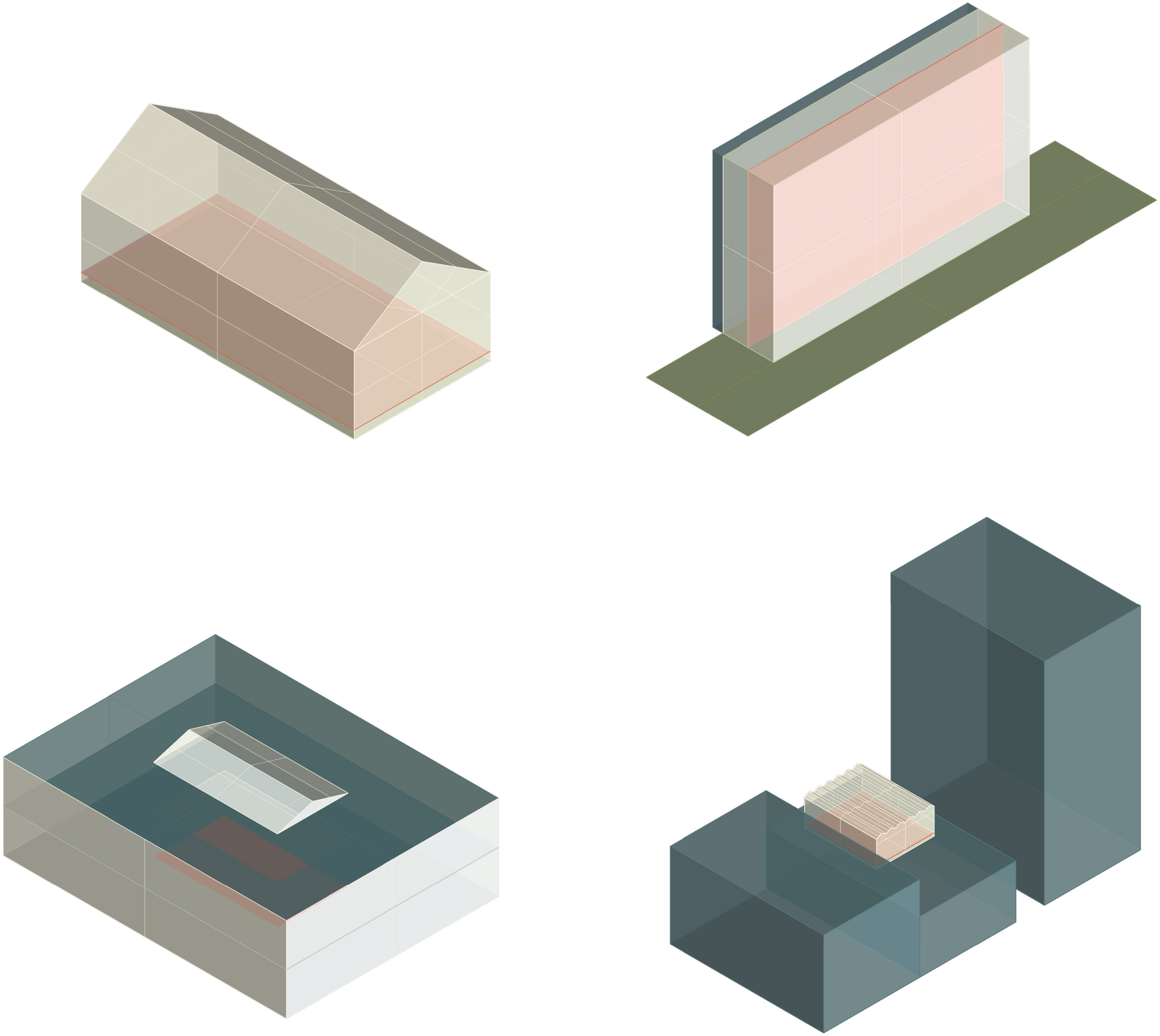


Fig. 25 : Sample Vignettes

5.3 Test Greenhouse

A second version of the single-gable greenhouse was designed for more complex daylight simulations. The building has a rectangular footprint measuring 50 feet in length and 25 feet in width. Three three gable trusses, one located at each end of the greenhouse and one in the middle, provide structural support for the envelope. The greenhouse envelope is constructed using a 72% transmissive dual-wall polycarbonate cladding, which allows a significant amount of natural light to penetrate while providing insulation and durability. The sidewalls are 14 feet high, providing ample vertical space for plant growth and cultivation. The roof has a 32-degree slope, which is a favorable angle for solar incidence as light entering the space will diffuse throughout the structure.

The spectral materials used for the simulations were limited to the same 72% dual-wall polycarbonate panel used in the previous round of simulations, a leaf top SPD curve for the interior floor of the greenhouse intended to mimic a densely planted leaf canopy. Finally, the structural columns used a standard white wall SPD to mimic painted steel frequently seen on newer integrated greenhouse structures.

