Synchronous Tropic Growth:

A Novel Algorithm for Accurately Modeling Future Plant Growth from Photo- and Gravi-tropic Forces

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Abstract

Plants modulate growth direction and maintain environmental stability through tropisms, reactions to environmental stimuli. In aerial organs, two tropic forces, gravitropism and phototropism (gravity and light stimuli, respectively), interact simultaneously to influence the development of a responsive aerial organ. By extrapolating these quintessential factors, an accurate prediction of future growth shape may be achieved with finite inputs. Shoot development is aligned with a photogravitropic equilibrium proportional to the ratio of tropic strengths between the angle of gravitational stimuli and the light source. To account for uneven strengths, this research elucidated the relative influence strength of photo- and gravi-tropic growth responses. Using unified tropic strengths, a recursive abstract trigonometric algorithm was fabricated to model growth shape using the light source coordinates relative to the shoot tip. This model was evaluated by comparing projected growth to both original experimental data and sample data from reputable research institutions. Phototropic response was revealed to be 85.78% stronger than gravitropic response. Model validation showed universal accuracy with a standard deviation of 10.61 mm from projected growth to actual growth at any stage in development. This researched algorithm was embedded in a web-based application for widespread utilization in numerous applicable fields. This accurate, novel, and accessible modeling tool may advance agriculture by maximizing needed stimuli to promote sustainability and survivability; by reducing needed space, thereby increasing food production; and by allowing the manipulation of plant development.

I. Introduction

Plants, like all other organisms, are in constant motion in their environments. These motions, albeit much slower, are vital in maintaining survival by maximizing vital stimuli such as light, water, or even physical stability. This subtype of movement, called tropism, is oriented by the sensory of environment stimuli, followed by a proportional growth reaction.

In shoots, differential growth that catalyzes attraction or repulsion to a stimulus is caused predominantly by two tropic forces: gravitropism and phototropism (the stimuli being gravity and light, respectively). Plant shoots generally exhibit negative gravitropism, wherein aerial organs grow in the opposite direction of the pull of gravity. Additionally, shoots exhibit positive phototropism, where the growth direction is aligned in the direction of a light source. Combined, both tropisms define the shape of shoot movement by interacting with each other in the same organ at the same time.

By extrapolating these quintessential factors of shoot growth, an accurate prediction of future growth direction and growth shape can be achieved only with a finite number of inputted distances. To achieve this, it is necessary to understand the basis of tropic shoot responses, then discover their relative strengths, and finally model a recursive function that calculates the growth angle—and therefore the future shape—at any given point in time from tropic forces.

1.1 Phototropism

In foundational tropism studies by Charles and Francis Darwin, it has been discovered that, typically, the sensory of environmental light stimuli is localized at the apex of an organ. These photoreceptors contain pigments that absorb blue light (wavelength ~400–500 nm). The photoreceptors then regulate the production of the plant hormone auxin, a hormone that, when sensed by cells, catalyzes cell elongation localized on the side of the shoot absent of light stimuli. This differential growth caused shoots to curve toward light sources. However, specific properties of this process vary across species of plants, resulting in slightly different phototropic responses. This variance in response remains almost entirely unknown, so, for the clarity of this study, the model was based on the studies of Darwin, and the possible variance in accuracy across multiple species was accepted.

1.2 Gravitropism

In contrast, the sensory of gravity is localized throughout the growth zone in statoliths, organelles in special statocyte cells. Statolith organelles are denser than cytoplasm and are thus more susceptible to gravity, which pulls them to one side of the cell. The pressure formed by the accumulation of statoliths triggers the asymmetrical distribution of auxin on that side of the stem, thus causing differential growth and curving against gravity. In normal growing conditions, the growth zone of shoots is within inches of the shoot tip, and for this reason, the model was simplified to localize the sensory of gravity stimuli at the tip of the shoot.

