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Modeling parthenium weed early canopy architecture in response to environmental factors and the impacts on biological control activity of the summer rust

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Highlights: An L-systems based 3D canopy architecture model is created for simulating and visualising the early growth of parthenium weed in response to four environmental factors (temperature, CO_2, soil moisture and plant density) and the activity of the summer rust. The outcomes provide a tool to help study the interaction between an invasive weed, a biological control agent and the environment.

Keywords: L-systems, 3D model, canopy architecture, Parthenium hysterophorus, Puccinia xanthii var. parthenii-hysterophorae, environment

INTRODUCTION

Parthenium weed (*Parthenium hysterophorus* L., Asteraceae) is an annual invasive species found across five continents with the potential to invade many more regions (McConnachie et al., 2011). With its characteristics of strong suppression and allergy, parthenium weed affects agriculture, natural ecosystems, and human and animal health (Navie et al., 1996). Management of parthenium weed is most effective if undertaken on young plants. Due to the ability of parthenium weed to adapt to environmental changes through alterations in its physiology, morphology and life cycle, it is becoming more vigorous and prolific (Nguyen, 2011; Shabbir, 2012) and difficult to control. Biological control agents are an important component of the current management strategy for parthenium weed. However these organisms are also affected by environmental changes. Research into the interaction between parthenium weed, biological control agents and the environment has been undertaken for certain insects but not for fungal pathogens, specifically the summer rust (*Puccinia xanthii* var. *parthenii-hysterophorae* Seier, H.C. Evans & Á. Romero). A changed plant architecture is suggested to in turn change the activities of a pathogen (Pangga et al., 2011), but this is yet to be confirmed for the case of parthenium weed. In order to determine how the early canopy architecture of parthenium weed responds to environmental factors and how this affects activity of the summer rust, a modeling study on parthenium weed early canopy architectural development in response to a number of abiotic (temperature, CO_2, and soil moisture) and biotic (plant density) factors was conducted by creating a three-dimensional (3D) model using Lindenmayer-systems (L-systems, Lindenmayer, 1968a, b).

PARTHENIUM WEED MODEL

The impacts of four abiotic and biotic environmental factors, i.e. temperature regime (day/night 22/15, 27/20, and 32/25 ± 1 °C), CO_2 concentration (350 and 550 ppm), soil moisture level (100 and 75 % of field capacity), and plant density (one and five plants pot^{-1}) on young parthenium weed plants (up to 28 days old) were studied using controlled environment rooms (CER) at Ecosciences Precinct, Brisbane. During the experimental period, the development of the parthenium weed plant canopy architecture was tracked with a sonic digitizer. Digitized points were used to calculate the parameter inputs (i.e. leaf length and width, petiole length, and internode length) for modeling the early growth and canopy architecture of parthenium weed in response to different environmental factors. At the end of experiment, all leaves were harvested and divided into four silhouette groups according to leaf age and lobing. Visualization of each leaf was modeled using this silhouette classification and image digitization of leaves, together with a texture mapping approach using a color scanner and Adobe® Photoshop® CS3, Gimp version 2.8.2 and L-studio software. Plant development was modeled using the thermal time concept in L-systems, where cumulative degree-days and node number were the parameters used to control maximum growth of parthenium weed plant. The initiation of a new metamer by an apex (A) forming an internode (I), a leaf (L) and a new apex repeated was activated by an L-system decomposition rule when cumulative degree-days (dd) was greater than the defined plastochron (PLASTOCHRON) in the time step:

A(treatment,dd,node):dd>PLASTOCHRON -->

I(treatment,dd-PLASTOCHRON,node)[L(treatment,dd-PLASTOCHRON,node)]
/(137.5)A(treatment,dd-PLASTOCHRON,node+1)

The correlation of plant growth to thermal time under each factor was studied by analysing the calculated plant height and total leaf area using an ANOVA General Linear Model (Minitab® 15) and a Polynomial Regression Analysis (SigmaPlot® 11.0). Three key findings were then obtained, *viz.* i) plant height and total leaf area were highly correlated with thermal time; ii) plant height was reduced under elevated CO_2 concentration ($F = 34.27$; d.f. = 1; $P < 0.01$), reduced soil moisture level ($F = 61.80$; d.f. = 1; $P < 0.01$) and an increased plant density ($F = 8.26$; d.f. = 1; $P < 0.01$) and iii) total leaf area was reduced under an increased plant density ($F = 19.23$; d.f. = 1; $P < 0.01$). As an example, a simulation and visualization of the effect of temperature regime on parthenium weed canopy architecture is shown in Fig. 1.

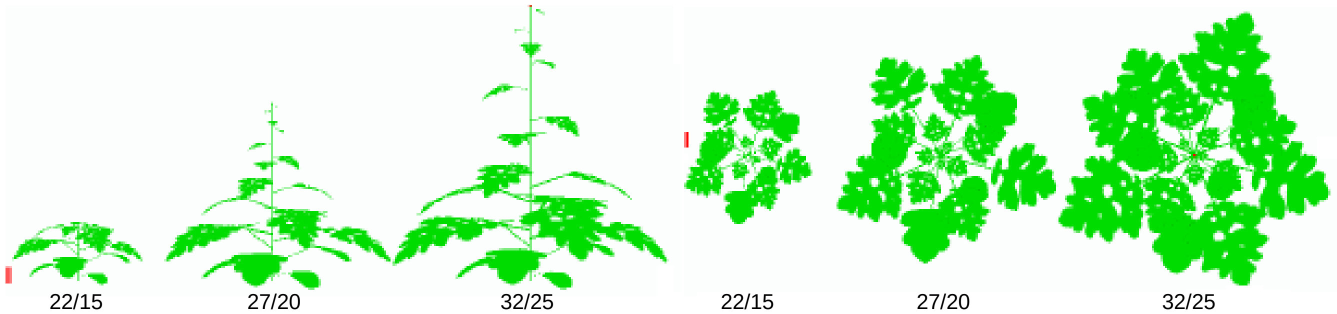

Fig. 1. Side- and top- views of the early parthenium weed canopy architecture in response to three different temperature regimes 28 days after germination. The red dot indicates the first flower formed on the plant. Red scale bar = 1 cm.

