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Computationally Modeling the Utility of Leaf-Closing in the *Mimosa pudica* Plant

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ABSTRACT

When touched or otherwise stimulated, the *Mimosa pudica* plant exhibits a rapid leaf-closing movement, thought to be a defensive mechanism against predators. However, this process is also highly energy-intensive for the plant. We propose a computational model to examine the trade-off between the energy cost of leaf closing and its potential benefits in reducing predation risk. The model estimates the energy required per leaf closing event by using the Finite Element Method, and the total energy available to the plant, based on the plants photosynthetic capabilities. Our preliminary results suggest that even with its high energy cost, the leaf-closing mechanism could provide an evolutionary advantage if it leads to a sufficient reduction in predation. However, our findings are based on several approximations and assumptions, highlighting the need for further experimental work to confirm these predictions. This work demonstrates the utility of computational modeling in studying the evolutionary pressures shaping plant behavior.

Introduction

Mimosa pudica is a plant which exhibits rapid plant movement when stimulated. The plant's leaves are sensitive to touch, as well as other stimuli such as shaking, blowing, and warming, which cause the leaves to close by folding. The reason for the *Mimosa*'s folding response has not been conclusively determined. However, several hypotheses have been proposed: the folding response may deter herbivores by making the leaves look smaller [1]; it may expose the thornes located below the leaf stem [2]; and it could cause insects that land on the plant to fly away [3]. Most hypotheses frame the leaf closing response as a defense mechanism against predators. This mechanism comes at a high cost to the plant. Not only is the movement highly energy intensive, requiring action potentials and changes in turgor pressure [4], it also inhibits photosynthesis. Photosynthesis is disrupted both because the folded leaves are no longer exposed to sunlight and because the electrical signal which triggers the folding inhibits photosynthesis and increases the release of CO_2 [5].

The question of whether Mimosa leaf folding is a defense mechanism has been studied experimentally. For example, Amador-Vargas et al. found that young leaves tend to close more fully when exposed to stimulus [6]. Since young leaves are more likely to be attacked by herbivores, this supports the hypothesis that the leaf-closing is a defensive behavior [7]. In this paper, we propose a complementary approach to study this phenomenon: the use of computational and mathematical modeling.

Methods

We propose a method to determine whether the utility of *Mimosa* leaf closing exceeds its energy cost by modeling the amount of energy required by the *Mimosa* for each closing. By comparing this value to the total amount of energy available to the plant, and the rate at which the plant closes for reasons unrelated to predation, we can determine the reduction in predation rate necessary for leaf-closing to be evolutionarily conserved.

Model Overview

For some time period T, the mimosa plant has some probability p of being consumed by a predator. The hypothesis is that its ability to close its leaves may deter predators and thus increase its chances of survival, meaning that a mimosa plant that does close its leaves has a probability p' of being consumed, where p' < p. For this feature to be evolutionarily selected, it must be the case that the increase in survival probability exceeds the negative impact of expending a large amount of energy on leaf closing.

A mimosa plant will accidentally close on average u times during the period T, for reasons unrelated to predation (the plant may be brushed by wind, an animal, rainfall, etc.), and each closing consumes e calories of energy. Since the closing process is very energy intensive, closing leaves unnecessarily will increase the plants "all-cause mortality" probability by some amount, which we will model with the function M(u, e, E_total). It thus must be the case that

$$p' + M(u, e, E\_total) < p$$

for the closing feature to be evolutionarily conserved. Note that p' = p - Δp, where Δp is the decrease in the probability of being consumed due to the leaf-closing mechanism. We can rewrite the inequality as:

$$M(u, e, E\_total) < \Delta p$$

We construct M as follows:

$$M(u, e, E\_total) = 1 - e\hat{}(-\lambda * ((u * e)/E\_total)$$

Where u is the average number of unnecessary leaf closings during period T, e is the energy cost per leaf closing, and E_total is the estimated total available energy for the plant during period T. The parameter λ controls the sensitivity of mortality risk to the fraction of energy expended on unnecessary leaf closings. The assumption underlying this model is that as the energy spent on closing increases relative to the total available energy, the increase in mortality risk accelerates.

Computational Modeling

Our model requires an estimate of e and E_total. To estimate e, we propose a novel use of the finite element method (FEM). The FEM is a numerical technique used for finding approximate solutions to boundary value problems for partial differential equations. The method subdivides a large problem into smaller, simpler parts, known as finite elements. These finite elements are connected at points called nodes or vertices and the solution is determined by creating simultaneous equations that together form a system of equations. The solutions to the problems are approximated across these individual elements and then combined together for the entire domain. The method results in a set of algebraic equations that can be solved simultaneously using matrix methods. Given a 3D model of an object, the FEM can be used to determine how that object will react to forces, vibrations, heat, and other physical effects. In this case, we can use the FEM to estimate the energy needed to close a leaf by considering the leaf as an elastic object and the leaf closing process as a deformation of this object. While the FEM has been applied to plants before [8], to the best of our knowledge, this is the first time it has been used to model rapid plant movement.

