JET PROPULSION LABORATORY SUMMER INTERNSHIP PROGRAM (SIP)- FINAL REPORT

Incorporating Plant Phenology Dynamics in a Biophysical Canopy Model

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The Multi-Layer Canopy Model (MLCan) is a vegetation model created to capture plant responses to environmental change. The model vertically resolves carbon uptake, water vapor and energy exchange at each canopy level by coupling photosynthesis, stomatal conductance and leaf energy balance. The model is forced by incoming shortwave and longwave radiation, as well as near-surface meteorological conditions. The original formulation of MLCan utilized canopy structural traits derived from observations. This project aims to incorporate a plant phenology scheme within MLCan allowing these structural traits to vary dynamically. In the plant phenology scheme implemented here, plant growth is dependent on environmental conditions such as air temperature and soil moisture. The scheme includes functionality that models plant germination, growth, and senescence. These growth stages dictate the variation in six different vegetative carbon pools: storage, leaves, stem, coarse roots, fine roots, and reproductive. The magnitudes of these carbon pools determine land surface parameters such as leaf area index, canopy height, rooting depth and root water uptake capacity. Coupling this phenology scheme with MLCan allows for a more flexible representation of the structure and function of vegetation as it responds to changing environmental conditions.

CONTENTS

1 INTRODUCTION

Over the last decade, evidence has been presented showing that increases in the amount of carbon dioxide has caused dramatic changes in land-atmosphere interactions and surface hydrology. One question that has become increasingly important in light of ongoing and future atmospheric changes is how perturbations in atmospheric forcing, specifically elevated carbon dioxide and air temperature, affect plant germination and growth over time [1]. Dynamic vegetation modeling is used for the consideration of vegetative response to the changing climate and is crucial in predicting land-atmosphere exchange over the next century. Currently, the multi-layer canopy-root-soil model (MLCan) has been successfully created and validated. It is capable of accurately predicting canopy-atmosphere exchange of CO_2, water vapor, and sensible heat. MLCan is used to analyze the impact of observed vegetation acclimation to elevated CO_2 on the canopy-scale gas energy exchange [1]. This paper addresses the next step for this vegetation model, which is to make MLCan dynamic by including functionality that models plant germination and growth over time. Coupling this phenology scheme with MLCan allows for a more flexible representation of the structure and function of vegetation as it responds to changing environmental conditions.

2 BACKGROUND AND OBJECTIVES

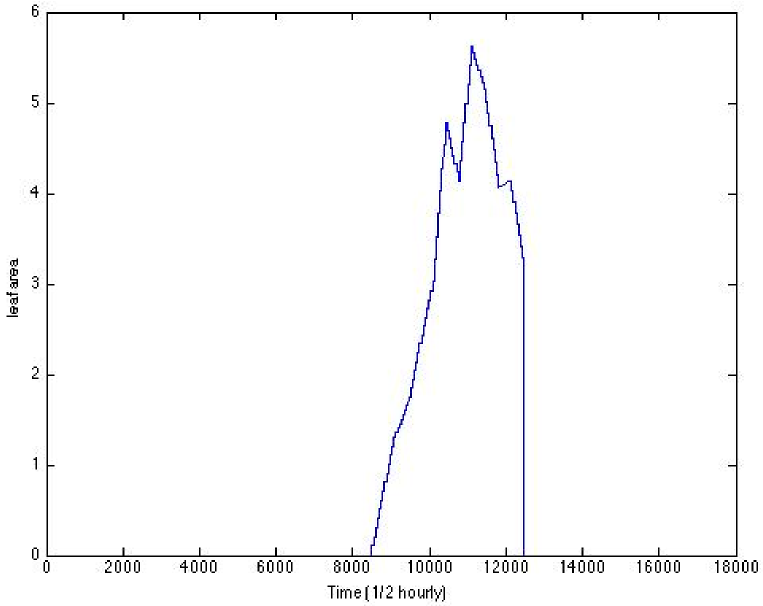

Figure 2.1 Observed leaf area of a soybean plant every half hour for one year. Originally utilized within MLCan.