II. Engineering Methodology

2.1 Research Objectives

The primary goal of this research is to apply a system for predicting future plant growth to an easily accessible web-based application, thus providing a revolutionary botanical tool to applicable fields. This research will develop a model of how the initial light source coordinates from the shoot apex relate to the future growth direction and shape using a combination of trigonometry, programming, and the unification of gravi- and photo-tropic forces.

Design Criteria

1. *Accurate:* The algorithm will predict a growth shape proportional to the actual future growth found in test specimens.
2. *Simple:* The algorithm requires little input from the user and models understandable results.
3. *Applicable:* Results will be accurate across multiple fields, situations, and plant species and be easily accessible for application.

2.2 Photo- and Gravi-tropic Strength Ratio Experiments

Both tropisms have different strengths of reaction; thus, in order to compute an accurate model, their relative strengths must be elucidated. It is worth clarifying that these strengths do not require a real measure; they are relative to each other and can be modeled simply by a ratio.

In these experiments, plant specimens were tilted 90 degrees so that they lay horizontally on their sides. The measurements were the vertical height from a perpendicular, horizontal line at the point where the specimen emerged from the soil to a horizontal line at the tip of the shoot.

(See Appendix A for more procedural details.)

CONTROL

Artificial violet LEDs were located directly parallel to the estimated point of shoot emergence both above and below each horizontally growing specimen. The direction of growth will elucidate the relative influence strength of gravitropism on plant species growth response, as both light sources cancel out to leave only the pure stimulus of gravity and therefore the force of gravitropism.

PHOTO1

Identical artificial violet LEDs were located directly parallel to the estimated point of shoot emergence, directly above each horizontally growing specimen. These data model the combined reaction of both gravitropism and phototropism. Data found in Control will be subtracted from the data to find the individualized relative influence strength of phototropism on plant species growth responses.

Identical artificial violet LEDs were located directly parallel to the estimated point of shoot emergence directly below each horizontally growing specimen.

This model causes gravitropism and phototropism to contradict each other, and therefore, when calculated with Control Group data, the direction of growth reveals the individualized relative influence strength of phototropism on plant species growth response. This was used in conjunction with Photo1 to verify the strength of the phototropic response.

Control data will reveal the gravitropic response strength, while data from Photo1 and Photo2 will be used in conjunction with Control data to measure individualized phototropic responses. Data across groups will only be aligned with that of the same species. Comparing the final value of phototropic response to gravitropic response will give the relative ratio of tropic strength for that species. Finally, the average of these ratios will give an accurate general ratio of tropic strength across multiple species.

2.3 Computational Modeling

Using the inputted coordinates of the light source relative to the shoot tip, an abstract trigonometric visualization may be fabricated to elucidate the recursive algorithm needed to model future growth shape.