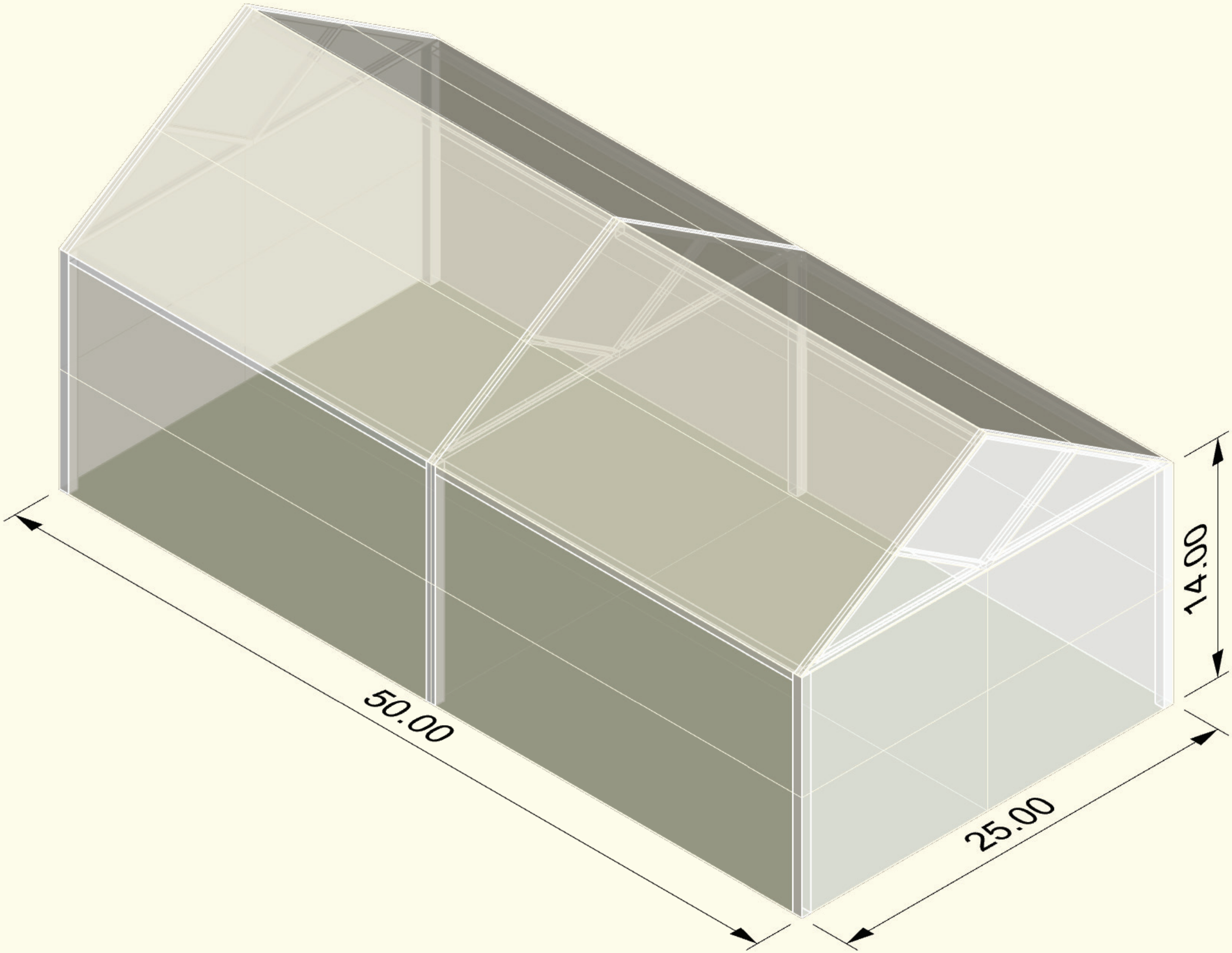


Fig. 5.3 : Single-Gable Greenhouse Model

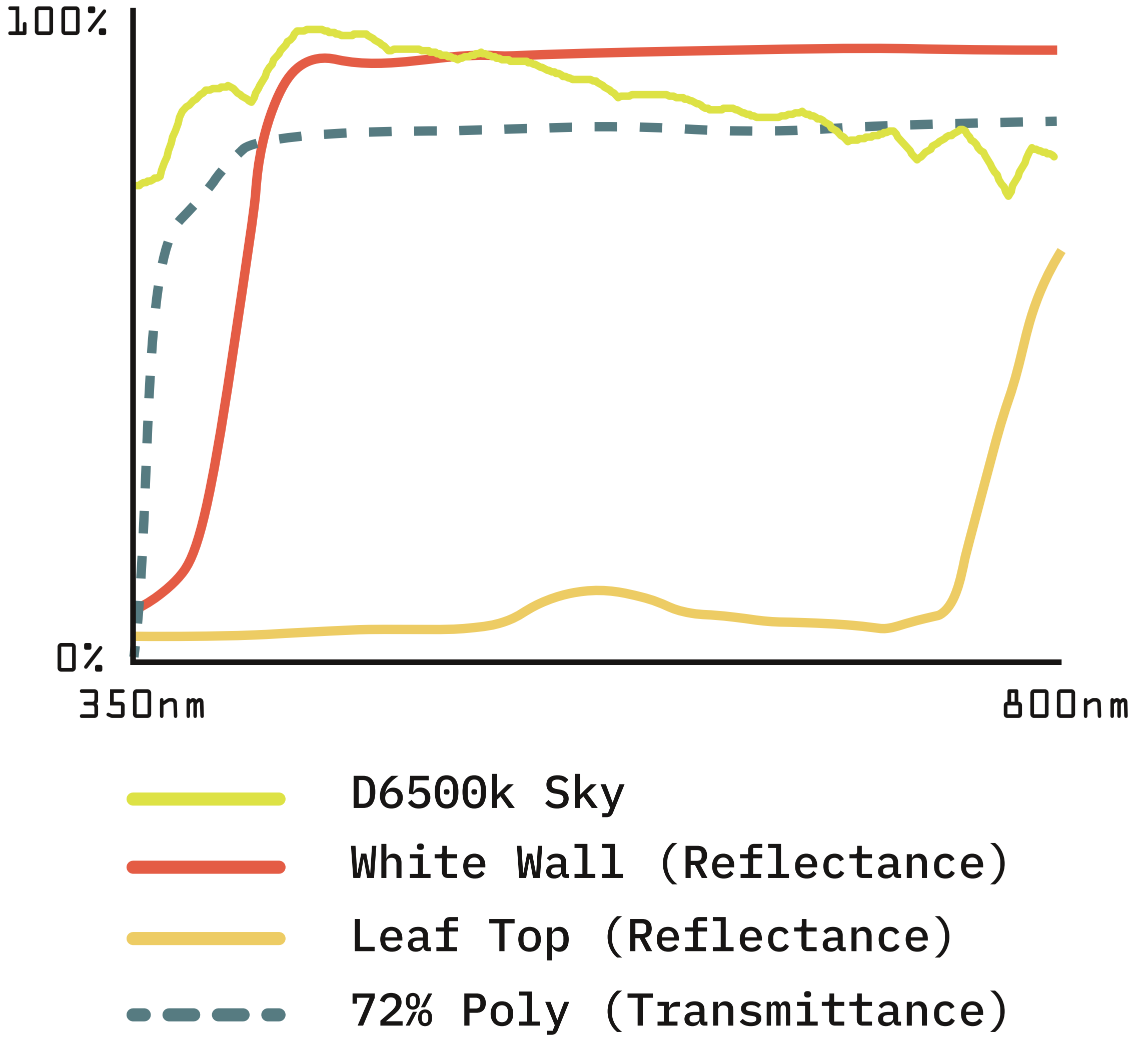
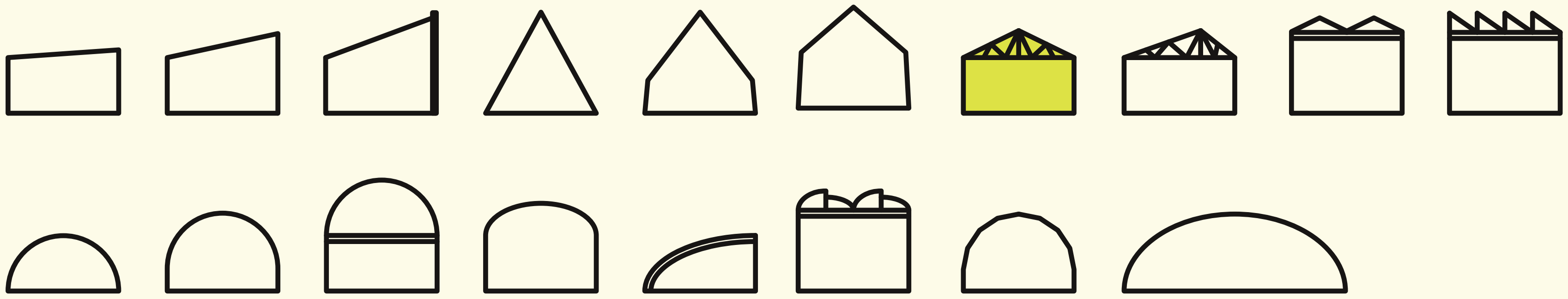


Fig. 5.4 : SPD Curves

Roof Typology

LOW-TECH / FLAT
Lower Performance

HIGH-TECH / ANGLED
Higher Performance



TOTAL FOOTPRINT : 1250sf

ROOF PITCH : 32.6 degrees

Fig. 5.5 : Roof Selection

5.4 Climate Simulations

The impact of climate on greenhouse performance can vary significantly depending on the location. In order to test the impact of climate on agricultural daylighting in a controlled environment, three different climates—Chicago, IL, Seattle, WA, and Tucson, AZ—were simulated with the test single-gable greenhouse. Twelve simulations were ran in total to find the DLI at each location across four key dates: March 21st, June 21st, September 21st, and December 21st. Given that greenhouses are complex environments that require the balance of multiple factors for sustained plant growth, while the simulations represent daylight performance, each of the climate locations would have additional performance requirements to balance.

Chicago, IL

Chicago experiences a continental climate with cold winters and hot summers. In this climate, heating during winter is a primary concern. The greenhouse will require a heating system to maintain a stable growing environment, especially during the colder months. The cost of heating can be quite high due to the extended duration of cold weather. Additionally, the greenhouse will also require cooling during the hot summers, which may include ventilation systems, shading, or evaporative cooling. Lighting may be required to supplement natural sunlight during the shorter winter days. The cost of lighting will depend on the duration and intensity required.

Seattle, WA

Seattle has a marine west coast climate characterized by mild, wet winters and cool, dry summers. The climate in Seattle is relatively moderate compared to Chicago. The greenhouse will still require heating during the winter months, although the duration and intensity of heating may be less compared to Chicago. Cooling requirements may be minimal due to the mild summers. Natural ventilation and shading techniques might be sufficient to manage the temperature. Seattle receives a fair amount of cloudy days throughout the year, which can impact the availability of natural sunlight for plant growth. Therefore, the cost of lighting to supplement sunlight may be higher than in some other locations.