MLCan is driven by atmospheric observations of shortwave and longwave radiation, air temperature, vapor pressure, carbon dioxide concentration, wind speed and precipitation. It is designed to intake half hourly data for up to three years while considering photosynthetic and biophysical traits specific to either maize or soybean crops. MLCan is a complex canopy model that vertically resolves carbon uptake, water vapor and energy exchange at each canopy level for every half hourly timestep. In addition, soil moisture is considered vertically within each layer of the root system [1]. The original formulation of MLCan utilized canopy structural traits derived from observations. For example, the leaf area of the plant throughout each year fluctuates solely based on surveys off maize or soybean plants, independent of all environmental conditions (see Figure 2.1). Similarly, canopy height and root depth are set to be constant throughout the entire simulation (see table 2.1).

Description	Units	Soybean	Maize
Canopy height	m	1	2.5
Root depth	m	1.5	1.5

Table 2.1 Original constant values of biophysical properties within MLCan.

This project aims to incorporate a plant phenology scheme within MLCan allowing these structural traits to vary dynamically. To accomplish this, within MLCan a subroutine has been added that allocates the carbon uptake to specific components of the plant, as well as another component that converts the amount of carbon allocated into physical plant characteristics such as root depth, canopy height, and leaf area.

3 APPROACH

Initially, a literature review of the references listed below was required to examine the many different techniques for both allocation of carbon and the conversion of carbon into physiological and structural traits. For every technique there are different constructions for each individual variable, such as when and where in the plant the carbon is being allocated, and what those allocation fractions are. While exploring each reference, Matlab was used to examine the techniques outlined for further understanding of the influence of each variable and to gain intuition for the models. Ultimately, a combination of schemes from Pavlick et al [2], Kleidon and Mooney [3] and Arora and Boer [4] were chosen to implement and couple with MLCan.

3.1 GERMINATION AND GROWTH

The phenology scheme that was implemented is designed to run once at the end of each simulated day (48 timesteps) within MLCan. The foundation of the scheme is a set of parameters that dictate plant growth. These parameters correspond to growth response time, allocation to above ground vs below ground growth, turnover rates, etc (full list can be seen in Table 6.1). These parameters vary from 0 to 1 and describe the characteristics of the plant. For example, if a plant is able to survive in conditions with very little water it must respond slowly to changes in the soil moisture. The parameter that controls response time to moisture conditions must be near to one, representing a long memory and a slow response to change (see Figure 3.1).

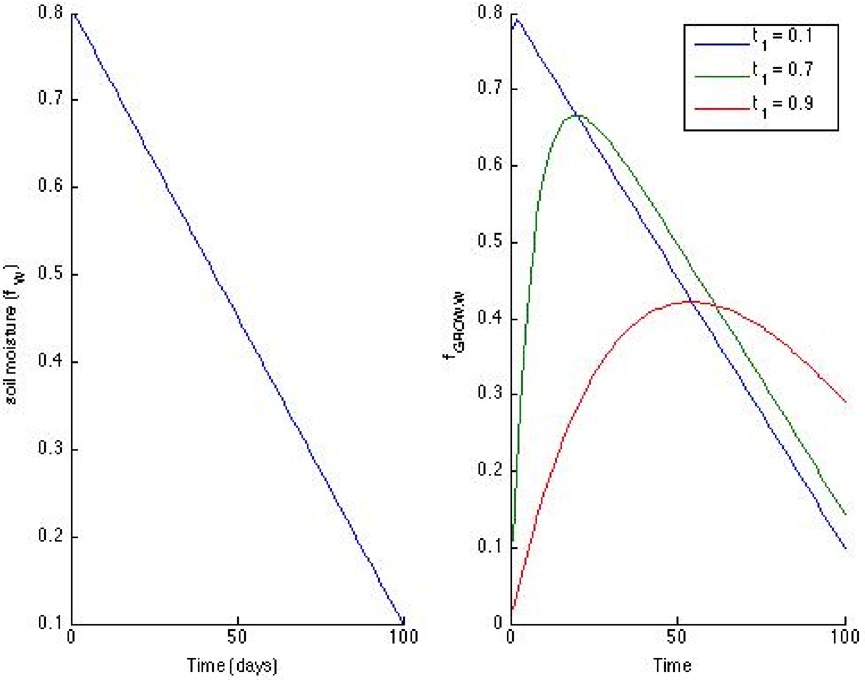

Figure 3.1 The left panel shows soil moisture (f_W) over time. The right panel depicts the dependance of the plant's response time of the moisture sensitivity parameter (t_1).

