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Differentiating dynamic system outcomes in CAM photosynthesis through sonification

An Honors Thesis Presented in Partial Fulfillment of

Bachelor's Degree in Environmental Engineering

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Abstract

Sonification is a powerful tool that is harnessed by modern engineers to represent information through audio, and is beginning to be used to interpret more complex data sets. Sonification can be used to facilitate the listeners' ability to grasp microscopic or complex changes in the state of a system. This study uses the assigning of sound patterns to model outputs that indicate chaotic or non-chaotic systems in Crassulacean acid metabolism photosynthesis. Using sound allows the interpretation of chaotic data without the more time intensive processes typically used, such as of Fast Fourier Transformations. Based on past research, it is known what environmental conditions result in chaos for the photosynthesis model, Photo3. The goal of the *agave* script is to enable instantaneous understanding of the chaos state of the photosynthetic system. By changing model inputs using a musical instrument digital interface controller, model inputs for light intensity, light period, and temperature, can be manipulated in real time to move between chaotic or non-chaotic regimes. Changes in the audio pattern played from norns illustrates when the model shifts between dynamic system outcomes. The results were successful in distinguishing chaotic regimes, showing all three possibilities that exist in this dynamic system: periodic, chaotic, and a stable fixed point.

Introduction

Crassulacean acid metabolism (CAM) photosynthesis is one of three photosynthetic pathways that exist in nature, and it evolved primarily in plants growing in high temperature or low water environments (Heyduk, 2022). Unlike the other two photosynthetic pathways (C3 and C4) CAM takes in CO_2 during the night rather than during the day. This allows plants using this method to close their stomata during the day, reducing water loss during evapotranspiration. Light is required for the Calvin Cycle, so CO_2 brought in during night must be stored until morning. Malic acid serves as a storage apparatus within CAM plants for this CO_2. The circadian rhythm can be modeled using a pair of coupled nonlinear differential equations. The first differential equation tracks storage of malic acid, and the second equation calculates the circadian state of the plant. In conjunction, these equations describe a circadian rhythm oscillator model formulated by Bartlett et al. (2014). An exploration into the effects of environmental forcing was then carried out for the circadian oscillator as implemented in the Photo3 model (Hartzell et al., 2018). Forcing light conditions produces chaos, making interpretation of results difficult when analyzed visually. This study will compare different temperature and light initial conditions that result in the dynamic system represented by the coupled equations to exhibit chaos, periodic, or stable fixed point behavior.

Appearing in natural environments regularly, chaotic systems have been researched for years. The definition of chaos is not universally agreed on, but all definitions agree on three elements that are key to the definition. The first is “aperiodic long-term behavior” (Strogatz, 2000). Aperiodic systems do not maintain predictable values, nor do series of values repeat during the iteration of the system, which is why they become known as chaotic systems. (Lorenz, 1962). The second requirement for a chaotic system is that it is deterministic: “so that the system has no random or noisy inputs or parameters” (Strogatz, 2000). It is key to not confuse predictability with determinism, as many chaotic systems may be predictable if the true initial conditions are known. The third requirement for the definition of chaos is a “sensitivity to initial conditions” (Strogatz, 2000). Dynamic systems are highly sensitive to the initial conditions. This means that any uncertainty of the measurement in the initial conditions prevents a deterministic solution. Sensitivity to initial conditions or variance in state conditions can then result in outcomes drastically different from those predicted. There are three possibilities that exist in a dynamic system: stationary (steady-state), periodic, or aperiodic. Stationary systems are those that iterate to a static value or maintain a constant value. Periodic systems operate in symmetric intervals after iteration. Dynamic systems should not be considered to be stochastic, as they are not truly random, demonstrated by the three aspects of chaos’ definition. Natural phenomena related to both animals and plants often show chaotic data, with research identifying chaos in more than 30 percent of a database of 172 population time series, with the most common displays of chaos being in plankton and insects

(Rogers et al., 2022). Research into CAM photosynthesis has also seen chaos appear in the circadian oscillations, under certain environmental conditions (Hartzell et al., 2015; Luttge and Beck, 1992; Leloup and Goldbeter, 1999). Study of dynamic systems has created a number of tools to understand these complex systems. Fast Fourier transformations (FFT), Poincare maps and bifurcation diagrams are few of these tools. FFT determines periodic from chaotic behavior, by mapping the frequency of oscillations in a data set. Poincare maps graph a planar sectional of a mapped three-dimensional space showing where, in the two dimensions, crossings occur. Bifurcation diagrams map minimum and maximum values of a variable against different parameter values. These tools can be opaque to those with little background in mathematics. Sonification is a possible new tool for understanding and describing these chaotic regimes, especially for a general lay audience.

Representation of information through sound is a task of varying difficulty. Variance arises from the complexity of the message. Simple notifications (text alerts, alarms) and drastic warning messages (tsunami warnings, and other sirens) have been common uses for data sonification for many years. Contrasting simple alerts, sonification of more complicated data sets can require a more complex sound. The ubiquity of sonification, or the presentation "of information by using sound, so that the user of an auditory display obtains a deeper understanding of the data or processes under investigation by listening," is today at an all-time high with the prevalent use of a plethora of chimes coming from a wide range of devices (Hermann, 2008). Despite this ubiquity, there is still a perceived disconnect between the general population's understanding of what sonification is when the word is mentioned and the concept of receiving information via sound. Other examples of sonification that exist are increasing researcher's abilities to facilitate distinction of root cell files in biology studies. The matching of cell divisions to chord scales of C major and F sharp major, was done to enhance human recognition of the position and timing of cell division (Goh et al., 2023). This power of sound, to aid in the differentiation of small changes in state, is being harnessed by a many groups to monitor a variety of environmental factors in relation to plant ecology.