Tucson, AZ

Tucson has a desert climate with extremely hot summers and mild winters. In this climate, the primary concern is cooling rather than heating. The greenhouse will require effective cooling systems to combat the intense heat, such as evaporative cooling or shade structures. Cooling costs can be significant due to the long duration of hot weather. In contrast, heating requirements may be minimal during the relatively mild winters. Tucson benefits from ample sunshine throughout the year, which reduces the need for supplemental lighting.

Overall, the cost of running a greenhouse in each of these climates can vary due to different heating, cooling, and lighting needs. Chicago will have higher heating costs, Seattle may have higher lighting costs, and Tucson will likely have higher cooling costs. The specific costs would depend on factors such as the size of the greenhouse, insulation levels, energy efficiency of the systems used, and local energy prices, demonstrating the impact a single factor such as climate can have on long term performance of a greenhouse, as well as shed some light

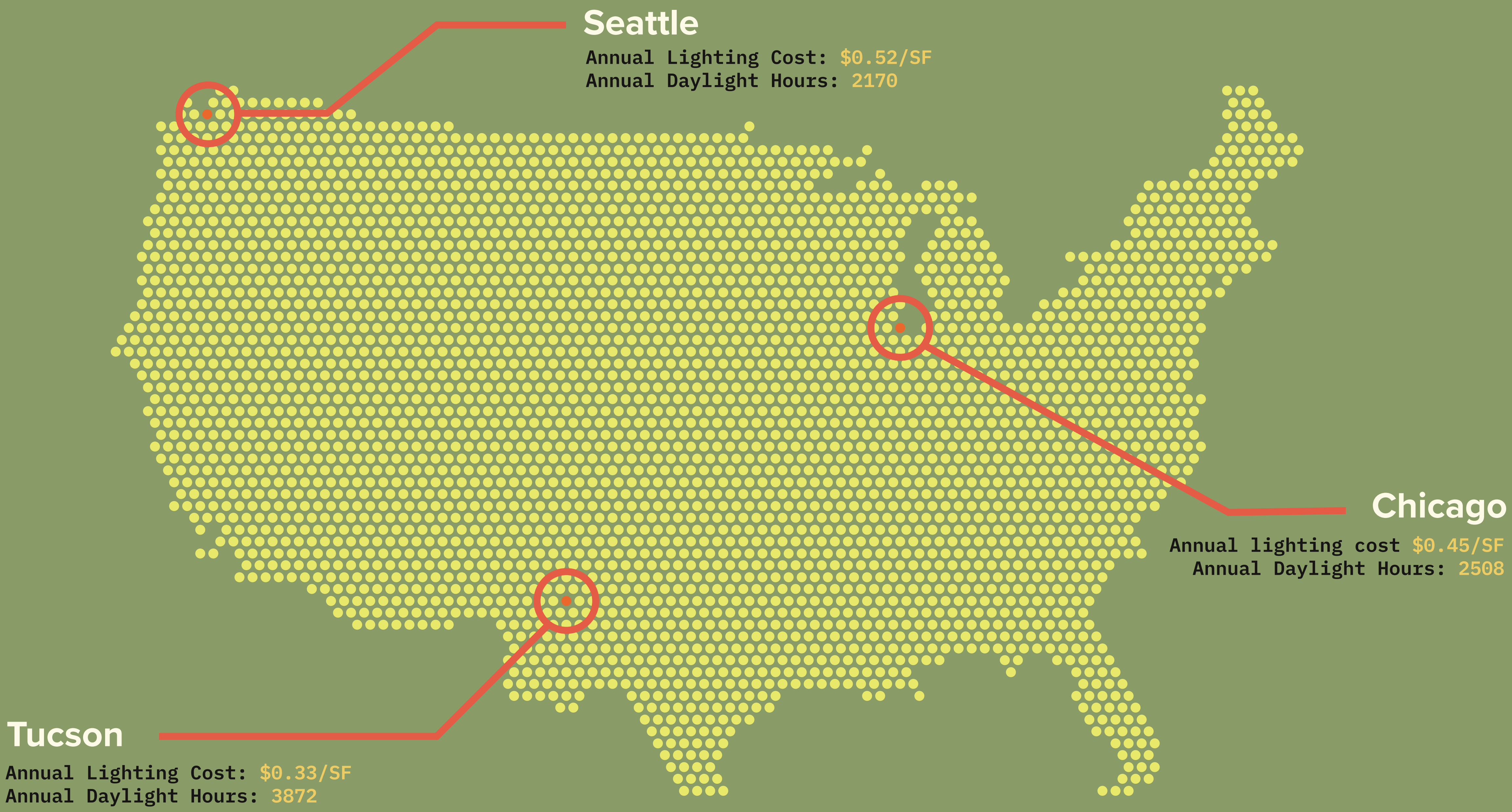


Fig. 5.6 : Climate Simulations

on potential advantages to developing symbiosis with an existing building that might offset certain costs in certain regions.

Across the solstices and equinoxes, the data was as follows (Fig 29):

Seattle: Mean = 9.55, Standard Deviation = 6.21 DLI.
Chicago: Mean = 10.75, Standard Deviation = 7.32 DLI
Tucson: Mean = 15.3, Standard Deviation = 6.01 DLI

Results show that generally, the further south the location, the higher the DLI, with winter months receiving the lowest light and the summer months, the highest. This all matches what one would expect to find in the Northern Hemisphere, and represents how diverse changing a single factor, such as the day of the year or the geographical location might have on the DLI. Since DLI is measured for every 24-hour photoperiod, it's easy to see how expensive supplemental light becomes in northern climates where year-round growing is impossible without a controlled environment. By maximizing daylighting, greenhouses can see significant savings that accumulate over the course of the building's lifespan.

5.5 Envelope Simulations

The next set of simulations compares what a change in envelope material has on lighting. The same greenhouse model was used, but in place the 72% dual-wall polycarbonate panel, a double glazed lowE glass was used as the simulation material (Fig 30).

5.6 Electric Lighting Simulation

For the final round of sample simulations, the 9-channel PAR/Electric lighting template was tested to look at daylight, electric lights, and blended sources (Fig. 31). The scene was set for September 21 at 4pm, and three simulations were run in a row to compare the impact of lighting on the low daylight values.

The process of simulating electric lighting brought up an important issue that designers looking to integrate agricultural elements into their project will undoubtedly face: while it's not difficult to find the spectral curves for horticulture lighting, the .ies files of the corresponding luminaries are rare. IES files are a common resource for lighting designers, but since horticulture lighting is not frequently used in buildings where people are the main occupants, the format is difficult to find. The IES has recently released a set of horticulture lighting standards, and with new standards and better tools,