We construct a 3D model of a *Mimosa* leaf using *Blender*, a 3D computer graphics program. We simplify the geometry of the leaf in order to reduce the computational cost of our model. Figure 1 shows the completed 3D model, while Figure 2 shows the model split into finite elements.

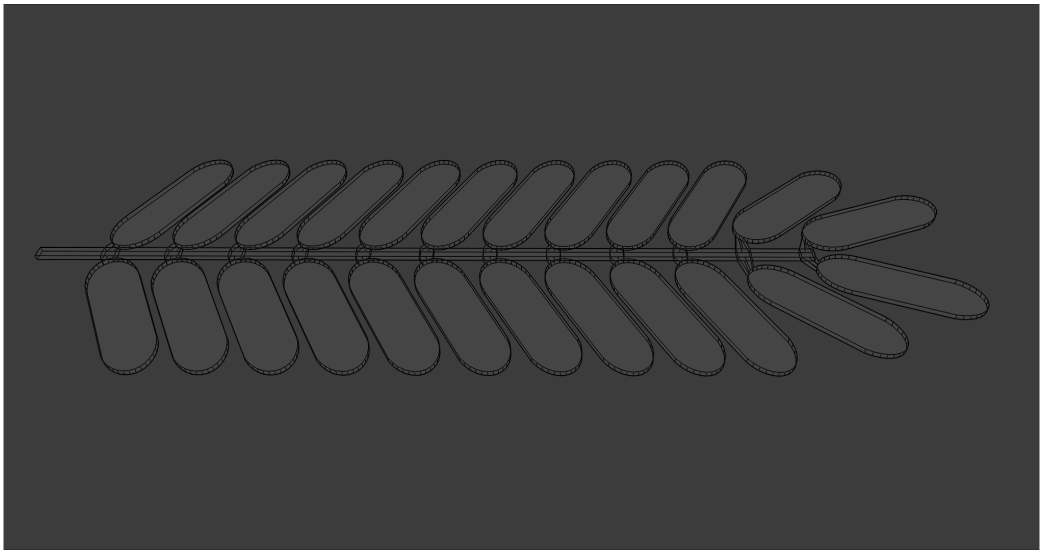

Figure 1. The 3D model of the *Mimosa* leaf

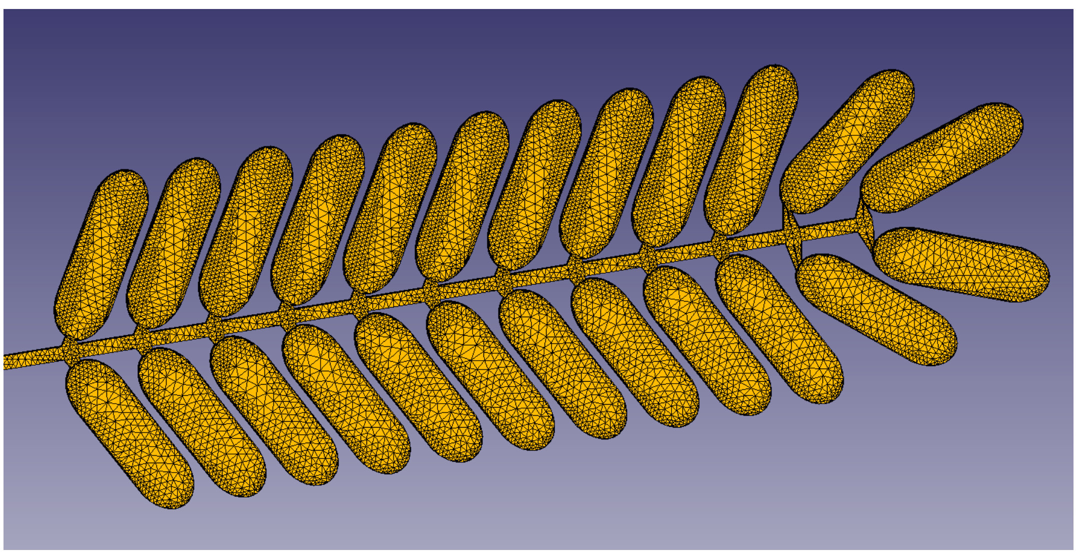

Figure 2. The 3D model split into finite elements

The FEM requires parameters that describe the material properties of the leaf, namely the Young's modulus and Poisson's ratio. Determining these parameters experimentally would be beyond the scope of our study, so we will instead use the value of other leaves from the literature. Ciupak et al. measured the mechanical properties of maple leaves and found a Young's modulus of 4MPa, and a Poisson's ratio of 0.5 [9]. Though the leaves of maple and mimosa are different, we choose to use these parameters as an approximation, and leave experimental measurements for future work.