Data sonification is becoming more accessible with various real time sensors such as WeatherChimes, Plantwave or MIDI Sprout. WeatherChime is an open source Arduino programmable device that can gather the following data: soil moisture, soil electrical conductivity, soil temperature, air temperature, humidity, and solar luminosity. This data is logged to a cloud database, MongoDB. That data is then pulled for sonification using the platform Max. The software allows the visualization and sonification of data to communicate the purpose of the measurements to a broad audience, allowing for the exploration of natural phenomenon through creative expression (Woo et al., 2023). One of the main priorities of many sonification experiments is making the understanding of complex environmental processes more accessible to a general audience. Plantwave and MIDI Sprout are both devices that sonify electrical data from senors placed on the leaves of a plant. Various interesting sound profiles tied to leaf conditions such as soybean nitrogen deficiencies have been created using these techniques (Kurundkar et al., 2023). These real time sensors are easily purchasable and enable sonification in a wide range of applications, but offer less parameters to sonify than model sonification. One reason to sonify a model over real time environmental data is that it allows for higher degree of manipulation by the user (Walker and Nees, 2011). The reason that the user has more power in model sonification is because all variables in a system become accessible for sound generation and interaction. There are distinct benefits to interaction with a model in real time. It allows for a deeper understanding through allowing the human brain to create similar interaction pathways intrinsic to the natural learning process. Research indicates that these interactions with auditory processes are a powerful tool in learning (Hunt and Hermann, 2004). Interactive sonification allows for understanding of experimental data in a way that more easily explains small changes in data sets that would otherwise require more abstract mathematic representations to explain. The focus of this experiment was on the conditions that cause the Photo3 model to break down into chaos using the two nonlinear dynamic equations used to describe CAM photosynthesis.

Dynamic systems have been used to create other sonification experiments. A sonification of the oscillatory behaviors of bifurcation diagrams illustrates how the complex chaos attractor Rossler equation created a period doubling bifurcation diagram for parameter a. The sonification of this diagram begins with a gradual single tone and creates descending octave (western octaves are a collection of eight notes spread between two frequencies, one of which is twice the other) tones (Kita, 2007). Other explorations into sonification are exploring complex data sets of two natural systems, a predator prey model of hares and lynx, and yeast cells cultured until the environment became toxic. Each of the systems expressed ten parameters with combinations of four sounds using Max. The researchers found that creation of default settings and explanation of sonified model still was met with varied responses to interpretation of sounds (Pfeiffer, 2001). This highlights that sonification responses are heavily perceptual due to different cultural backgrounds or musical knowledge. The highly perception based interpretations of sonification means that properly defining the audio displays and how interactions work is important. Due to the nature of how sonification is perceived, descriptions of the CAM circadian oscillator equations are laid out, along with summaries of how to interact with and control the sonification script *agave*. Sonification profiles for each of the outcomes of a dynamic system are explored to understand the different impact of varying temperature and light conditions. The utility and level of intuitiveness of interpretation of this sonification approach is explored in the discussion.

Figure 1: monome norns sound computer

Methodology

Hardware

A laptop or computer with minimum specs able to handle Windows 10 or 11 is required for running necessary software. For the sonification, the primary piece of hardware needed is the norns sound generation computer. Norns is a small, portable, open-source sound computer that dynamically runs scripts. Part of the power of norns comes from prebuilt Lua and SuperCollider (SC) programming libraries for a variety of music making scripts. These libraries enable users with less coding experience immediate access to sound production. Those with a higher level of coding experience can write their own scripts in Lua that allow the norns wrapper to access the engines written in SC (Crabtree, 2021). Operation of norns can be handled directly on the device with four encoders and three buttons, all of which are programmable. Alternatively, the use of a musical instrument digital interface (MIDI) controller allows for a higher degree of manipulation of the model. Recordings can be made without speakers, but for model interaction the norns requires an external speaker.

Software

The Norns basic coding environment is accessed through any internet browser through the IP address of the norns device, typed into the URL bar. The IP address is found on the norns through the system Wi-Fi menus. It is possible to use a variety of integrated development environments (IDEs) to code in Lua and SC. An IDE such as Visual Studio Code (VSCode) can handle all the relevant languages with the following extensions, Pylance, vscode-supercollider, norns REPL, and Lua. Recordings must be retrieved from the device through the use of a file transfer program, e.g. Cyberduck or FileZilla. For analysis of soundwaves, the program Audacity was used. To reduce file size, thirty-second clips were analyzed. Photo3 was a model created for modeling photosynthesis of different C3, C4 and CAM plants. The model parameters used in this study were the ones developed for *Agave tequiliana* a CAM plant native to Jalisco, Mexico. More plants species have been parameterized for evapotranspiration and are available in Python code on Github. The *agave* is only applicable to CAM species due to the parameters used for sound generation. The Photo3 model was converted from Python into Lua to build *agave.*