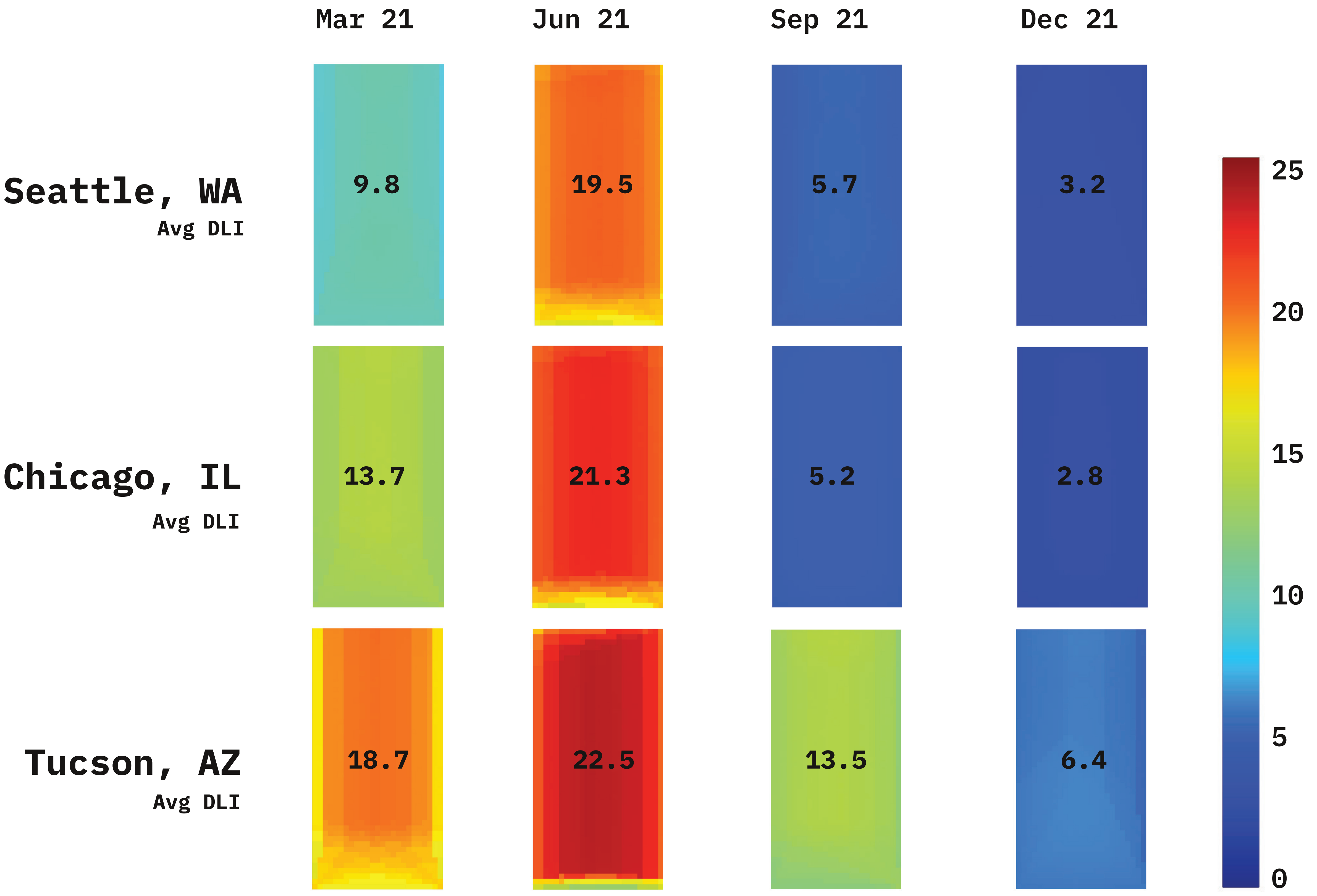


Fig. 5.7 : DLI Climate Simulations

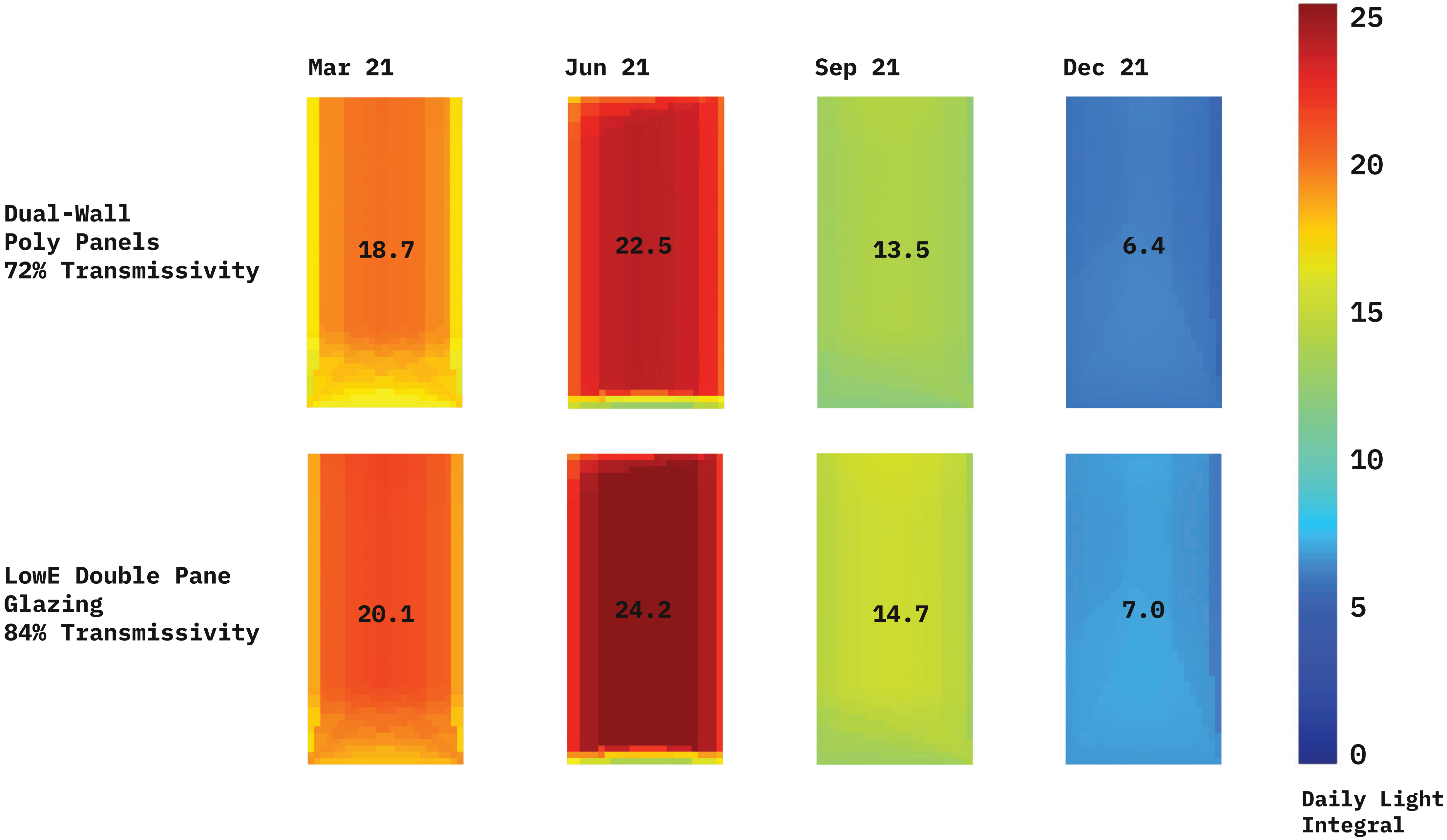
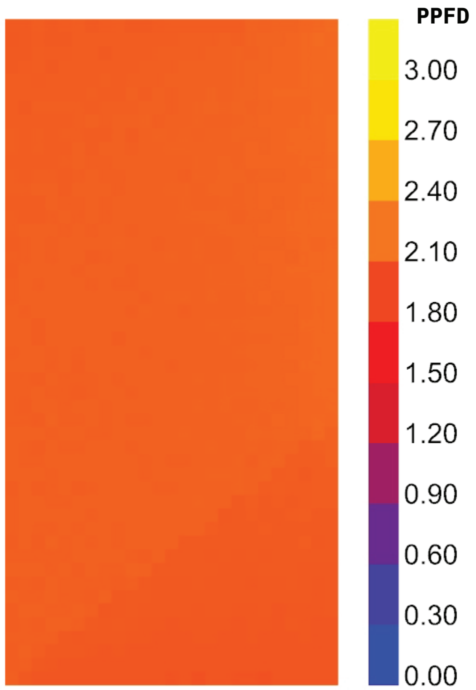
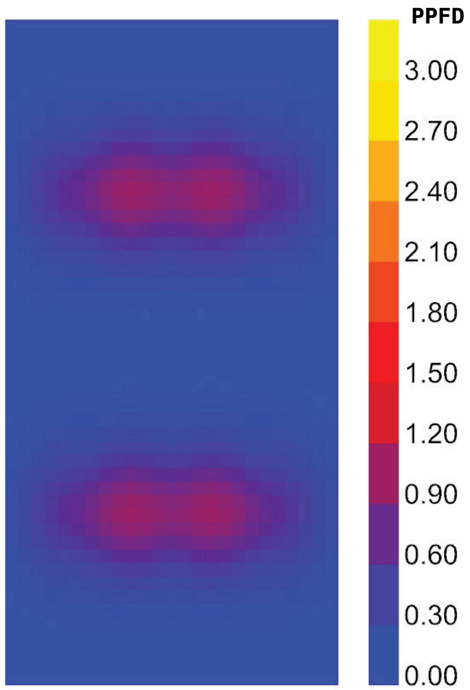