The function describing the plant's response to soil moisture ($f_{GROW,W}(t)$) must reach a certain threshold before the moisture conditions for plant growth are met. A similar construction describes the plant's response to air temperature with the function ($f_{GROW,T}(t)$). Both of these growth functions must be above a specified threshold for growth to be initialized (for further details see Equations 6.1-6.5) [2].

Plant senescence is represented within the model by a function of net primary productivity (NPP). Net primary productivity is the amount of carbon taken up by the plant per day. Similar to growth, the parameters that describe plant growth can be chosen to lengthen or shorten the plant's senescence response time to productivity conditions [2] (see Equations 6.8-6.9). The initiation of senescence increases the amount of leaf and fine root turnover while stem and woody root turnover remains constant independent of plant senescence (see Equation 6.10-6.14).

Other biological factors also represented within the model are vegetative cover (Equation 6.14), reproduction (6.7), and germination (6.1-6.6). When germination conditions are favorable (i.e. $f_{GERM} = 1$), an initial amount of carbon is added to the seed carbon pool which then allows growth to begin [2].

3.2 CARBON ALLOCATION

The model chosen considers six plant pools when allocating carbon; storage (A), seed (S), leaves (L), fine roots (R), coarse roots (WR), and woody stem (WL). As mentioned above, when germination occurs an initial amount of carbon is added to the seed pool. From that point on, allocation to the different pools is defined by allocation fractions (see Equation 6.15). Allocation to the seed pool is initiated only when reproduction conditions are favorable, whereas allocation to growth pools is initiated when growing conditions are favorable [2]. These allocation fractions are fractions of the storage pool, where there remaining fraction stays in storage. They are constructed to sum to less than one, which insures conservation of mass within the model. The changes in the vegetation pools are described by the following differential equations.

$$
\begin{aligned}
\frac{dC_A}{dt} &= NPP + GERM - \sum C_A A_{tissue}(1 - c_{RES,tissue}) \\
\frac{dC_S}{dt} &= C_A A_S(1 - c_{RES,S}) - GERM - \frac{C_S}{\tau_S} \\
\frac{dC_L}{dt} &= C_A A_L(1 - c_{RES,L}) - \frac{C_L}{\tau_L} \\
\frac{dC_R}{dt} &= C_A A_R(1 - c_{RES,R}) - \frac{C_R}{\tau_R} \\
\frac{dC_{WL}}{dt} &= C_A A_{WL}(1 - c_{RES,WL}) - \frac{C_{WL}}{\tau_{WL}} \\
\frac{dC_{WR}}{dt} &= C_A A_{WR}(1 - c_{RES,WR}) - \frac{C_{WR}}{\tau_{WR}}
\end{aligned}
$$

At the end of each day, the total amount of net primary productivity (NPP) goes straight into the storage pool (C_A). Germination is represented by the transfer of carbon ($GERM$) from the seed pool (C_S) to the storage pool (C_A). The amounts added to each growth pool is proportional to the size of the storage pool and the carbon allocation fractions (A_S, A_L, A_R, A_{WL}, A_{WR}). A designated amount of respiration ($C_{RES,tissue}$)is removed from each tissue pool signifying the amount required to grow the plant. Litter loss (turnover, τ_S, τ_L, τ_R, τ_{WL}, τ_{WR}) is proportional to the amount of carbon in each pool and is also removed.

3.3 LAND SURFACE PARAMETERS

The magnitudes of the carbon pools determine several land surface parameters. Dynamic leaf area, canopy height, and rooting depth are incorporated into the phenology scheme. Leaf area index (LAI) is a product of the amount of carbon in the leaf pool and specific leaf area (SLA). The estimation of SLA is based on leaf lifespan and turnover [2] (Equation 6.17). The method for deriving rooting depth is taken from the paper by Kliedon and Mooney [3]. It is a function of the amount of carbon in the woody root pool with a minimum depth of 50mm (Equation 6.18). The construction for canopy height was taken from Arora and Boer [4] and takes into account the amount of carbon in both the woody root and leaf pools (Equation 6.19).