Having obtained a value for e, we must also find E_total, the total available energy for the plant during period T. We estimate E_total based on how much photosynthesis the leaf can carry out. This value is dependent on the surface area of the leaf, sunlight exposure, and overall efficiency of photosynthesis. We can estimate the energy produced per square meter of leaf area from the literature [10], and obtain the total leaf area from our 3D model. Sunlight exposure can be modeled as constant for an outdoor plant located at a given latitude. Lastly, the efficiency of photosynthesis for most common plants is estimated at 3% [11].

Results

Applying our model requires experimentally determined values (Young's modulus and Poisson's ratio for *Mimosa* leaves, as well as the average number of unnecessary leaf closings) that we do not yet have. However, with the use of approximate values, we can demonstrate the principle of our model. From the FEM simulation, we find an average energy consumption of 4.03e-3 joules per closing. We estimate E_total to be 529.2 joules (setting T to one day, during which there are on average 7 hours of sunlight). Since finding u, the average number of unnecessary leaf closings, would require observation of *Mimosa* plants in their natural habitat, and the correct value of λ is unclear, we conduct a sensitivity analysis by plotting M for various choices of u and λ (see figure 3).

We find that leaf closing can be conserved evolutionarily even when the number of unnecessary leaf closings is high, given a reduction in the daily probability of predation of 0.00759%. This suggests that the leaf closing mechanism could be at play even if it appears energetically costly, since the gain in survival may outweigh the cost. Future experimental studies could determine if the reduction in predation caused by leaf-closing is indeed significant enough to balance its associated energy costs.

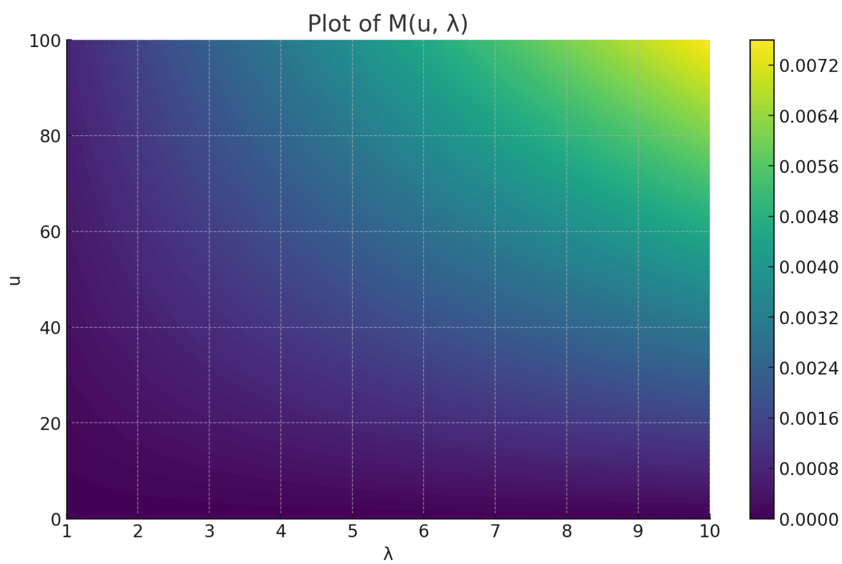

Figure 3. Sensitivity analysis of M as a function of u and λ

Discussion

Our model provides a theoretical framework for assessing the evolutionarily conserved utility of leaf closing in the *Mimosa pudica* plant. While our current results are based on approximate values, they nonetheless affirm the potential for leaf-closing to be an advantageous survival strategy despite its high energy cost.

However, there are limitations to our study that future research could address. This study has assumed constant parameters for energy costs and rates of predation, which in reality can vary based on several factors such as environmental conditions, availability of sunlight, and plant health among others. Further, factors such as plant health, growth stage, and environmental stressors could potentially affect the leaf folding behavior and should be incorporated in future models.

The reliance on approximate values for energy costs and rates of predation and the usage of mechanical properties of maple leaves due to lack of available data for *Mimosa pudica* indicate areas for future empirical research. Precise measurements for these model input parameters could significantly improve the accuracy of the model.

Conclusion

In this work, we demonstrate that the FEM can be used to model the energetic costs of the rapid plant movement observed in *Mimosa pudica*. By coupling this estimation of energy expenditure with a probabilistic model of predation, we show how computational modeling can shed light on the evolutionary pressures that might have led to the leaf-closing mechanism in this plant.

Our preliminary results suggest that, despite its high energy consumption, leaf closing could confer an evolutionary advantage if it significantly reduces predation. However, our model relies on a number of assumptions and approximations, indicating that further experimental and observational research is needed.

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