Fig. 5.8 : DLI Envelope Simulations



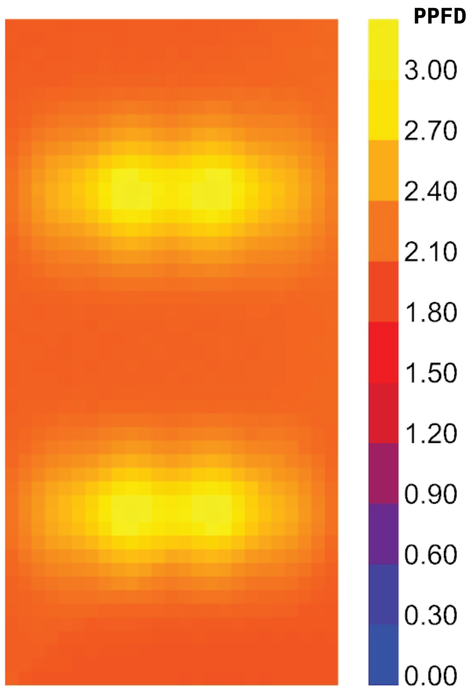
Daylight Only

Avg PPFD: 2.15 μ*mol* • *m*² • *s*



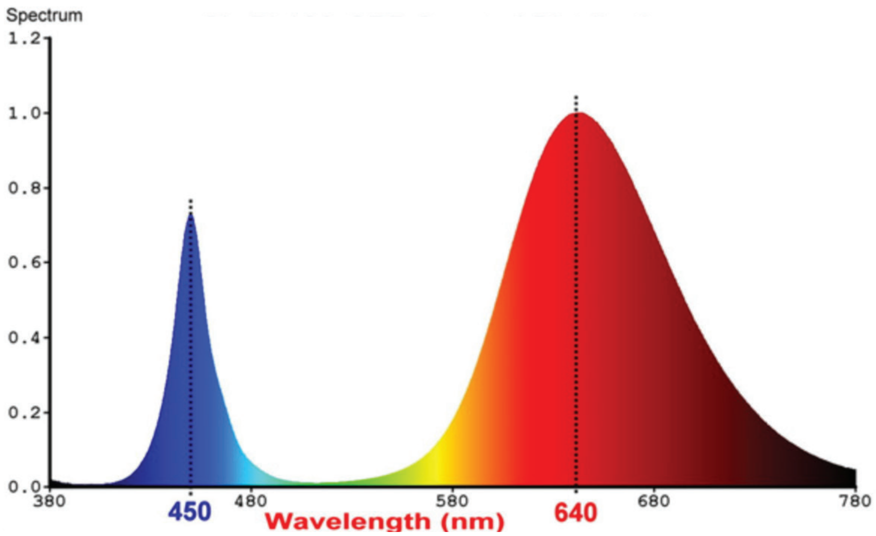
Electric Light Only

Avg PPFD: 0.35 μ*mol* • *m*² • *s*

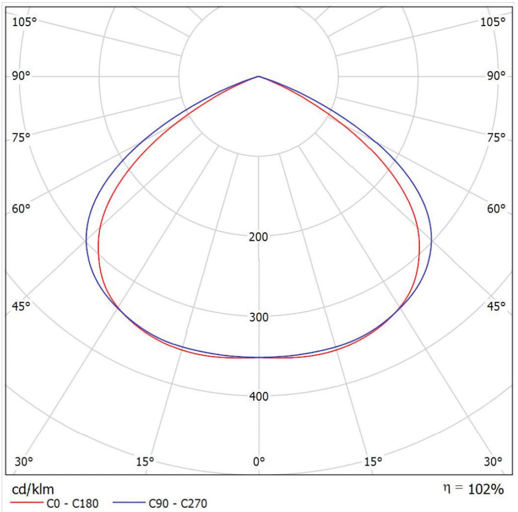


Blended Sources

Avg PPFD: 2.51 μ*mol* • *m*² • *s*



Spectral Distribution
*



***.ies file visualization**

* http://www.glaciallight.com/products/Horticulture-Lighting-GL-BL190-GRP.htm

Fig. 5.9 : Electric Lighting Simulations

VI. Discussion & Conclusions

Full Spectrum, Full Circle

Chapter 6: Discussion & Conclusions

6.1 The MicroArcology Revisited

The outcome of the simulation application on a testing model demonstrated Specularia can successfully simulate a range of lighting conditions with a variety of spectral materials, sky, and geometry inputs. However, what the testing showed most was that Specularia is best in complex, architectural simulations that don't fit the typical controlled agriculture footprint. Enter the MicroArcology (Fig. 6.2).

The MicroArcology is an applied design project developed over the course of my Master of Architecture Thesis , serving as the test bed for a theoretical design framework testing the capacity of symbiotic building integrations with agricultural elements. It also has a rooftop greenhouse, a vertical farm, and an interior living wall set inside a glass atrium, all recent integrated agricultural typologies.

The presence of these growing spaces in one building make it an excellent candidate for the sort of complex geometry Specularia should excel at simulating. After simplifying some of the geometry and developed a palette of spectral materials similar to the proposed building design, I ran a series of simulations across three dates to look at daylight performance, particularly DLI, which would provide an idea of the types of plants that could sustain growth inside the space.

One of the core strategies of the integrated greenhouse was the adoption of polyculture aeroponic towers, and Specularia turned out to be a great tool for testing that assumption. For integrated agriculture, there are certain logistical issues, especially for rooftop farms, than can create challenges for maintaining the same level of production as a ground-based, freestanding farm.

Rather than try to accommodate a more traditional monoculture operation in an urban setting, I proposed the space use smart, flexible planting strategies that thrive in a balanced environment. While the final series of simulations only takes into consideration the daylighting element, it provides a valuable entry point into making quantitative design decisions regarding integrated agriculture.

6.2 Smart Planting

Based on the simulations, the rooftop greenhouse received an average of 23 DLI in June (Fig 6.3), 15 DLI in September (Fig. 6.4), and 6 DLI in December (Fig 6.5).. While a monoculture strategy would require a significant amount of supplemental lighting to maintain a crop like tomatoes year round, a crop like lettuce, which needs 14-16 DLI for stable production, would be suitable.