3.4 COUPLING PHENOLOGY WITH MLCAN

In the original MLCan application [1], leaf area was distributed proportionally throughout the canopy grid using a normalized distribution based on observations. However, since canopy height within the model was constant, the distribution of foliage throughout the canopy was unchanging. To make these aspects dynamic, the normalized LAI distribution was multiplied by the height of the canopy, thus ensuring there would be no leaf area in a canopy grid layer above the height of the plant. Leaf area is then redistributed within each layer as the canopy height changes. For example, if the plant has barely begun to grow and the height is completely contained within the first grid cell, the fraction of the leaf area in the first grid cell will be one. This construction allow the shape of the distribution of foliage over the canopy to be maintained. Dynamic leaf area is then distributed proportionally to the new normalized and scaled LAI distribution.

Root depth was originally also constant in the model formulation. To implement dynamic root depth, the maximum root depth within MLCan was replaced with the calculated root depth at each time step. By doing this, the amount of roots within each layer is cut off at the new calculated root depth and then normalized by the total amount of root biomass. The amount of water within the lower layers of the soil grid will not be available to the plant until the roots have reached those depths. This makes root depth and soil moisture availability dynamic.

4 RESULTS AND CONCLUSION

The figures shown are a result of MLCan utilizing soybean parameters over one simulated year. They show only the time steps for which leaf area is greater than zero.

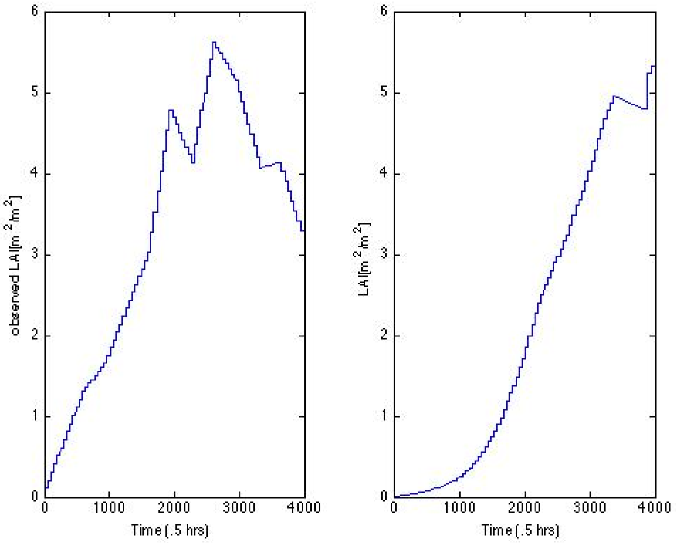

Figure 4.1 The left panel shows observed LAI over time. The right panel depicts the simulated LAI over time.

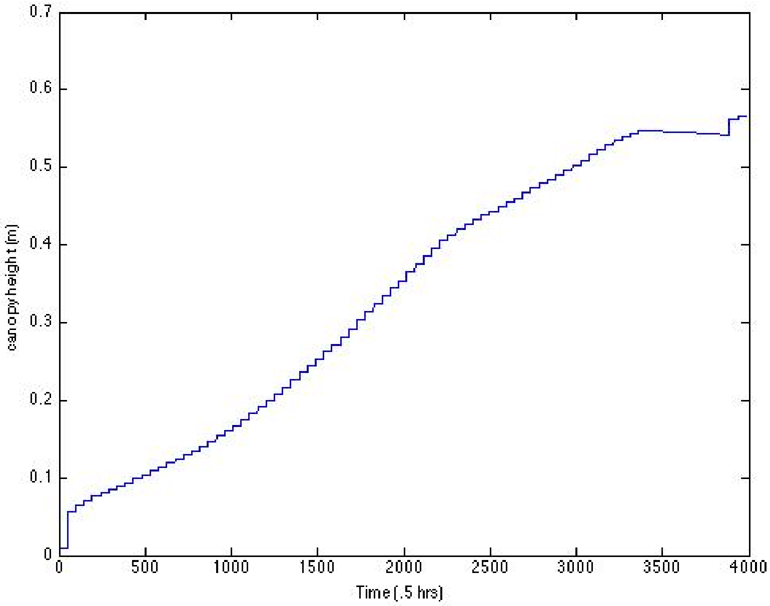

Figure 4.2 This figure shows the canopy height over time.