Sonification Control Equations

Photo3 is a model designed to represent the C3, C4, and CAM photosynthetic pathways. The two main equations that will be investigated here are the two linked non-linear equations describing the circadian rhythm of CAM photosynthesis. The first nonlinear differential equation of the CAM circadian rhythm oscillator is for the overall circadian state of the plant described by the order variable z and given by

$$t_r \frac{dz}{dt} = \frac{M - M_E(z, T_l)}{M_{max}}, \tag{1}$$

where t_r is the relaxation time that controls the rate of change in z. Low z values (less than 0.5) indicate malic acid is being stored. High z values (higher than 0.5) indicate that malic acid is being utilized. $M_E(z,\ T_l)$ is a nonlinear function representing the malic acid equilibrium as a function of z and leaf temperature (T_l). Leaf temperature is equal to ambient temperature in the *agave* script, which means as the temperature parameter is changed, the modeled temperature of the leaf also changes. M_{max} is the malic acid maximum.

The second nonlinear differential equation describes the rate of change in the concentration of malic acid in the cell vacuole, M, as

$$L_M \frac{dM}{dt} = A_{sv}(M, z, T_l, \psi_l, \phi) + R_{dv}(T_l, \phi) - A_{vc}(M, z, T_l, \phi), \tag{2}$$

where L_M is the ratio of malic acid storage volume to the carbon flux surface are and has units of length. Three terms represent carbon fluxes to and from the cell vacuole. A_{sv} tracks the incoming flux of carbon from the atmosphere. R_d represents the flux of carbon from the dark respiration node. This respiration accounts for the use of oxygen and the release of carbon dioxide, which allows the breakdown of carbohydrates for the release of CO_2 to the Calvin cycle (R_{dc}) or the cell vacuole (R_{dv}). A_{vc} is the carbon flux from the cell vacuole to the site of carbon assimilation. The carbon assimilation site is where CO_2 is formed into glucose (Bartlett et al., 2014). These fluxes are illustrated in Figure 2 showing the cell vacuole storing the malic acid (M) as a function of the circadian state (z) before being used for carbon assimilation A_d (Hartzell et al., 2018). The water potential of plants is represented with the variable ψ and measures of plant water stress. The variable ϕ represents the incoming solar radiation, a controllable variable within the *agave* script.

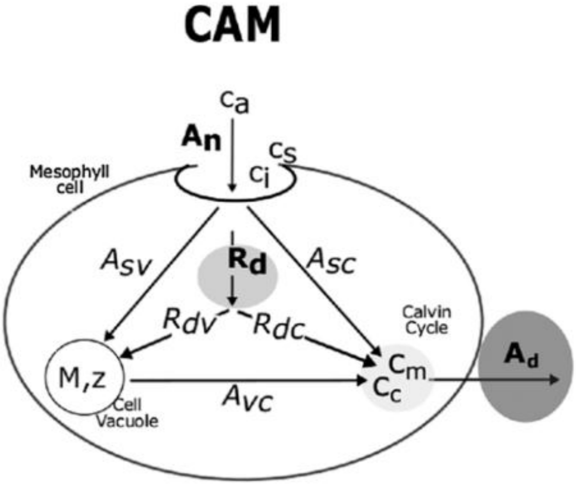

Figure 2: CAM Photosynthesis diagram (Hartzell et al., 2018)

Both of the equations of Photo3 were originally intended for irradiance forcing. So in three of six experiments, ϕ was held constant, while in the other three the value of ϕ varied according to time of day, t (hours). The equation for day/night light equation was written as

$$\phi = \begin{cases} (\frac{\phi_{max}}{36} * (-(t \bmod 24)^2 + 36 * (t \bmod 24) - 288), & \text{if } t \bmod 24 \geq 12 \\ 0, & \text{if } t \bmod 24 < 12 \end{cases} \tag{3}$$

which allows for changing the light type parameters.

norns Operation

There are separate controls within the norns menus and within the script. For operation of the norns within the main menus, key 1 is used to go between the script and the norns system menus. Key 2 is used to select options in menus. Encoder 1 moves between the script selection menu, the recording menu, and the parameters menu. The parameters menu allows each of the setup params in the code to be used in conjunction with a MIDI controller instead of the encoders on the device itself. Encoder 2 selects options on the current screen.

The *agave* script uses encoders 2-4. Encoder 2 changes what screen is being viewed (a full detail of screens is in the visualization subsection). Our script offers control of environmental inputs to the model using five temperature settings (285 K, 289 K, 293 K, 297 K, 300 K). The temperature settings are set to encoder 3. Encoder 4 controls light levels along six levels: 10, 50, 100, 150, 300, and 500 W/m^2. The main parameters of temperature control (T_l) and irradiance level (ϕ) were coded to the device encoders for the convenience. The use of a MIDI controller allows easier access to parameter of light type rather than accessing the parameters menu each time. The third parameter of light type represents two options for the modality of light in the simulation, either constant (forced) light at set energy levels or light representing a day/night cycle. Light type can only be changed in the system parameters menu or by connecting a MIDI controller and syncing the MIDI controller to the norns. Syncing MIDI to norns requires the user to navigate to the “Devices” submenu and selecting the MIDI controller after it has been plugged in. After the device is synced, the MIDI menu will allow a controller to be parameterized.

