Simulation and Visualisation of Plant Growth Using a Functional-structural Model

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Abstract: This paper investigates the simulation of plant growth in a virtual model using a combination of computational techniques. Equations from the GreenLab model are used to calculate the quantity of new biomass produced through photosynthesis, while a modified space colonisation algorithm is used to describe geometric growth. The geometric model is used to calculate intercepted light, which is fed back to the production equation. This simulation-modelling approach is used to generate visualisations of plant growth under varying environmental conditions and in mixed communities. The macro and micro scale virtual environment influences plant architecture and development. Semi-realistic simulation of growth is achieved across a number of plant species with the possibility of further application. The species are selected from those installed at a trial project in Sydney, Australia. Maintenance processes such as pruning and coppicing are implemented in the dynamic growth model. Challenges include increasing computational complexity when plants are simulated on a large scale site, and cost to validate growth parameters from in-situ study of plants.

Keywords: Simulation, functional-structural plant models, space colonisation

1 Introduction

In the field of landscape architecture and design, there has been limited application of simulation models of plant growth and development. Landscape architectural practice is increasingly embedded in the digital realm, with the uptake of Landscape Information Models (LIM) and microclimatic simulation becoming part of the design process. Within these models, vegetation is typically represented as a static element. While these models may be sufficient for inorganic built structures, they do not articulate the growth patterns of living vegetation, along with plant response to dynamic site conditions. This paper investigates the use of a simulation based plant model to predict and visualise both individual and community plant growth. These digital simulations of growth and competition may provide an opportunity to study the complex systems underlying vegetation communities before completing design and breaking ground for construction. In this paper, we demonstrate a method for simulating the growth of plant specimens within a landscape information model. In the next stage of research, the results of the modelling will be compared and validated against outcomes from physical planting trials. This will support the use of simulation tools to make decisions about species selection and design in the future practice of landscape architecture.

1.1 Simulated Vegetation in Landscape Architecture

Simulation models are used in landscape research to understand and explore complex environmental systems. Cantrell and Holzman describe dynamic simulation models of such landscape systems as Synthetic Ecologies (CANTRELL & HOLZMAN 2014). Models of simulated vegetation have been investigated by Ackerman and Belesky (ACKERMAN 2021, BELESKY 2015, 2018). The validity of the use of such simulation tools by landscape architects has been

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discussed by Ervin and Raxworthy (ERVIN 2001, RAXWORTHY 2018). Criticisms include the challenges in accurately simulating highly complex systems, and an over-reliance on their assumed validity. Kullman also discussed the challenges associated with the use of hyper-realistic models and simulations in the practice of landscape design (KULLMAN 2014). These cautions, while valid, do not preclude the development of a more sophisticated and botanically accurate methodology for the simulation of plants on site.

1.2 Functional Structural Plant Models

Functional–structural plant modelling (FSPM) combines processes with architectural models describing plant form and development over time (LINDENMAYER 1968, BORCHERT & HONDA 1984, KURTH 1994). These models aim to understand 'the complex interactions between plant architecture and the physical and biological processes that drive plant development' (GODIN & SINOQUET 2005). Functional-Structural Plant Models were developed for the study of factors affecting plant growth, competition and environmental dynamics (GODIN & SINOQUET 2005). By including a 3D structural model, FSPMs are better able to express interactions in space, for example the effects of self-shading or density on leaf access to light, and photosynthesis. FSPMs describe the changing structure of plants determined by physiological processes, while at the same time modifying the environment through their development (BORCHERT & HONDA 1984). In 2000, the Greenlab model was developed by CIRAD (DE REFFYE 2003). Greenlab is a mathematical dynamic model in which development and functional processes are described through equations. Further development in the agricultural and forestry industries has led to 'virtual experiments' in which simulations of plant communities drive commercial and conservation decision-making. It is this capability that makes FSPMs a candidate for further application in performative landscape design.

This paper utilises an adapted and simplified formula for biomass production based on GREENLAB, as outlined in the following method section. It specifically investigates:

1) How can a simulation model help to describe plant growth within a virtual environment?

2) Does this model allow for dynamic modifications to structure such as pruning and coppicing?

3) Which species or architectural groups are well presented by this growth model, and which require further development or additions?