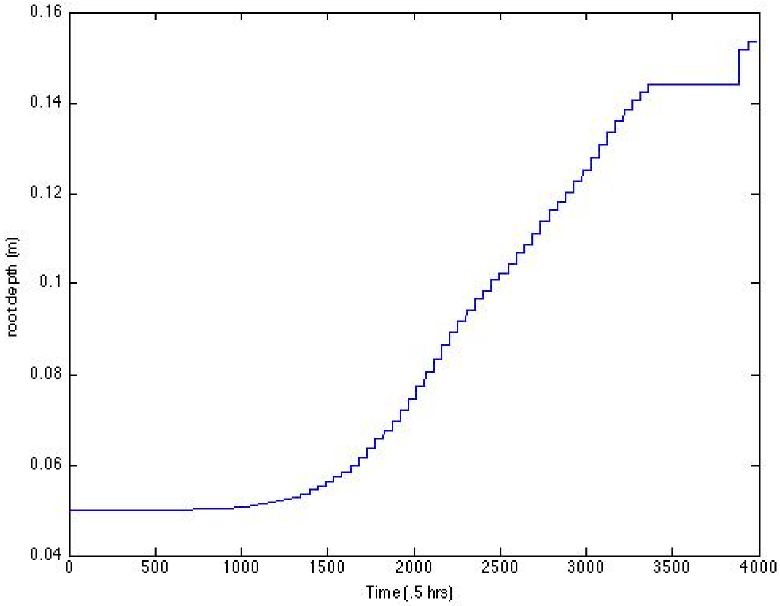

Figure 4.3 This figure shows the root depth over time.

As seen in Figure 4.1, the magnitude of the simulated LAI is similar to the magnitude of the observed LAI, which was a desired result. However, the rate of growth of the observed LAI with in the first 2000 time steps is higher than the simulated LAI. A tighter correlation between the rates of change would be ideal. Modifications to the parameters controlling plant growth will be required to see better agreement with the observation. Canopy height nears a value of 0.6 meters as time goes on, as seen in Figure 4.2. The magnitude is close to the observed value, but remains smaller than the maximum of 1 meter. Root depth, however, does not exceed 0.2 meters (see Figure 4.3). This may be a result of an unrealistic approximation for root depth. Modification to the parameters describing plant growth may be required to increase below ground structural growth. Additional figures are included in the appendix.

The original intention of the project was to incorporate germination into the phenology scheme. The code was intended to simulate each day of the year, whereas it currently only simulates the time period in which observed LAI is greater than zero. Germination requires that the phenology scheme alone is run until germination occurs, which would allow each day to be simulated even if vegetation is not present. The incorporation of germination resulted in unexplained errors within the model and was not completed due to time constraints. Water uptake capacity is a fourth land surface parameter typically formulated from the amount of carbon in the fine root pool. This parameter has yet to be considered within the phenology scheme. Incorporation of water uptake capacity with MLCan will require a deeper knowledge of the biophysical functionality modeled by MLCan. Incorporation of this last parameter will make growth within MLCan fully dynamic.

5 ACKNOWLEDGEMENTS

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6 APPENDIX

Details of the equations and various terms used within the phenology and land surface schemes are described here. All equations are from the paper by Pavlick et al [2], unless otherwise stated.

Parameter	Description
t_1	growth response time to moisture conditions
t_2	growth response time to temperature conditions
t_3	critical temperature for growth
t_4	germination fraction
t_5	allocation to reproduction
t_6	allocation to aboveground growth
t_7	allocation to belowground growth
t_8	allocation to storage
t_9	relative allocation to aboveground structure
t_{10}	relative allocation to belowground structure
t_{11}	turnover time of structural pools
t_{12}	turnover time of leaf and fine root pools
t_{13}	senescence response time to productivity conditions
t_{14}	relative senescence above ground

Table 6.1 These parameters define plant growth with in the model. All parameters vary from zero to one.