Visualization Setup

The norns has a 128x64 pixel screen which allows for a visualization portion of the model in addition to the sonification. On norns the user interface is handled with the main Lua script *agave*. The change in the malic acid over time is displayed on the first screen, and the change in the circadian state is displayed on the second screen. A third screen graphs M against z. The goal was to recreate the phase portrait of those two variables, Figure 3c of Hartzell et al. (2015). This creates an image that helps visualize the impact of changing temperatures on the circadian rhythm oscillator.

Sonification Design

Audio processing on norns is handled within SuperCollider. Synthdefs are functions within SC that generate audio based on variable inputs. Synthdefs range in purpose from sound generators, deterministic and nondeterministic, to a variety of filters. Filters are used to modify signals further after generation. The synthdefs can be played individually for simple sounds or layered together for more complex sounds. The way in which the synthdef generates sounds is unique to the code of that synthdef. Many wave types are possible within the prebuilt Ugens. An Ugen represents a calculation of signals. These signals can be for control or audio. Layered together, Ugens act as building blocks for the synthdefs and allow for manipulation of the sound engine by allowing variables from the model running in Lua to be passed to Ugen signal calculations. Many instruments have been created and are accessible through communities dedicated to sound creation on norns and other similar devices. This study takes advantage of a prebuilt engine known as theBangs (credit Ezra Buchla) which is a collection of SuperCollider scripts that has eight instruments constructed for use at download. The instrument in use for sonification experiment was one of the eight named square mod1. The rewritten model that is run by the *agave* script is continuous and generates an output for every thirty-minute time step. At each input calculation, the script appends relevant values to globally available data tables that values from which can be passed to control commands for the sound engine.

The variable that controls our sonification experiment is primarily the circadian state (z). There are two occurrences where the script utilizes the values of z. The first occurrence, z controls the pitch that gets delivered to the instrument through the Lua function malic content; this function maps the z value to a frequency range to create a base note in the sonification. The value of z oscillates between zero and one which as a frequency would be too low for human hearing, so it is exponentially mapped between the values of 40-3000. In the Lua function named circadian rhythm, z controlling two functions represents the coupling of the two base nonlinear equations. The circadian state drives processing of malic acid, high z values (higher than 0.5) indicate that malic acid is being utilized. To describe this phenomenon, it plays a second scale using a minor chord sequence starting with MIDI note 40. The minor chord was chosen as minor is societally perceived to be a "sad" sound. It is acknowledged that further learning shows this idea to be rooted in a recent modern western understanding of basic music theory (Nettl, 1983). The feeling of losing malic acid (a philosophical debate could be had about the plant being sad at this, but is beyond the scope of this paper) is the intent of the minor chord, as the malic acid decreases during use. Low z values (lower than 0.5) indicate that malic acid is being stored. Storage of malic acid in the cell vacuole (Figure 2) is represented by a major chord sequence beginning with MIDI note 120. Variable M is passed to the sound engine to control the volume. This command means that at low malic acid content, the sound level should fade to nothingness. Silence from the sonification experiment enforces that there is no production happening when malic acid isn't able to be properly utilized. These commands are all handled within the main Lua script.

There are two filters that modulate the frequency that is allowed through the sound engine that are coded into theBangs engine. The first filter is a band pass, which allows for a defined range of frequencies through cutting off anything else. The filter range used for the band pass was half the value of z. A second filter is a comb delay filter, so named for the shape created by their wave. A comb shape is made from the wave due to a delay on the sound from the filter. This delay causes destructive and constructive interference in the wave form that causes the distinctive shape of a comb. Initially, filters were implemented to practice more coding and for further experimentation.

Conditions

This experiment for the *agave* script focused on three temperature levels under constant light conditions. The irradiance level was kept at 500 W/m^2 for all six samples discussed as a control variable to focus on the effects of temperature. Changing the temperature was the main driver of qualitatively different outcomes, a dynamic system can iterate to. The first case which represented the aperiodic (chaos) result was temperature set to 285K. The second temperature setting under these light conditions was 293K because past research (Hartzell et al., 2015) showed the model to be periodic. The third was temperature setting was at 301K to represent the sonification profile of the model at a stable fixed point. Three additional runs were taken under the day/night light conditions at the same three temperatures (285k, 293K and 301K) to compare to constant light. The impacts of light level are discussed.