Perhaps even a better strategy would be to adopt a polyculture planting plan which divides the greenhouse into zones based on DLI, and rotates crops seasonally

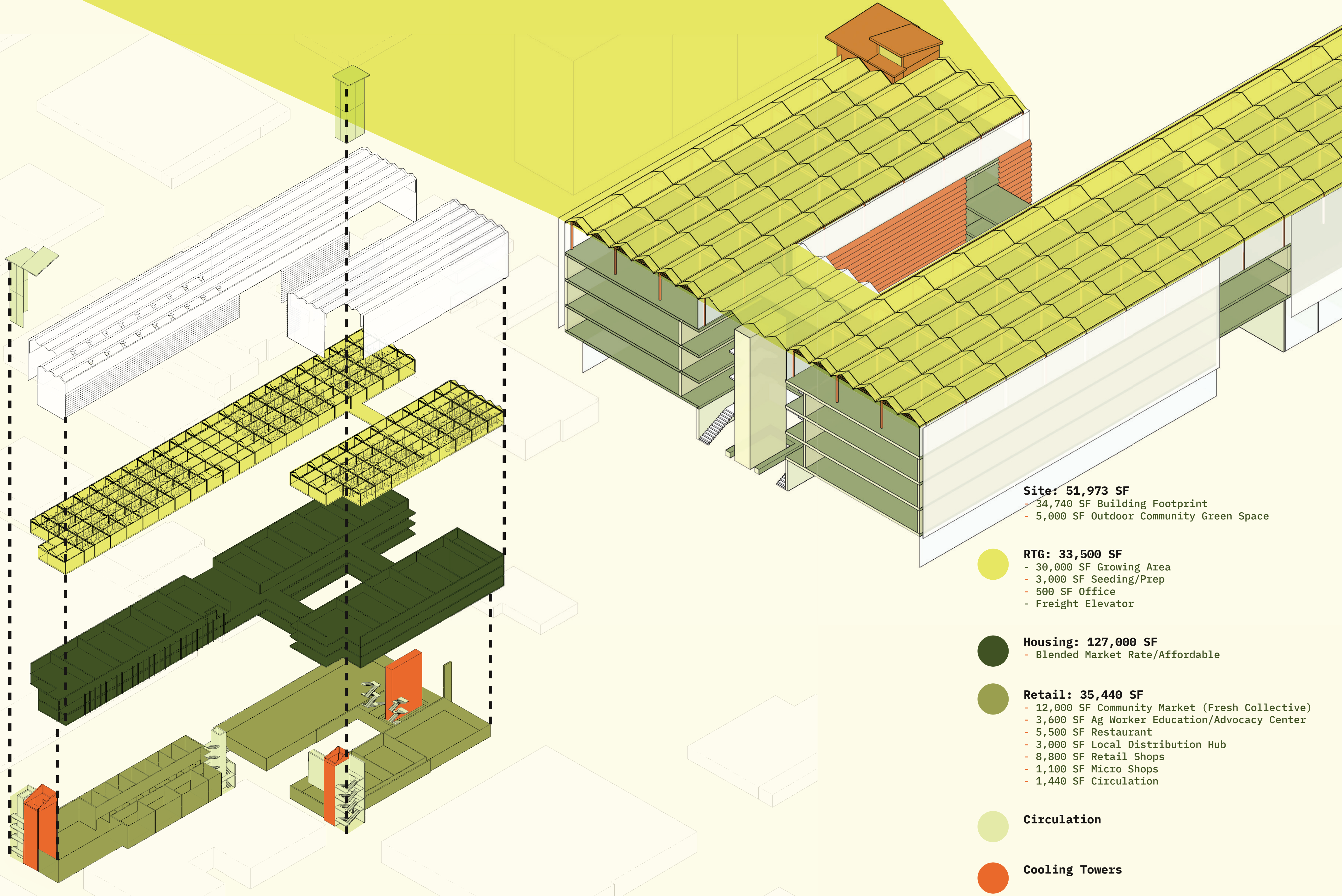
Vertical Farm

Integrated RTG

Atrium Garden

Fig. 6.1 : Building-Integrated Agriculture Typologies

Fig. 6.2 : MicroArcology Revisited



Site: 51,973 SF
- 34,740 SF Building Footprint
- 5,000 SF Outdoor Community Green Space

● **RTG: 33,500 SF**
- 30,000 SF Growing Area
- 3,000 SF Seeding/Prep
- 500 SF Office
- Freight Elevator

● **Housing: 127,000 SF**
- Blended Market Rate/Affordable

● **Retail: 35,440 SF**
- 12,000 SF Community Market (Fresh Collective)
- 3,600 SF Ag Worker Education/Advocacy Center
- 5,500 SF Restaurant
- 3,000 SF Local Distribution Hub
- 8,800 SF Retail Shops
- 1,100 SF Micro Shops
- 1,440 SF Circulation

● **Circulation**

● **Cooling Towers**

to minimize supplemental lighting costs. In a setup like this, a high DLI crop like lettuce would thrive in June into September, where a transition to a lower DLI crop such as spinach, which requires around 9, would take a lot less supplemental lighting to bring the natural light at DLI 6 up to 9, versus trying to bring a DLI of 6.

6.3 Full Spectrum Access

New research challenges the idea that plants can only utilize light in a certain range, and findings suggest plants use light a more complex manner according to wavelength and intensity than previously thought (Wu et al. 2019). The ability to model light accurately has led to additional insights around the value of DLS, which has demonstrated that with the addition of a dynamic lighting system, lighting costs may be reduced by as much as 60% when the amount of supplemental light entering a greenhouse is compared to historical solar radiation data to ensure the crop meets but does not exceed DLI (Watson et al., 2018).

Together, these concepts support a larger idea that controlled agriculture thrives when daylight is the primary source of PAR, and supplemental lighting is used as that: a supplement. With multispectral plant lighting now accessible, new best practices around controlled agriculture in the built environment may begin to emerge. As a starting point, we could expect to use the following when assessing a space for plant lighting:

Set Smart Lighting Goals: Using a simulation tool such as Specularia can offer specific data on what light is available for a given space, reinforcing the need to determine specific lighting goals based on crop requirements and selecting plants which are suited to the range of available daylight, rather than selecting the crop and supplementing with little regard for the intensity, duration, and photoperiod of light.

Determine Light Distribution: Light does not fall on a space equally, and depending on a number of factors including overhead structure, building orientation, and plant density, some areas of the growing space may receive significantly more DLI. Running a simulation of the building to determine these high and low areas can help create an accurate map of light distribution in the space, enabling more strategic use of planting locations.

Realistic Lighting Parameters: Establish the desired lighting parameters based on the crop's light requirements. This includes determining the light intensity (measured in micromoles per square meter per second, $\mu mol/m^2/s$), photoperiod (number of hours of light per day), and spectral composition (wavelengths of light).

Implement Lighting Control: Utilizing dynamic lighting control systems to regulate and automate the lighting parameters for supplemental,photoperiod, and spectral output based on pre-determined schedules or real-time sensor data. Control systems may also incorporate feedback loops to optimize lighting conditions based on plant responses and environmental factors.

Active Light Monitoring: Light sensors or spectrometers can be used to regularly measure light intensity and spectral distribution, which when paired with lighting simulations provides an accurate picture of expected versus actual performance.

Supplemental Lighting Strategies: Supplemental lighting may be simulated to help test more specific applications