6.1 GERMINATION AND GROWTH

Both germination and growth are controlled by environmental conditions. f_W is a ratio of the available moisture to the maximum and T is air temperature.

$$f_{GROW,T}(t) = \frac{T + \tau_T f_{GROW,T}(t - \Delta t)}{1 + \tau_T} \tag{6.1}$$

$$\tau_T = 10^{(4t_1 - 2)}$$

$$f_{GROW,W}(t) = \frac{f_W + \tau_W f_{GROW,W}(t - \Delta t)}{1 + \tau_W} \tag{6.2}$$

$$\tau_W = 10^{(4t_2 - 2)}$$

$$f_{GROW,G}(t) = \frac{f_{W,bare} + \tau_W f_{GROW,G}(t - \Delta t)}{1 + \tau_W} \tag{6.3}$$

$$f_{W,bare} = \frac{W_{bare}}{W_{MAX,0}}$$

The previous equations describe the plant's current response to environmental conditions and are essentially weighted averages dependent on the values of the parameters. The value of the function from the previous day will vary between being weighted equally or a negligible amount when averaged with the current day value. The variable W_{bare} (the storage capacity of bare non-vegetated soil) was undefined in the paper by Pavlick et al ($W_{bare} = 30$ was arbitrarily chosen). Growth is initiated when f_{GROW} has a value of one. Similarly, germination is initiated when f_{GERM} has a value of one.

$$f_{GROW} = \begin{cases} 0 & f_{GROW,W} < 0.5 \text{ and } f_{GROW,T} < T_{crit} \\ 1 & f_{GROW,W} \geq 0.5 \text{ or } f_{GROW,T} \geq T_{crit} \end{cases} \tag{6.4}$$

$$f_{GERM} = \begin{cases} 0 & f_{GROW,G} < 0.5 \text{ and } f_{GROW,T} < T_{crit} \\ 1 & f_{GROW,G} \geq 0.5 \text{ or } f_{GROW,T} \geq T_{crit} \end{cases} \tag{6.5}$$

Here, T_{crit} is a linear function of the parameter t_3 between -5^{o}C and 10^{o}C. Germination initiates allocation from the seed pool to the storage pool. The amount of carbon transferred is denoted by $GERM$. Both p and k_{GERM} are undefined in Pavlick et al [2] and both were arbitrarily chosen to have the value 2.

$$GERM = f_{GERM}\gamma_{GERM}\frac{C_S}{max(p, k_{GERM})} \tag{6.6}$$

$$\gamma_{GERM} = 10^{(4t_4-4)}$$

Allocation to the seed pool occurs when net primary productivity is greater than zero.

$$f_{SEED} = \;1 \quad \text{when } NPP > 0 \tag{6.7}$$

6.2 SENESCENCE

Senescence is controlled by the net primary productivity NPP.

$$f_{NPP}(t) = \frac{NPP + \tau_{NPP} f_{NPP}(t - \Delta t)}{1 + \tau_{NPP}} \tag{6.8}$$

$$\tau_{NPP} = 10^{(5t_{13}-2)}$$

$$f_{SEN} = \begin{cases} 1 & f_{NPP} < 0 \text{ and } NPP < 0 \\ 0 & f_{NPP} \geq 0 \text{ or } NPP \geq 0 \end{cases} \tag{6.9}$$

Senescence is initiated when f_{SEN} has a value of one. Senescence initiates increased turnover rates of the leaf and fine root pools controlled by the equations below in which $\tau_{L,0}$ is the base turnover rate. The variable τ_{SEN} is undefined in Pavlick et al [2] and arbitrarily chosen to have a value of 50.

$$\tau_{L,0} = \frac{365}{12}10^{2t_{12}} \tag{6.10}$$

$$\tau_L = \Big(\frac{1}{\tau_{L,0}} + \frac{1}{\tau_{SEN}} f_{SEN} t_{14}\Big)^{-1} \tag{6.11}$$

$$\tau_R = \Big(\frac{1}{\tau_{L,0}} + \frac{1}{\tau_{SEN}} f_{SEN}(1 - t_{14})\Big)^{-1} \tag{6.12}$$

There are continuous turnover times in the woody tissue pools. Storage turnover τ_S is undefined in Pavlick et al [2] and arbitrarily chosen to have a value of 30.

$$\tau_{WL} = \tau_{WR} = 365(79t_{11} + 1) \tag{6.13}$$

The fractional vegetation cover (f_{VEG}) is determined by the leaf area according to the Lambert-Beer law [2].

$$f_{VEG} = 1 - e^{-kLAI} \tag{6.14}$$

$$\text{where } k = -.5$$

6.3 CARBON ALLOCATION

Each of these growth functions feed into the allocation fractions below. These fractions are constructed to sum to less than or equal to one.