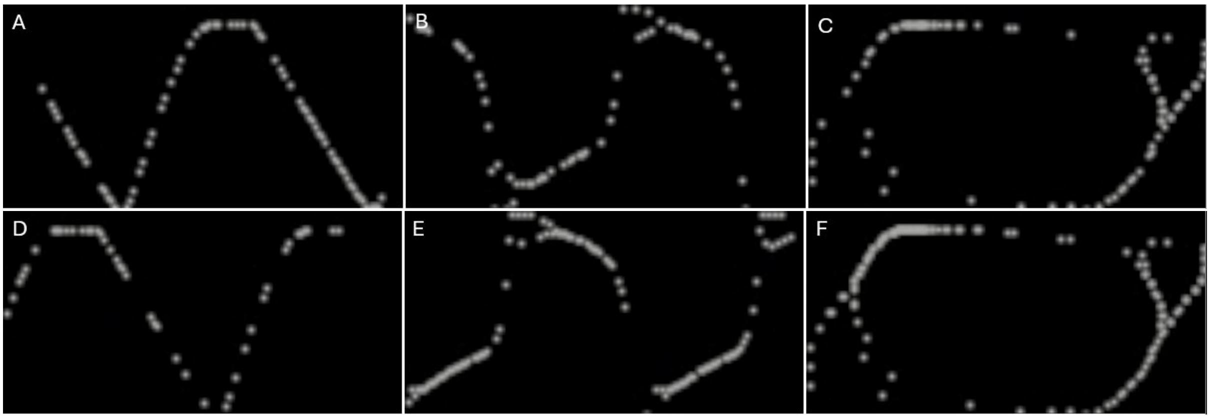

Figure 3: Visualizations for constant light (a-c) and day/night light (d-f) at temperature 285K light level was a constant or maximum of 500 W/m^2: (a, d) malic acid over time (M), (b, e) circadian state over time (z), (c, f) phase portrait of M against z.

Results

Visuals

Chaotic and non-chaotic conditions are visualized for each of the foundational equations for the circadian rhythm oscillator. The norns produces dynamic results that are not stored permanently, each image taken is a snapshot in time of the outputs. Forced light conditions at different temperatures are visualized first. Images (a-c) in Figure 3 are results at temperature 285K and 500 W/m^2 for forced light intensity. The time series for malic acid can be seen to oscillate up and down in a periodic pattern across the screen. The circadian state time series from screen two of the visualizations shows periods of rapid oscillation at the lowest and highest points before changing direction. The third screen shows the phase portrait of the M and z variables. Rapid oscillations can be seen in the phase portrait as well when the model changes direction, this is where a distinct drone happens in the sound.

At the temperature 293 the chaos in the model has disappeared from the visualizations on both the circadian state time series and the phase portrait. The model has changed from the chaotic conditions into periodic conditions. Visualized in Figure 4 both the malic acid and circadian state equations are in a regular periodic pattern. The oscillations that were characteristic of the peaks and valleys at lower temperatures are completely gone. There are also twice as many periods in the model run across the screen. The phase portrait at this temperature as discussed has ceased to display chaotic oscillations. The entire visual appears compressed horizontally and vertically. The similarity of the shapes in these runs emphasize the periodicity of these conditions.

Changing the temperature to 301K, shows the stable fixed point for both light conditions. The malic acid content level remains close to zero, and the circadian state is almost exactly at 0.5. The phase portrait in Figure 6 shows that the main change in shape as the temperature increases is that the malic

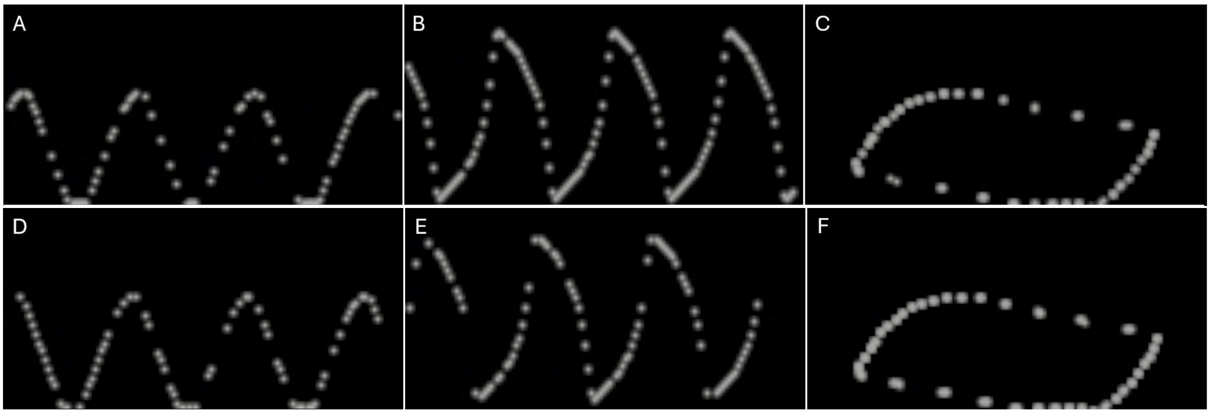

Figure 4: Visualizations for constant light (a-c) and day/night light (d-f) at temperature 293K light level was a constant or maximum of 500 W/m^2: (a, d) malic acid over time (M), (b, e) circadian state over time (z), (c, f) phase portrait of M against z.