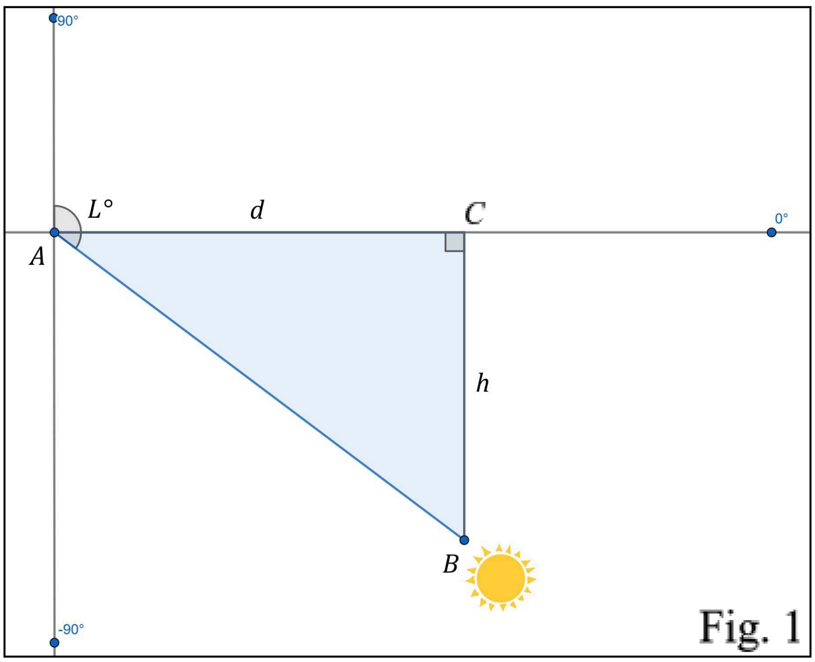


Fig. 1 shows the initial conditions that may be found, where A is the tip of the shoot, B is the light source, d is the x-coordinate of B, h is the y-coordinate of B, and L is the angle from the sensory of gravity stimuli (90°) to $\angle BAC$. (Clarification: h may be negative if the y-coordinate of B is negative, as in Fig. 1)

$$L = 90° - \tan^{-1}\left(\frac{h}{d}\right)$$

Equation 1

Equation 1 shows how L may be calculated with the inputted d and h.

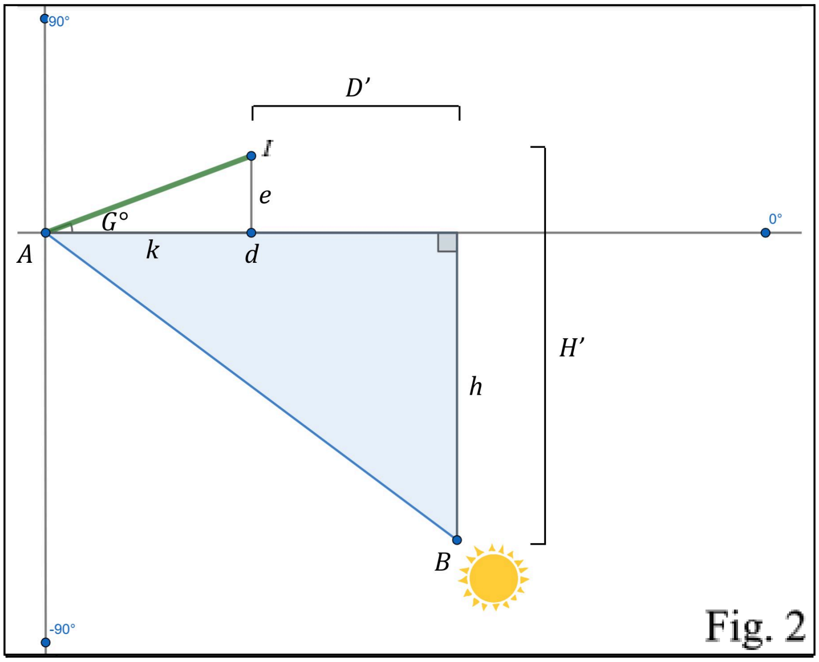


Fig. 2

Fig. 2 shows the new distance and height from the tip of the shoot after 1 unit of growth to the light source, where *G* is the angle of photogravitropic equilibrium growth, *I* is the shoot tip after 1 unit of growth, Δ*AFI* is the right triangle created by an angle *G* and a hypotenuse of 1 unit, *k* is the horizontal leg of Δ*AFI*, *e* is the vertical leg of Δ*AFI*, *D'* is the horizontal distance from the *I* to the x-coordinate of *B*, and *H'* is the vertical height from the y-coordinate of *I* to *B*.

$$G = [(T)(L)] - \tan^{-1}\left(\frac{h}{d}\right)$$

Equation 2

Equation 2 calculates G, the angle of photogravitropic equilibrium growth, where T is $\frac{gravi.\ strength}{gravi.\ strength + photo.\ strength}$.

$$k = \cos(G)$$
$$D' = d - k$$

Equation 3

Equation 3 calculates D’, the horizontal distance to the x-coordinate of the light source relative to the new shoot tip after 1 unit of growth.

$$e = \sin(G)$$
$$H' = h - e$$

Equation 4

Equation 4 calculates H’, the vertical height to the light source relative to the y-coordinate of the new shoot tip after 1 unit of growth.