$$\begin{aligned}
A_S =& f_{SEED} \frac{t_5}{t_5 + t_6 + t_7 + t_8} \\
A_L =& f_{GROW}(1 - t_9) \frac{t_6}{t_5 + t_6 + t_7 + t_8} \\
A_R =& f_{GROW}(1 - t_{10}) \frac{t_7}{t_5 + t_6 + t_7 + t_8} \\
A_{WL} =& f_{GROW} f_{VEG} \frac{t_6}{t_5 + t_6 + t_7 + t_8} \\
A_{WR} =& f_{GROW} f_{VEG} \frac{t_7}{t_5 + t_6 + t_7 + t_8}
\end{aligned} \tag{6.15}$$

All of these elements are implemented within the differential equations that determine the change in the carbon pool sizes. All respiration coefficients, $c_{RES,tissue}$, are undefined in Pavlick et al [2] and arbitrarily chosen to have the value 0.1.

$$
\begin{aligned}
\frac{dC_A}{dt} &= NPP + GERM - \sum C_A A_{tissue}(1 - c_{RES,tissue}) \\
\frac{dC_S}{dt} &= C_A A_S(1 - c_{RES,S}) - GERM - \frac{C_S}{\tau_S} \\
\frac{dC_L}{dt} &= C_A A_L(1 - c_{RES,L}) - \frac{C_L}{\tau_L} \\
\frac{dC_R}{dt} &= C_A A_R(1 - c_{RES,R}) - \frac{C_R}{\tau_R} \\
\frac{dC_{WL}}{dt} &= C_A A_{WL}(1 - c_{RES,WL}) - \frac{C_{WL}}{\tau_{WL}} \\
\frac{dC_{WR}}{dt} &= C_A A_{WR}(1 - c_{RES,WR}) - \frac{C_{WR}}{\tau_{WR}}
\end{aligned}
\tag{6.16}
$$

6.4 LAND SURFACE

Leaf area index $[m^2/m^2]$ is proportional to the amount of carbon in the leaf pool.

$$LAI = C_L SLA \tag{6.17}$$

$$SLA = .03(\tfrac{365}{\tau_{L,0}})^{-.46}$$

Root depth $[m]$ is based on of the amount of carbon in the woody root pool. The maximum set within the equation assures that there will always be a minimum root depth of 50 mm. This construction of root depth is described by Kliedon and Mooney [3].

$$W_{max} = .001(max(W_{MAX,0}, c_{wmax}\sqrt{C_{WR}})) \tag{6.18}$$

where $W_{MAX,0} = 50$ and $c_{wmax} = 20$

Canopy height $[m]$ is formulated around the amount of carbon in the stem and leaf pool. This construction is described in Arora and Boer [4].