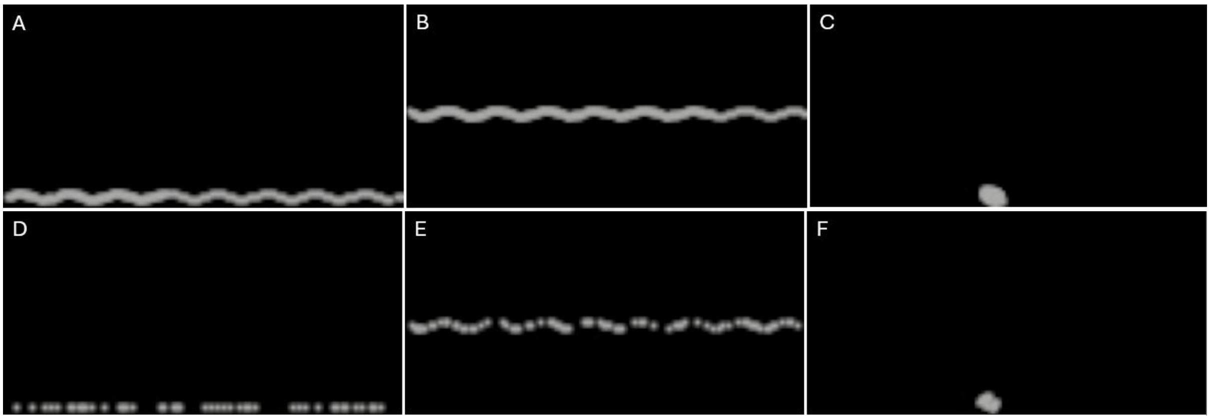

Figure 5: Visualizations for constant light (a-c) and day/night light (d-f) at temperature 301K light level was a constant or maximum of 500 W/m^2: (a, d) malic acid over time (M), (b, e) circadian state over time (z), (c, f) phase portrait of M against z.

acid vs circadian state moves towards a stable fixed point. This is the final of the three possible conditions of a dynamic system. The previous research indicates a lack of productivity at temperatures higher than 301 (Hartzell et al., 2015). Productivity near zero at 301K for both light types. It is visualized by the fixed point for phase portrait, Figure 5 (c and f). Additionally, the sound engine is controlled by the malic acid content, so the sound at these parameters is also zero.

The phase portrait of M and z for all the modeled temperatures is illustrated in Figure 6 and can show how the oscillations disappear at the temperatures above 289K. Chaotic features were only visualized at temperatures 285 K and 289 K. At 289K, the oscillation range decreases. The phase portrait of M and z from Hartzell et al. (2015) was successfully animated at each temperature setting within *agave*. When animated, the phase portrait shows the same distinct shape at each temperature level. There is a rapid oscillation at the top right and bottom left corners of the temperature line 285 which can be seen additionally in Figure 3 (c and f).

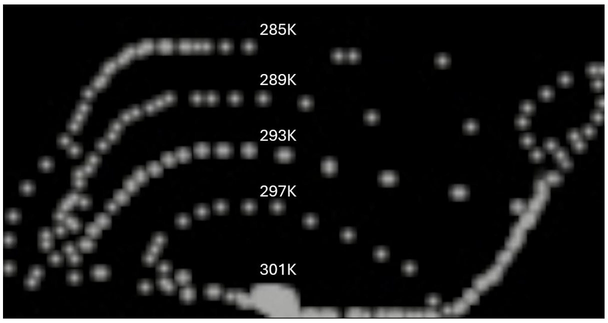

Figure 6: Phase Portrait, M and z at each of the modeled temperatures

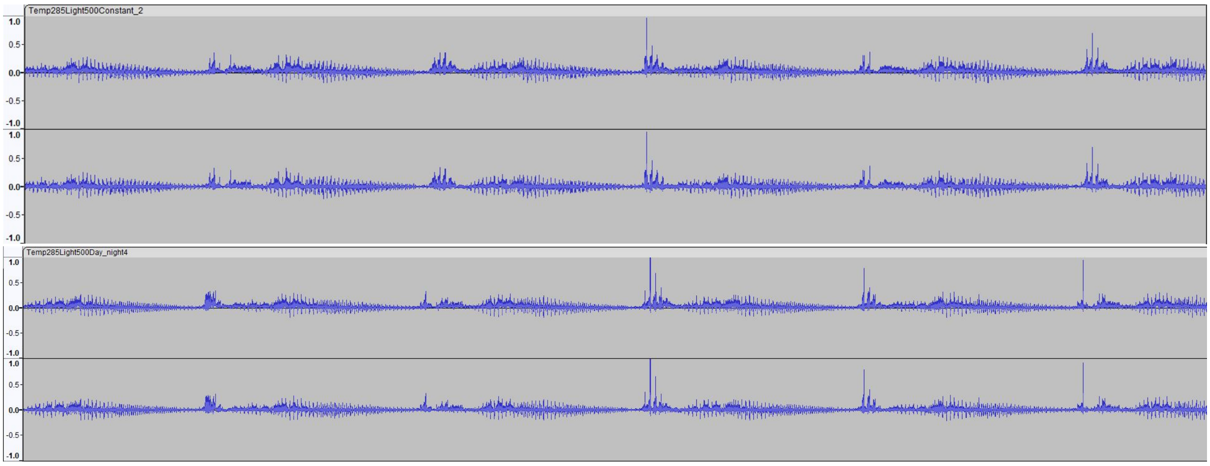

Figure 7: Soundwaves at temperature 285K forced irradiance on top and day/night light on bottom, chaos conditions

Sonification

Sonification examples are available along with the script in the acknowledgements. Images of the soundwaves generated were captured from Audacity. There were minor differences between the sounds generated by the constant light profile and the day/night light profile. The temperature 285K which produced the chaotic results produced rhythmic pulses in which lower notes are generated when the value of z reaches 1 or a note of 3000 Hz from the exponential mapping. The pulses were rarely the same but maintained similar timings in each run. The pulses were roughly twice the volume of the base notes generated. Volume between left and right audio channels is depicted on the y-axis and time of sample is along the x-axis, all samples were stopped at 30 seconds of length.