Figures 1-2 and Equations 1-4 intake the initial coordinates of the light source relative to the initial shoot tip to calculate the coordinates of the light source relative to the new tip of the shoot after 1 unit of growth. These steps repeat, with each iteration intaking *d* and *h* and outputting *D’* and *H’*, with *D’* and *H’* becoming *d* and *h* in the next iteration, respectively. The resulting graph is several infinitely small linear segments connecting, with the angle changing slightly each iteration. This models a curve, which is the estimated future growth shape of a specimen, based on the location of a light source.

2.4 Model Validation Experiments

The fabricated abstract trigonometric growth model was evaluated by comparing projected growth to both original experimental data and sample data from reputable research institutions and databases.

Experimental Comparison Setup

Given set light positions (as outlined below), plant growth data was gathered and photographed for comparison to modeled growth.
Replications:

E1: Dill seedlings. Initial light location: d = 10 cm; h = 17 cm
E2: Dill seedlings. Initial light location: d = 10 cm; h = -17 cm
E3: Cilantro seedlings. Initial light location: d = 10 cm; h = -17 cm

External conditions were identical to Tropic Strength experiments.

Sample Data Comparison Methodology

Numerous data from reputable research institutions of actual plant growth were compared to the growth modeled by the algorithm. Primary database utilized: [Plants In Motion (Roger P. Hangarter and Indiana University)](). Plants in Motion contained invaluable time-lapse pictures of controlled tropic growth.
Replications:

D1: Corn seedlings. Initial light location: d = 6 cm; h = 1.5 cm. Prior growth: 2 cm
D2: Corn seedlings. Initial light location: d = 7 cm; h = 4 cm. Prior growth: 4 cm
D3: Sunflower seedlings. Initial light location: d = 10 cm; h = 8 cm. Prior growth: 0 cm

Graphs of actual growth modeled from both Experimental and Sample Data were compared to graphs of projected growth in identical conditions modeled from the abstract trigonometric algorithm. Actual growth data graphs were overlapped with their corresponding projected growth graphs, and an absolute deviation was found at each point in growth. Averages were found per specimen and for the entire dataset.

III. Results

3.1 Photo- and Gravi-tropic Strength Ratio Experiments

Over 38 days, data was found and calculated. Fig. 3 shows the average tropic strength ratio of all specimens each measurement date.