June 21

Suggested Planting

Tomato

Day: 70-82 degrees F
Night: 62-64 degrees F
60-70% Relative Humidity
DLI: 23

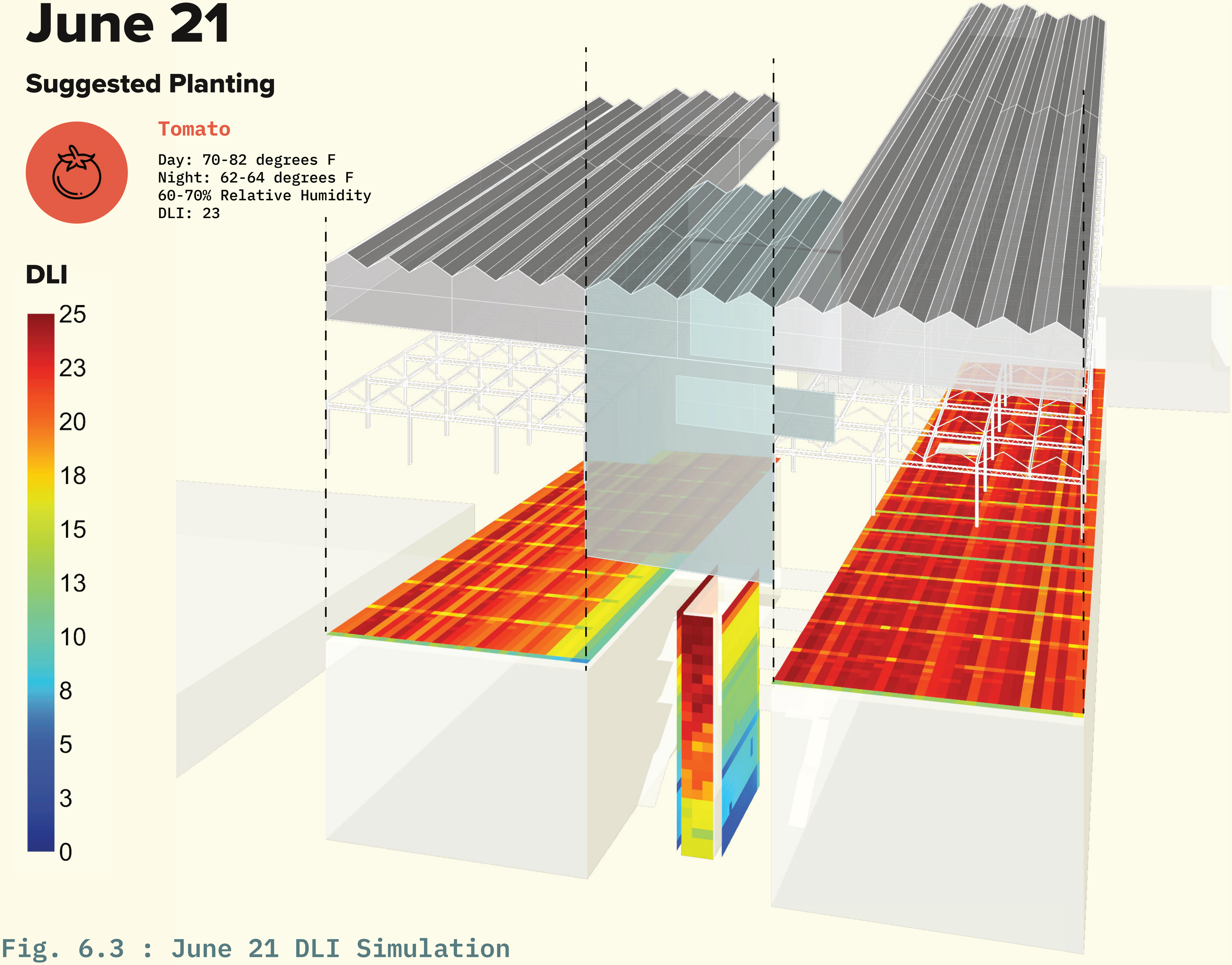


Fig. 6.3 : June 21 DLI Simulation

September 21

Suggested Planting

Romaine Lettuce

Day: 50-70 degrees F
Night: 45-55 degrees F
70-80% Relative Humidity
DLI: 14-16

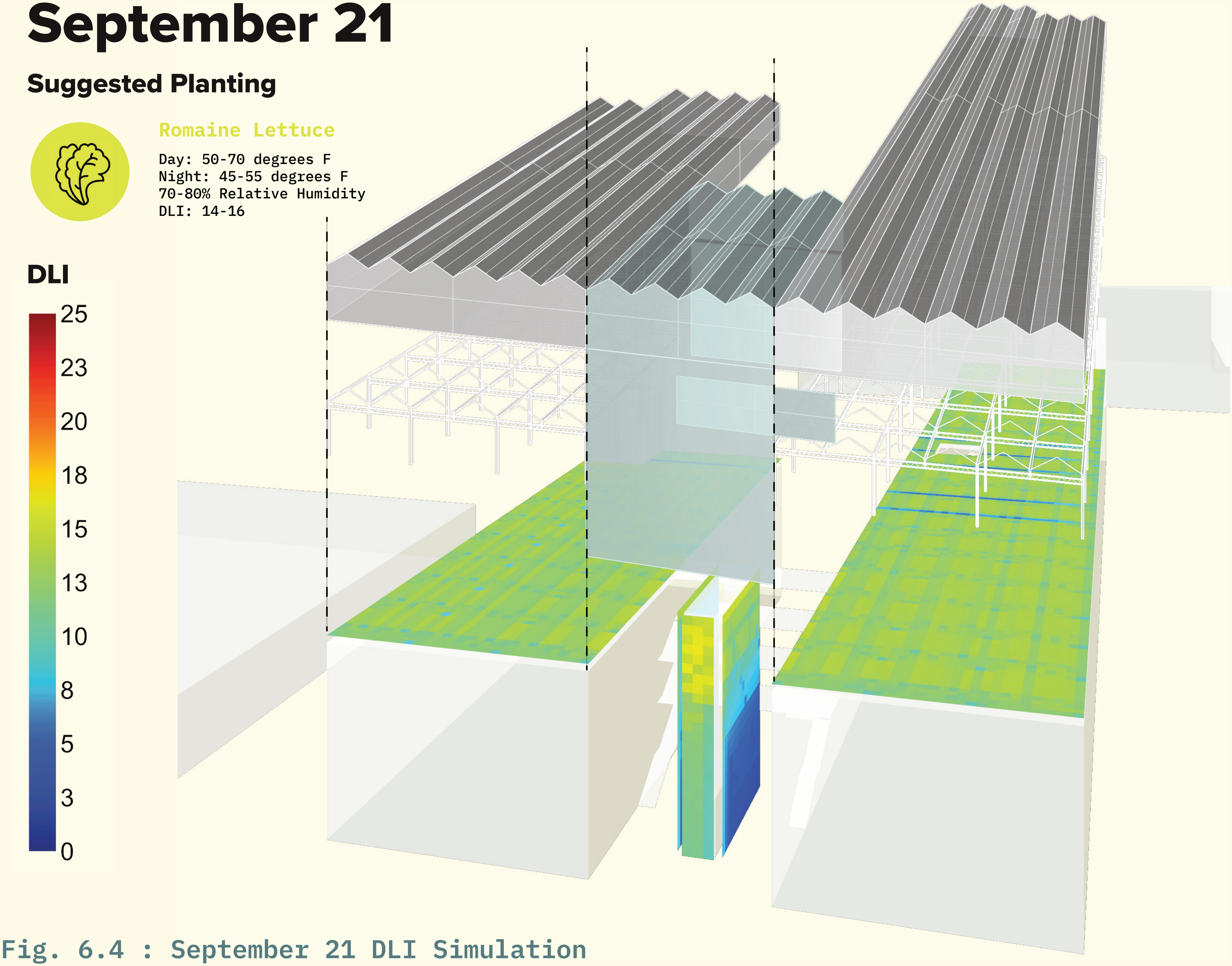


Fig. 6.4 : September 21 DLI Simulation

December 21

Suggested Planting

Spinach

Day: 50-70 degrees F
Night: 45-55 degrees F
70-80% Relative Humidity
DLI: 10-12

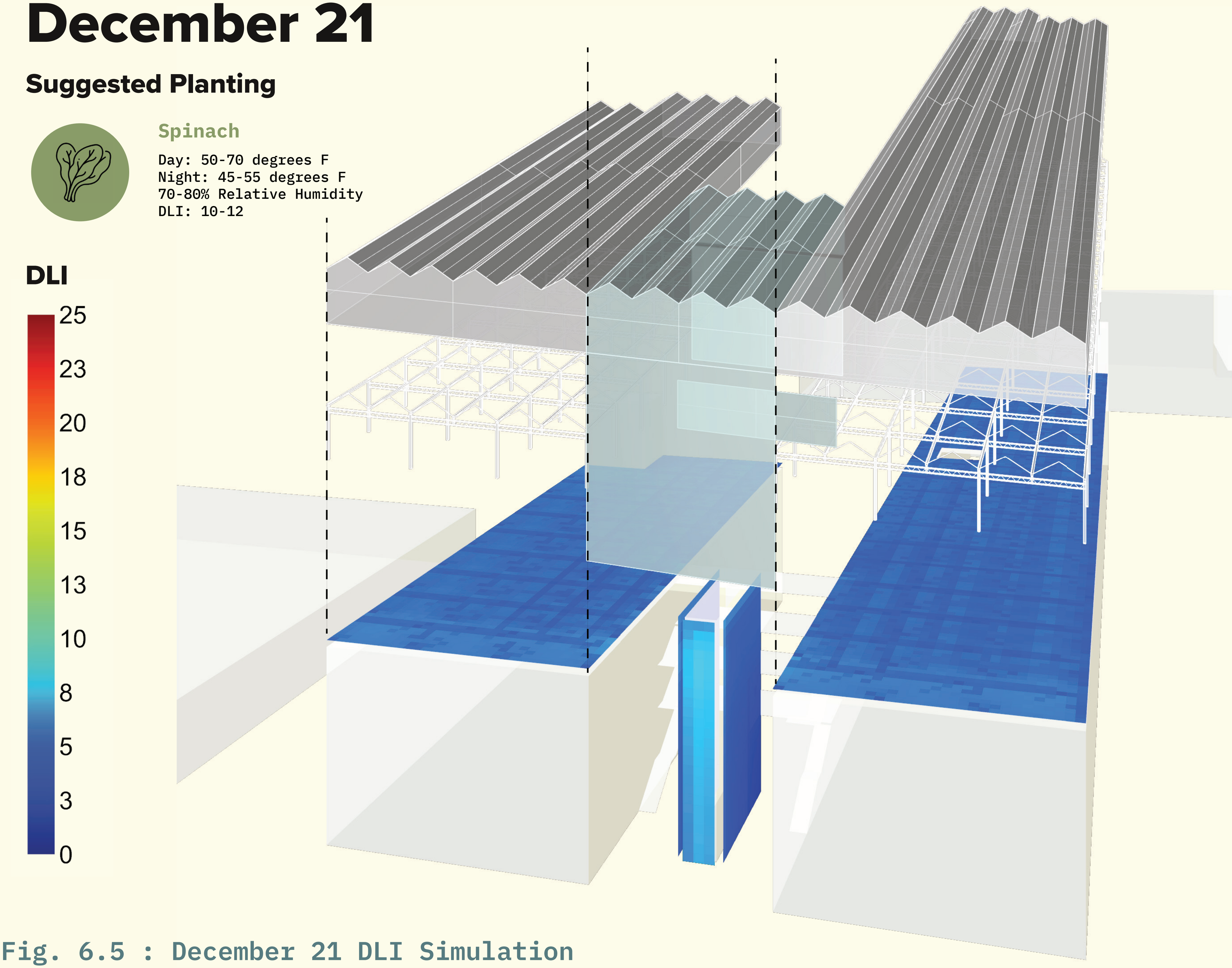


Fig. 6.5 : December 21 DLI Simulation

beyond adding more energy for PAR., Supplemental lighting could be applied more as a method of adjusting the spectra, rather than a tool for increasing global intensity, for example.

Greenhouse Evaluation: While all the simulations in this work were performed on hypothetical spaces, multispectral simulation could be paired with a physical space, and a digital twin of the building could be used in conjunction with light sensors to compare data sets and run optimization tests that create a holistic loop between real-world data and simulated results.

6.4 Conclusion

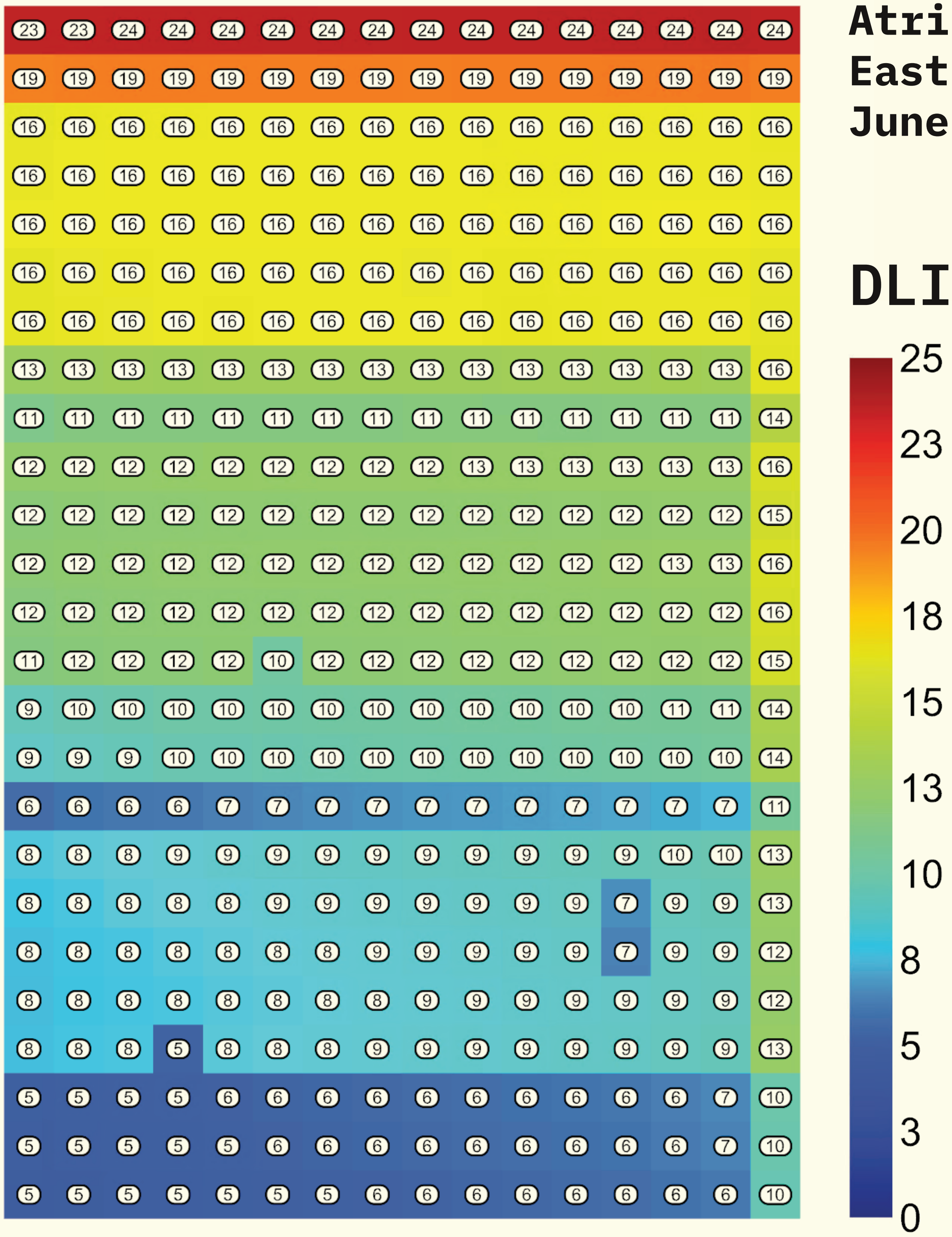
As of February, 2022, the IES published the ANSI/IES RP-45-21 Horticulture Lighting Standards, which seeks to establish consistent expectations as more and more designers explore the addition of plant lighting and daylight into new spaces. Specularia is positioned to serve as a tool for testing these new integrations, hopefully leading to more opportunities for new ways of thinking and using plants in the built environment, in spaces that are shared with people and designed to maximize the benefits of daylight.

Looking Ahead

ANSI/IES RP-45-21

> “Horticultural lighting design involves more than greenhouses and vertical farms. For architectural lighting designers, perhaps a more relevant issue is the design of lighting for building atria and living walls...
>
> This means that lighting designers will need to broaden their conversations with the architects to include daylighting design and the choice of glazing materials — plants have lighting requirements that may be at odds with those of humans occupying the space.”

Atrium Living Wall
East Face
June 21st



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5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	10

Fig. 6.6 : Complex Lighting on a Living Wall

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