Periodic conditions sampled at 293K produced waves with a smaller range of amplitudes than model results at 285K. Comparison of both temperatures is illustrated by Figures 7 and 8. There is little difference in the size of pulses in comparing constant and day/night conditions.

The stable fixed point conditions (Figure 9) represents a total breakdown of malic acid conversion. The lack of productivity results in a sound profile of silence. These silent files were the clearest representation of no malic acid production occurring. Breakdowns in production only happen at the highest

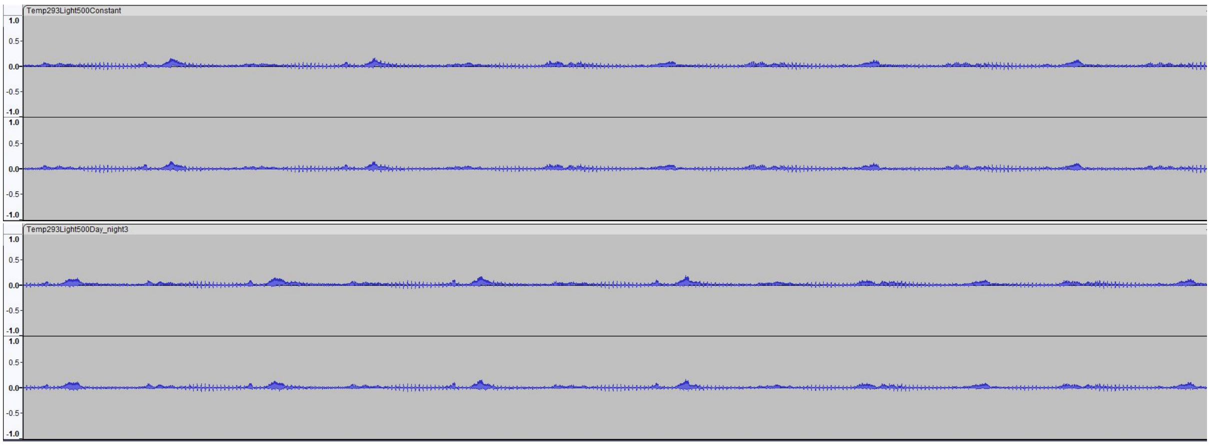

Figure 8: Soundwaves at temperature 293K forced irradiance on top and day/night light on bottom, periodic conditions

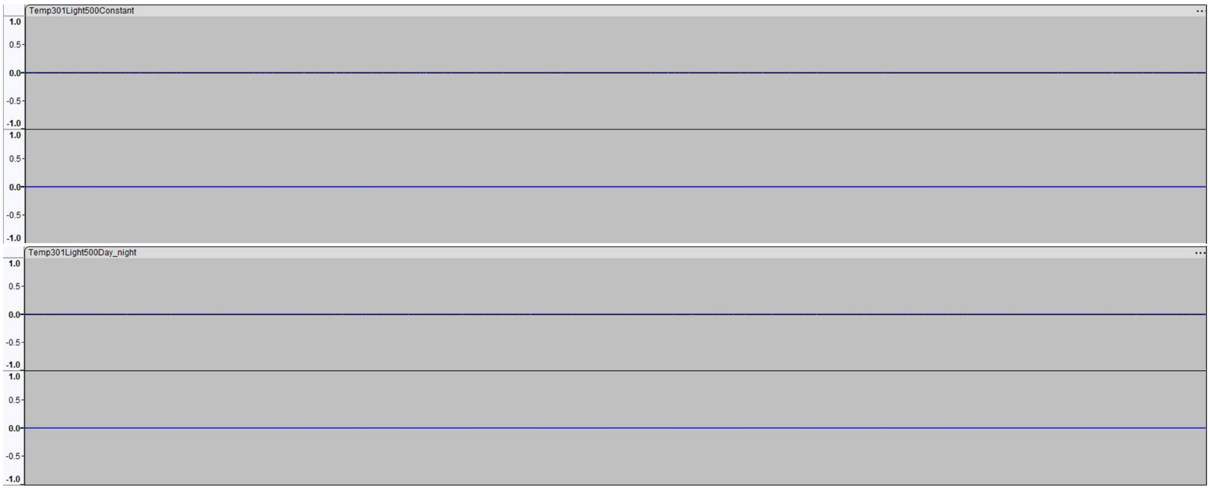

Figure 9: Soundwaves at temperature 301K forced irradiance on top and day/night light on bottom, stable fixed point

modeled temperatures.