2 Method

2.1 Overview

This paper seeks to evaluate the use of a computational model of plant growth and development for effectiveness in predicting and visualising real site outcomes. The model used here is composed of two layers: a process model which tracks environmental variables, biomass production and allocation, and an architectural model responsible for the expression of three-dimensional growth and organogenesis of individual and plant community growth. At each time-step, the architectural model is used to recalculate environmental parameters, as feedback to the process-model.

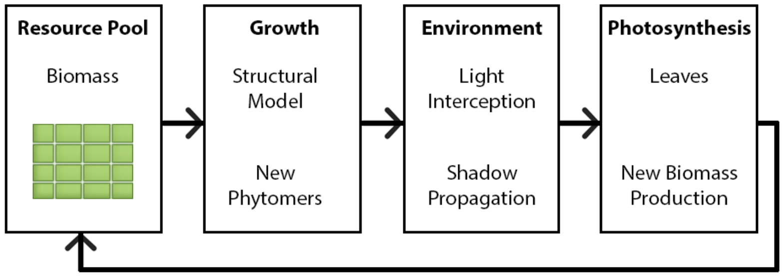

Fig. 1: This diagram illustrates the process model used to simulate individual plant growth. Photosynthesis is based on the amount of leaf area exposed to light from the environment. This determines a quantity of new biomass, which is allocated to the production of new phytomers. These phytomers provide additional leaf area, but also create a shading effect, intercepting light before it reaches lower leaves.

2.2 Computational Growth Model

The pseudocode process below describes the implementation of this formula into a model of virtual plant development:

Begin

For each plant agent:

> *Calculate intercepted Photosynthetically Active Radiation by leaf area*
> *Use Growth Equation to determine new biomass availability*
> *Add new biomass to common resource pool*
> *Allocate biomass to new phytomers in Space Colonisation process*
> *For each new phytomer:*
>> *Deplete light resource in host voxel by light interception value*
>> *Propagate light interception to voxels below*

End of cycle n

The first layer of the functional-structural model is the process layer, in which the biological processes of photosynthesis and biomass production and allocation are modelled for each plant using mathematical equations. These processes are modelled individually for each plant-agent, and do not include any explicit awareness of three-dimensional location, context or form. The GREENLAB model uses a discrete time-step system, below represented by the current growth cycle n. At each time step, biomass is generated through source organs, in this case leaves. This creates a pool of available biomass resources to be used for growth. This biomass is spent on the production of new organs and the expansion of existing ones through primary and secondary growth processes. This leads to another time-step of biomass generation through photosynthesis processes, updating the common resource pool and continuing. The equation use for the production of new biomass at each time step is below (UVED 2017):

$$Q(n) = \frac{E(n).S_p}{r}\left(1 - exp\ \ (-k\ \frac{S_l(n)}{S_p}\right)$$

In this equation: "Q(n) is the fresh biomass produced at cycle n, E(n) is an aggregate variable standing for environmental resource conditions, typically LUE (light use efficiency) and PAR (photosynthetically active radiation), r represents the water resource, proportional to the Water Use Efficiency inverse (WUE-1), k stands for the Beer Law extinction coefficient, S_p stands for the projection area, $S_l(n)$ stands for the total functional leaf area of the plant" (UVED 2017). Additionally, in our model: New phytomers = int(Q(n) / phytomer biomass approximation), Total functional leaf area = simple leaf area * number of leaves.

The techniques used for the structural component of the model in this paper to visualise plant growth and form are an adaptation of space colonisation techniques (RUNIONS et al. 2007). First, a volume-envelope is generated representing the mature space of the plant. Leaf objects are distributed stochastically within this volume representing the termination points of branch growth. A 'root' is generated from the ground plane, growing upwards until it reaches a given distance from the point cloud of leaves. From this point, branches are pulled towards the closest leaf points, while repelled from competing branch nodes. This process simulates the competition for light that creates the observed branching structure of vascular plants. By utilising the process of space colonisation, an approximation of plant growth over time is achieved. The integration of the base production formula of Greenlab with a space colonisation model allows for rapid simulation to take place on a site scale. The Greenlab formula is used for the calculation of new biomass, which is allocated to new phytomer growth in the 3D space colonisation model. The resulting growth is used to recalculate light availability for each leaf cluster, providing the input for the photosynthesis calculation at step n+1.