$$H = (C_{WL}(.001) + C_L(.001))^{.385} \tag{6.19}$$

6.5 ADDITIONAL FIGURES

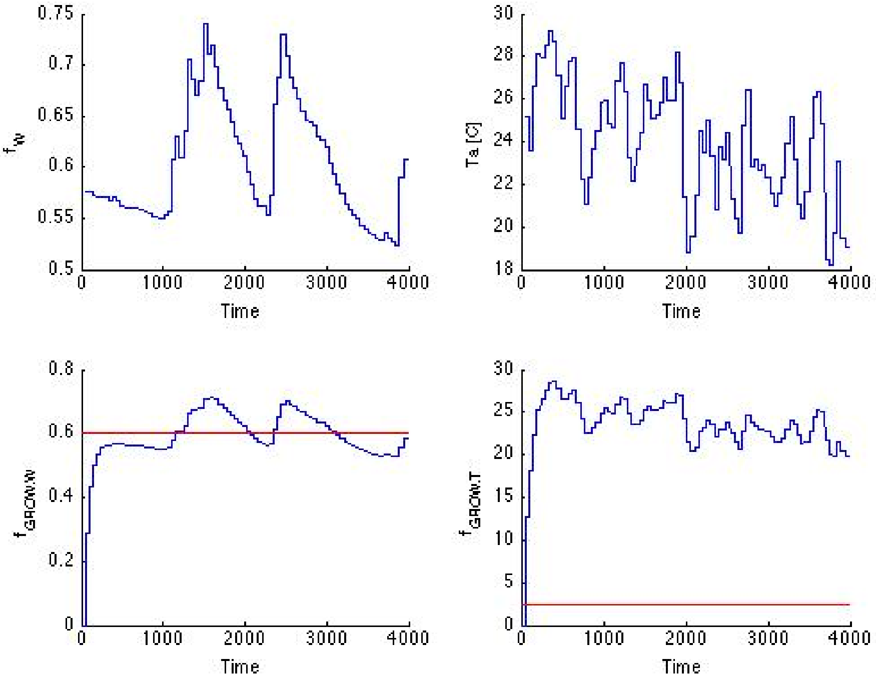

Figure 6.1 Top left- average daily normalized soil moisture. Bottom left- plant's growth response to soil moisture (Equation 6.2). Top right- average daily temperature. Bottom right- plant's response to temperature (Equation 6.1). The red lines signify the threshold above which growth conditions are satisfied. When both response functions are above the thresholds, growth in initialized.

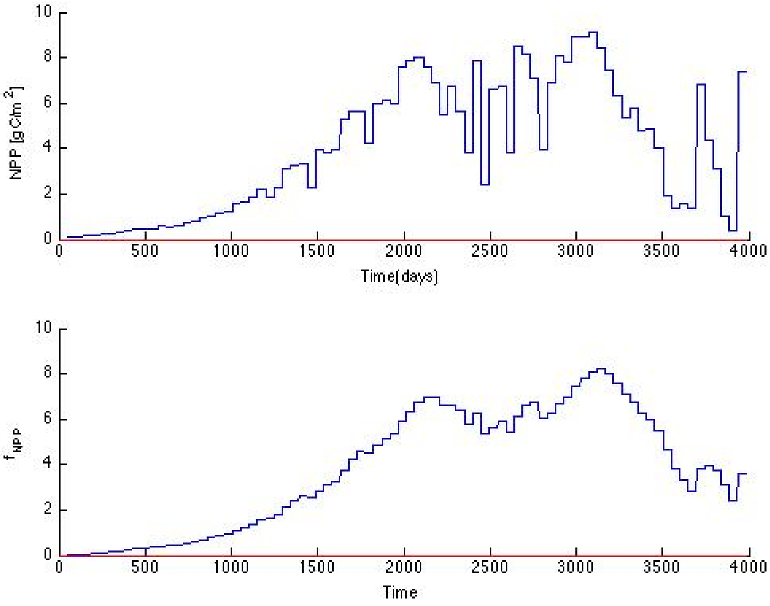

Figure 6.2 Top panel shows the total daily NPP taken up by the plant. Bottom panel shows plant growth response to productivity. The threshold for senescence is held at zero. If NPP has a value less than zero, senescence is initiated.

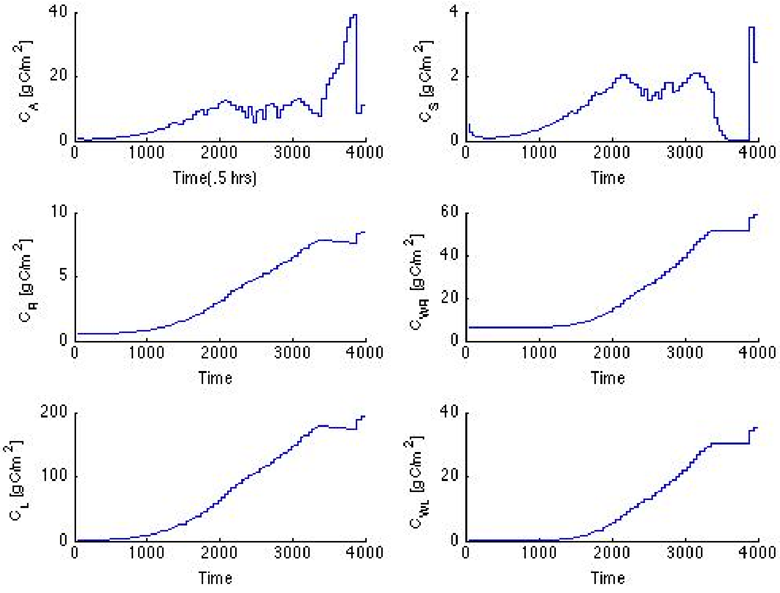

Figure 6.3 This figure shows the changes in the plant carbon pools based on equations 6.16. Top left- storage pool. Top right- Seed pool. Middle left- Fine root pool. Middle right- Woody root pool. Bottom left- Leaf pool. Bottom right- Woody stem pool.