Discussion

The *agave* script, produced a successful sonification of the CAM photosynthesis model Photo3. Differences in sound profiles at different temperatures again supports the goal; differentiation of dynamic system outcomes of the Photo3 model. The dependence of the dynamic outcomes based on temperature was an expected result. The chaotic results resulted in a more rhythmic sound than what would be expected from the visualization the Photo3 model has created in previous research (Hartzell et al., 2015). This suggests that there might be more structure to the chaotic systems present in the CAM system than initially believed. The arrangement of the sound, having these pulses that vary in tone and intensity somewhat, still provides a clear audio display for informing that indicates when the script peaks at a z value of one. The primary sound consists of constantly present warbles. The differences in sound profiles between the temperatures 283K and 301K enable a listener not versed in any of the mathematics to clearly hear the difference between both. Even though the sound at the peaks and valleys has some variance to the exact tone, pitch, and intensity, the listener can tell that the model has reached the peak and began to iterate values towards zero. The script's sound, other than the peak, is very similar when descending and ascending, which could indicate that the major and minor tones are not as clear as initially hoped. Clarity needs to be improved in future iterations, a feature echoed by other sonification experiments of complex data sets (Pfeiffer, 2001). Successful tests of the model rely on proper preface of the sonification experiment, this implies that the *agave* script is not as intuitive as hoped. The intuitiveness of the model could be improved by slowing down run time so that the minor and major chords are played longer, which could increase the natural clarity of the sonification experiment. Another possibility to improve ease of understanding could be removal of major and minor chords and creating more distinct and unique sounds to indicate the filling and emptying of the cell vacuole. This still runs into a problem of perception, as sounds can be interpreted by those of various backgrounds differently. The subjectivity of music could be a barrier to creating universally understood sonification profiles. The visual display could be made to have more effect when the sound changes, possibly some effect to show the difference in chords.

Comparison of soundwaves generated by environmental sonification devices (Kurundkar et al., 2023) are quite different from those generated by the *agave* script. The sonification of the plant's electrical signals produced wider ranges in the oscillations with less regularity than the model approach. Sonification using the electrical signals of plants does provide an opportunity that model approach does not. As it doesn't require as much background research to investigate the impacts of nitrogen deficiency or rust. Which a model approach, to accurately depict, would need to have conducted those background experiments. However, there are similarities in the experiments regardless of the variations in approach. Both experiments are not inherently musical, but do enable the investigation of the impacts of environmental changes. The electrical signals of the same kind of plants in different soils were seen to have varied responses in their sonification profile. By studying how the environmental data impacts the sound, insights can be made to the health of the plants. The fact that neither experiment produced a naturally musical sound does not mean that either one is less able to produce sounds that could be used in a variety of fields, from music to possible agricultural uses. By creating measuring devices that play sounds when the environmental conditions are best for the plants being grown. These same conclusions were found in other sonification approaches such as the WeatherChime (Woo et al., 2023) where the environmental impacts were used to play different sound sets to indicate the best conditions for optimal growth.

Distinct outcomes happened for each of the different dynamic system outcomes. This indicates that the sonification approach to differentiating chaos from periodicity or a stable fixed point was successful. The variation in the audio pattern can be heard when the lower temperatures of 285K and 289K have a distinctive spike in sound in a rhythmic (although not perfectly) fashion every five seconds. The visualization of the soundwaves (Figure 7) provided shows that the spike in sound are not the same each time, which can be interpreted as how the chaos of the peaks in the visualizations (Figure 3) manifests itself in through the audio display. Where the periodic conditions of the temperatures 293K and 297K appear to have a more random sound to the oscillations played. It does create a new question to investigate, why does variation exist in both the periodic sound levels? In assigning the stable fixed point to silence, it clearly differentiated it from the other two dynamic states. It is perhaps less of an active sonification though because it uses a lack of sound to suggest an outcome. The impact of assigning volume to the malic acid content may impact the clarity of the results, due to a decrease in volume making some changes harder to perceive and making the soundwaves visualized smaller and more difficult to interpret. By making the sound profile volume not impacted by the model and having a different quality or tone change assigned to the malic acid content, more information might be obtained through the sonification.

The sound profiles of the day/night conditions were more similar to the constant light conditions than expected. The results of each light condition shows that there is a higher dependence of the system outcomes based on changes in temperature rather than on light type. Light level was kept at 500 W/m^2 for the samples pictured here, but the impact of the light level was investigated (results not shown). The main impact of light level was the speed at which the pixels generated in the visualization. More research is required to understand why, since the light level should not impact the speed of the model.

The shutdown of productivity demonstrated by the stable fixed point at temperature 301K could be problematic in the future. Breakdowns in productivity could be problematic if true in regular day/night conditions, so more research into the impacts of temperature on productivity could be warranted. Periodic behavior around 293K has the highest levels of productivity in Hartzell et al. (2015) which could indicate temperatures similar to that could result in the highest growth yields for CAM plants. It could be interesting to compare the outcomes of previous CAM biomass production of prickly pear cactus and compare a similar three-year growth period between today and when the research was carried out in the 1990s to see if there has been a decline in productivity with increasing global temperature (Garcia and Nobel, 1992).

Conclusion

Using sonification to investigate chaotic systems is possible. It requires understanding all three possible outcomes in a dynamic system: aperiodic, periodic, and stable fixed point. The *agave* script was successful in separating all three of these clearly defined system states into sonification profiles that are determinable to listeners when they are properly briefed on what to expect. Changing how the malic acid productivity is mapped to a control variable could be interesting to see if the sound profiles that are zero could be changing at the stable fixed point. Hypothetically, it would be a set pitch at the fixed value. Sensors that help indicate how well a plant is utilizing CO_2 could increase productivity, and sonification devices that utilize current real time sensor capabilities combined with modelling could allow for sensors that calculate the growth rate of plants. Alternatively, the creation of alarms for when plants have entered non-productive states could be achieved.

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