PARTHENIUM WEED MODEL INCORPORATED WITH THE SUMMER RUST DISTRIBUTION

A study of the impact of canopy architecture on the distribution of the summer rust was undertaken by spraying spore suspensions onto parthenium weed plants with different canopy architecture. At the end of experiment (*ca.* 15 days after inoculation), all leaves were carefully harvested for image digitization processing and analysis. Disease severity was calculated for each leaf as follows:

disease severity = (disease area/leaf area) * 100 %

disease area = (captured pixels_{DA}/pixels of the image file) * dimensions of the image file

leaf area = (captured pixels_{LA}/pixels of the image file) * dimensions of the image file

where 'captured pixels_{DA}' defined the brownish colour of pustule-like telia of the summer rust using a colour threshold with hue ranging from 10 to 25 and saturation ranging from 0 to 100, while 'captured pixels_{LA}' defined the green colour of parthenium weed leaves using a colour threshold with hue ranging from 40 to 110 and saturation from 0 to 100. The impact of each environmental factor on disease severity was determined using an ANOVA General Linear Model (Minitab® 15). Two key findings were then obtained, *viz.* i) similar disease severities were found similar throughout temperature regimes ($F = 1.21$; d.f. = 2; $P = 0.32$), CO_2 concentrations ($F = 0.27$; d.f. = 1; $P = 0.61$), soil moisture levels ($F = 0.52$; d.f. = 1; $P = 0.48$) and plant densities ($F = 3.77$; d.f. = 1; $P = 0.07$) and ii) size of telia was observed variable across all factors. Fig. 2 shows the outcome of incorporation of the summer rust distribution on the model shown in Fig. 1.

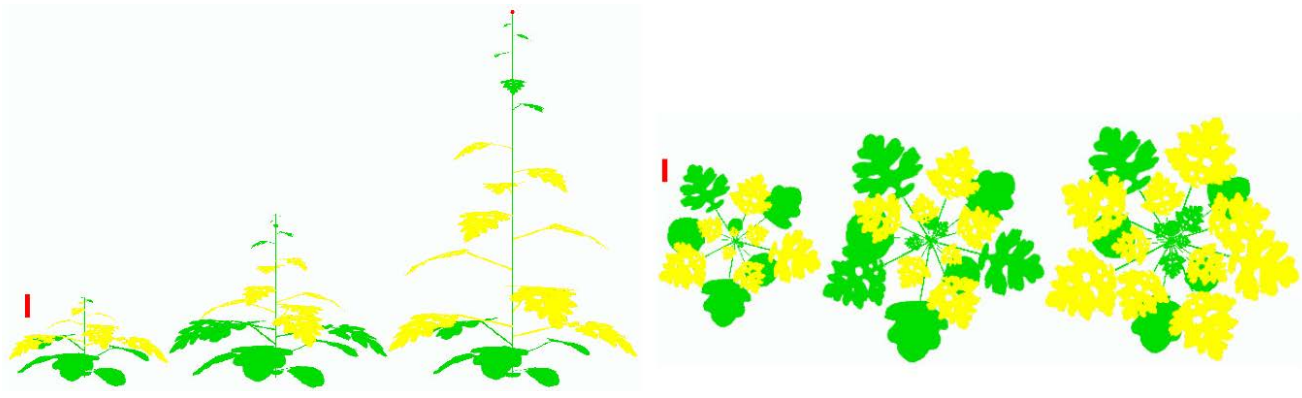

Fig. 2. Side- and top- views of the summer rust distribution and disease severity on early parthenium weed plant canopy grown at three different temperature regimes. The red dot indicates the first flower formed on the plant. Red scale bar = 1 cm. Leaves in green and yellow indicate 0 and ≤ 3 % disease severity respectively.

PERSPECTIVES

A 3D L-system based model of parthenium weed canopy architectural development has been created to provide a tool for simulation and visualization of the growth of young parthenium weed plants in response to four environmental factors (i.e. temperature, CO_2, soil moisture and plant density). The possibility of adapting this model for study of a biological control agent has also been demonstrated. Two aspects may be considered for future work in parthenium weed modeling, *viz*. i) a validation with an expanded range of environmental factors to refine the current model and ii) further modeling to simulate the development of inflorescence structures and flower and seed production. With these extensions, a better prediction may be made for not only the individual growth of parthenium weed but also the dynamic trend of its population in response to the environment over time, and thereby assist weed managers or ecologists to evaluate the risk of local parthenium weed population. In addition, two research gaps may be investigated for the summer rust, *viz*. i) modeling the spatial movement of spore and ii) modeling the epidemics and its impact on parthenium weed population over time. With these models, a better understanding in its activity of biological control will be provided. Furthermore, all these concepts can be applied to incorporate other biological control agents thereby developing a comprehensive model that simulates and predicts the interactions between parthenium weed and multiple biological control agents under a defined environment, allowing easier estimation of the effect of weed management.

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