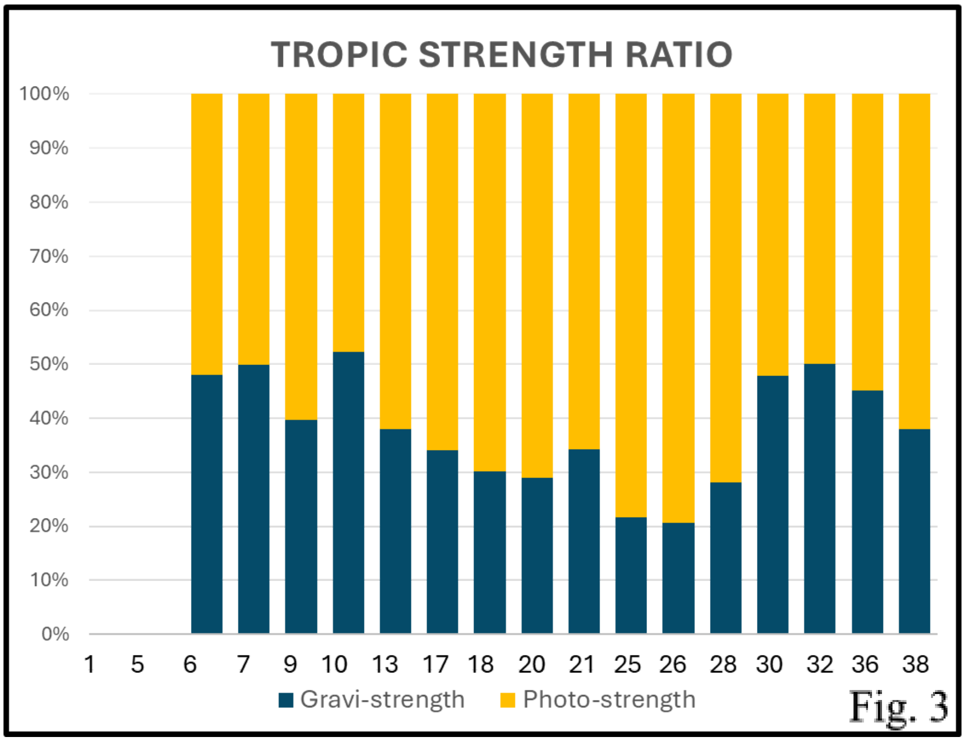


Fig. 3

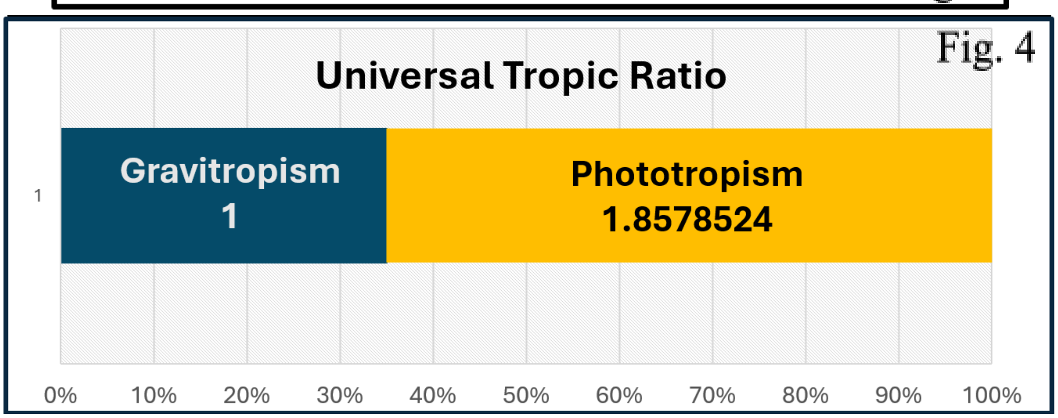


Fig. 4

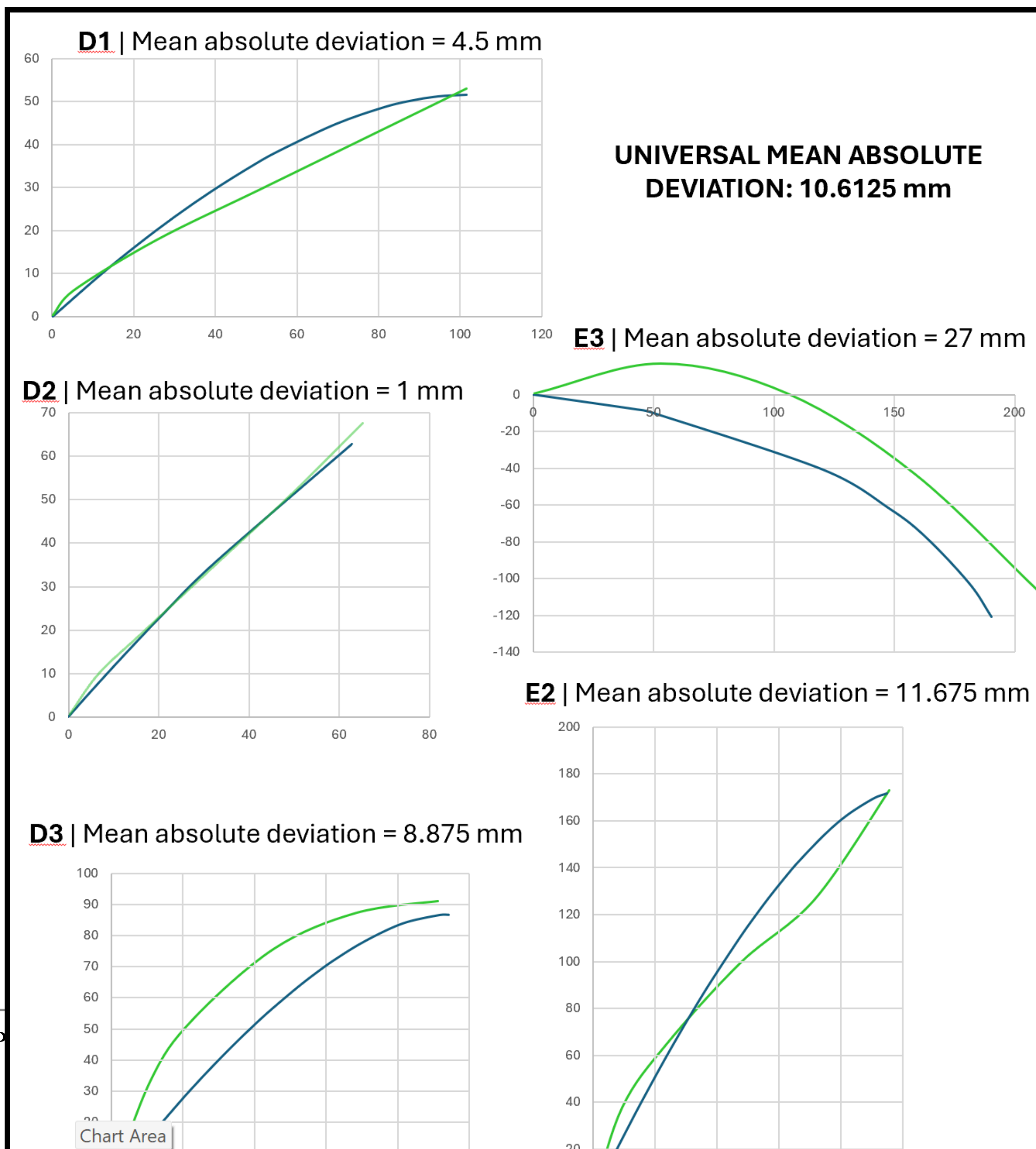
Fig. 4 shows the average relative ratio of gravitropic force to phototropic strength across the entire experiment. By these results, the constant ratio required in the algorithm is Equation 5.

$$T = \frac{1}{1 + 1.8578524...}$$
$$T = \frac{1}{2.8578524...}$$

Equation 5

3.2 Model Validation Experiments

Fig. 5 shows the resulting graphs of actual growth (green) from Sample Data (D1, D2, D3) and Experimental Data (E1, E2, E3) overlaid with the projected growth from the photogravitropic algorithm (blue).



A mean absolute deviation across all growth was found for each specimen. The mean absolute deviation across all specimens is 10.6125 millimeters. It is worth clarifying that this measure is relative to the conditions, namely the amount of distance and height to a light source, and may be scaled up or down to provide an accurate universal absolute deviation for differing conditions.

3.3 Photogravitropic Algorithm Web-based Application

The photogravitropic trigonometric algorithm was embedded in an application easily accessible via the World Wide Web. The web-based application may be found here for reference: Synchronous Tropic Growth - S. Goodman.

IV. Conclusions

The unification of shoot tropic forces and abstract trigonometry successfully develops a methodical algorithm to predict future plant growth shape.

The photogravitropic algorithm projects accurate plant growth (universal applied deviation: 10.6125 mm), provides simple and understandable inputs and results, and shows great potential for future applications due to its accessibility (online access, simple user interface). This research has fulfilled design criteria and the engineering goal and successfully peers deeper into computational botany.