2.3 Visual Representation & Rendering

To allow realistic visual representation of our model, the final step involves the distribution of detailed branch and leaf geometry to create a plant-model at each growth stage. The method used here involves the procedural adding of pre-built small branchlets onto the calculated skeleton model generated by space colonisation. This is similar to the lobe-method proposed by Livny, however the structural component extends to the detail of individual new stems (LIVNY 2011). For plants with significant seasonal variation, this variation can be achieved by selecting twig modules from a library which may include for example deciduous leaf changes. These branches are stored in a digital library of geometry and instanced onto the model at each time-step.

2.4 Simulation Growth Tests

The simulation study consists of three parts: 1) In Study A the growth of individual plant specimens is simulated in isolation and compared to photographs of real plants to evaluate the success of the model in reproducing their particular growth characteristics. 2) In Study B, individual plants are simulated while subjected to a pruning or coppicing regime in which new growth is cut back periodically to a fixed height, to stimulate lateral growth and increase plant density. This maintenance process is of interest because it forms part of the future physical plant trials on which the simulation model will be tested. The pruning regime is compared to a control model that is allowed to develop freely to maturity. 3) In Study C, a mixed community of native Australian plant species from the future trials are simulated in a 3m x 3m test bed to evaluate the influence of competition dynamics between adjacent plants in the model. Using the above methodology for the simulation model, three simulation studies were conducted. The simulation results will later be compared and validated to growth patterns observed in future physical planting trials in Sydney, Australia. For this reason, the plant species selected are drawn from a list to be installed on the subject site.

3 Results

Simulation studies were conducted using Rhino 3D and Grasshopper software. The growth algorithms were implemented in GHPython and used to generate the results below. Computation times were within an acceptable frame of 30-120s for mixed species communities of up to 250 plants, running on consumer hardware. Significant performance increases could be achieved with further code optimisation.

Table 1: Simulation Modelling Results (*Westringia fruticosa*)

Time Step *n*	Biomass *Q(n)*	Environment *E(n)*	Functional Leaf Area *Sl(n)*	Projection Area *Sp*
0	0.2	1	0	2
5	1.0	1	0.1	2
10	10.0	1	0.5	2
15	25.0	1	2.75	2

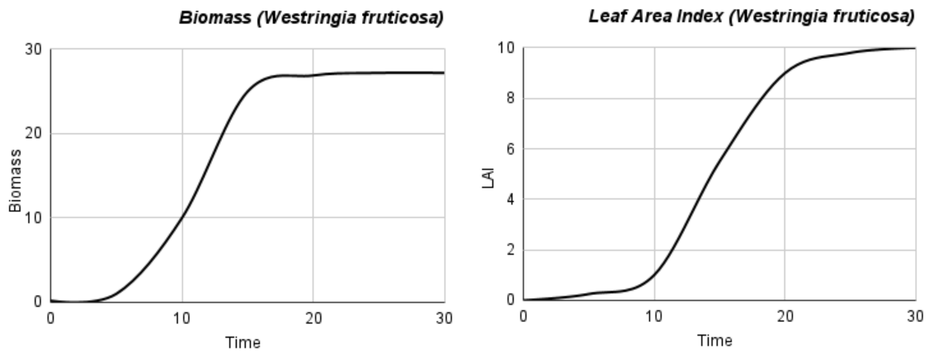

Fig. 2: Results of growth modelling in an optimal environment for Westringia fruticosa

Figure 2 shows the calculated change in biomass and LAI over the period of development, until reaching an equilibrium state under optimal conditions. This biomass availability variable is passed to the space colonisation function to control growth rate. In the live model, light availability informs environmental constraint E(n).