Furthermore, tropic science has been further elucidated with novel discoveries in phototropic and gravitropic strengths. Through meticulous research, phototropism has been estimated to be 85.79% stronger than gravitropism. Throughout millions of years of evolution, plants have universally adapted to favor light stimuli, largely due to their vitality in plant sustainability and development. Photosynthesis accounts for the vast majority of usable energy in autotrophs, a process that requires light energy.

4.1 Applications

Due largely to its novel potential, simple interface, and easy accessibility, the photogravitropic trigonometric algorithm has numerous profound applications in various fields. They are as follows:

1. Agriculture: Growth shape allows for vital stimuli to be maximized, thereby increasing sustainability and survivability in plants.
2. Vertical Farming: Controlling plant growth via light placement minimizes needed growth space. More space allows more plants to be grown and higher production of food in high-density and high-population locations.
3. Space Biosystems: Plant growth in different environments, such as alternate gravity levels, to maximize survival. Elucidating the effects of greater, lesser, or nonexistent gravitational stimuli could be vital for development in alternate worlds.
4. Scientific Research: The photogravitropic algorithm may optimize scientific research by allowing further control of constant conditions, ultimately allowing future botanical research to maximize accuracy.

4.2 Limitations

The photogravitropic model considers only the photo- and gravi-tropic forces that determine shoot growth in environments absent of alternate factors. This algorithm does not fully consider all plant growth variability, and should thus be utilized as a guide, rather than fixed reality

Plant health (overhydration, dehydration, disease, etc.), physical contact interaction, stimuli intensity, species, flexibility, germination quality, mutations, soil pH, etc. are not fully considered and may all cause variability in accuracy and results.

4.3 Future Directions

Elucidating the effects of stimulus intensity on tropic response, a widely unknown topic, is critical in determining the accurate growth shape. This study as well as many others do not consider stimulus intensity which may limit accuracy in application. Revealing this unresearched knowledge could be achieved with further research and experimentation on light intensity or even gravity intensity on alternate worlds.

Moreover, additional secondary forces that influence growth direction, such as proprioception and autotropism, were not considered. While these forces do not reach the degree of influence strength of gravitropism and phototropism, they do affect growth shape, namely by the tendency to align shoots linearly.

V. Key References

Bastien R, Douady S, Moulia B (2015) A Unified Model of Shoot Tropism in Plants: Photo-, Gravi- and Propio-ception. PLOS Computational Biology 11(2): e1004037. https://doi.org/10.1371/journal.pcbi.1004037.

Holland, J. J., Roberts, D., & Liscum, E. (2009). Understanding phototropism: from Darwin to today. Journal of experimental botany, 60(7), 1969–1978. https://doi.org/10.1093/jxb/erp113.

Morita M., Tasaka M. (2004). Gravity sensing and signaling. Current Opinion in Plant Biology, 7(6). https://doi.org/10.1016/j.pbi.2004.09.001.

VI. Appendices

A.

Violet LED grow lights were placed in varying positions. Lights were set to alternating periods of 12 hours of full light and 12 hours of no light for a measuring period of 35 days.

The experiments consisted of one control group and two experimental groups, each with varying light positions. Each group consisted of 10 replicates, each of different species:

1. *Zea mays convar. Saccharata* (Sweet Corn)
2. *Lycopersicon esculentum* (Tomatoes)
3. *Phaseolus Vulgaris* (Common Beans)

4. Varying species of wildflowers, including *Alyssum maritimum, Calendula officinalis, Centaurea cyanus, Cheiranthus allionii, Chrysanthemum shasta,* and *Coreopsis tinctoria*
5. *Helianthus annuus* (Sunflower)
6. *Coriandrum sativum L.* (Cilantro)
7. *Anethum graveolens* (Dill)
8. *Daucus carota* (Carrot)
9. *Mentha piperita L.* (Peppermint)
10. *Raphanus sativus* (Radis

Specimen species were chosen for their distinct variety to ensure the most accurate account of phototropic and gravitropic forces for a specific plant type. Only vascular plant species were utilized.