3.1 Visualisation of plant growth and development of selected species

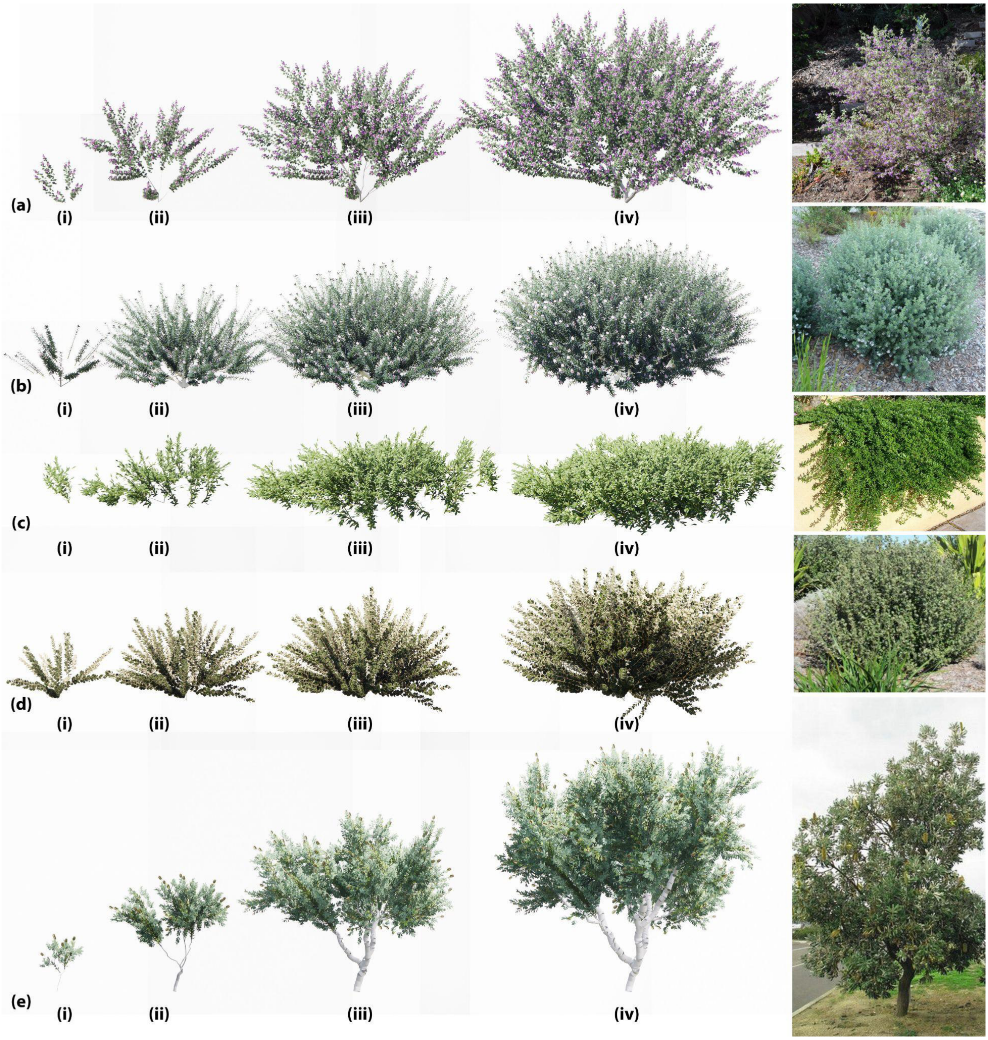

Fig. 3: Study A: Simulated growth pattern of native Australian plant species in isolation. (a) Prostanthera ovalifolia (b) Westringia fruticosa (c) Myoporum parvifolium (d) Correa alba (e) Banksia integrifolia. Numerals indicate maturity corresponding to a number of growth cycles. Photographs are included to compare the resulting models with real plants.

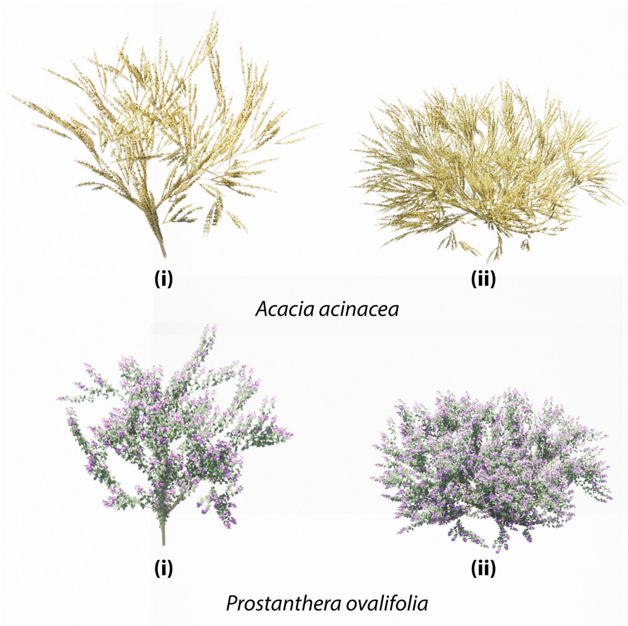

Fig. 4: Study B: A comparison of growth patterns resulting from 25 growth cycles under a coppicing maintenance strategy. Two species are shown. In both cases (i) represents unrestricted growth in an open environment, while (ii) shows the resulting architectural modifications to a mature plant after removal of all branches exceeding 300mm height above ground at 6 cycle intervals for the duration of growth.

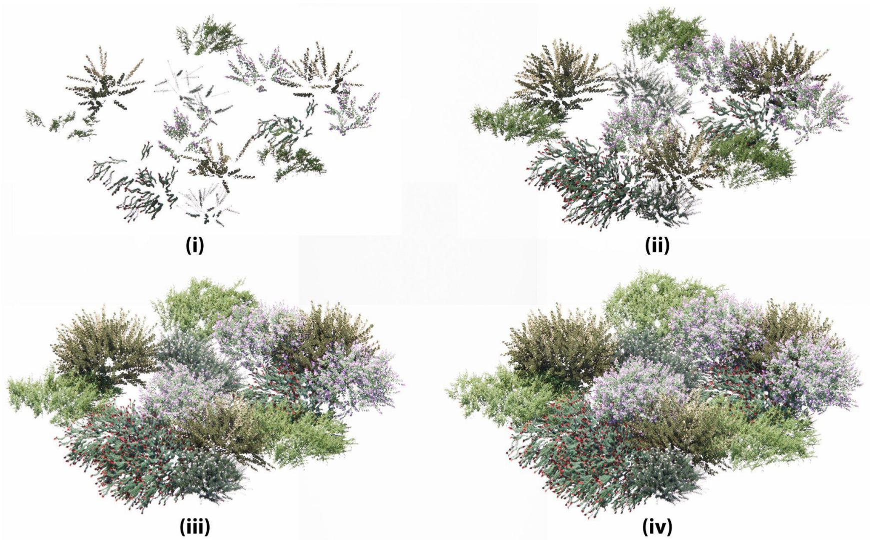

Fig. 5: Study C: Growth pattern of multiple species developing in a mixed vegetation community demonstrating competition for light influencing growth pattern

The space colonisation method for representing plant development has been demonstrated previously in prior work (RUNIONS 2007, PALUBICKI et al. 2009). The base methodology of space colonisation has been extended to better represent a variety of plant morphologies outside the temperate large tree species studied in previous literature. This includes application to ground covering plants, woody shrubs and grasses. Of the species tested, plants with a consistent overall density and growth habit including *Westringia fruticosa* developed architecture that closely resembles the observed patterns of growth in real specimens. Other species with a more variable branch density such as *Acacia acinacea* were less successful in achieving realistic structure. Possible causes are the influence of physical forces and stresses on plant development, and local interactions with light interception. This indicates future modifications to the process may be required to better represent these plants.

A number of remaining plant morphologies cannot be simulated effectively using this model. These include climbing plants and trees with complex seasonal changes to geometry such as periodic branch reorientation found in the Salix genus. The space colonisation model has also been extended to replicate the effect of coppicing and pruning practices on plant form. These ongoing maintenance practices are key to the practice of landscape architecture. The dynamic structural modifications tested in Study B achieved a generic structural response to pruning and coppicing. They were not able to account for species variation in response to the removal and reorientation of apical buds.

4 Discussion and Conclusion

This paper applies the concept of complex developmental models of plant growth to application for the practice of landscape architecture. It represents realistic and specific species of plants in an interactive site model, and proposes a methodology for the expansion of the library of possible species. The computational growth model was used to produce three simulation studies and resulting 3d models. While this model has shown some application and suitability for use in landscape architecture, a more advanced computational model would provide more accurate and reliable predictions.

The scope of modelling is currently limited to a relatively small number of plants. For application to wider landscape contexts refactoring and optimisation would be required to increase this. To transfer the modelling application to other regions requires collection of additional species and environmental data. Some species-specific parameters in the growth equation are substituted values from the generic model in the absence of experimentally validated measurements. Calibration with data collected from plants grown in a controlled environment would improve accuracy and potential benefit.

To further determine the effectiveness of the proposed methodology in practice requires further validation which will be addressed during the physical trials stage. Eventually this system could form the basis of a larger series of pre-installation growth and performance studies. A more realistic spatial growth algorithm based on biological systems including bud control and auxin is under development to replace the space colonisation component.

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