

# **Cellular Automata as a Model for Dynamic Leaf Structure**

**by**

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Dear Professor Kaplan,

In accordance with the requirements of the degree of Bachelor of Engineering (Honours) in the division of Software Engineering, I present the following thesis entitled “Cellular Automata as a Model for Dynamic Leaf Structure”. This work was performed under the supervision of Dr. Marcus Gallagher and the co-supervision of Dr. Jim Hanan.

I declare that the work submitted in this thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at the University of Queensland or any other institution.

Yours sincerely,

Nisansala Yatapanage.

## ACKNOWLEDGMENTS

The guidance and encouragement I received during all phases of this project from my supervisors, Dr. Marcus Gallagher and Dr. Jim Hanan, is gratefully appreciated.

## ABSTRACT

Cellular automata is a system in which continuous processes are modelled in terms of discrete components. Numerical values are used to define the possible states for each component. The change of state is governed by a set of rules incorporating the states of neighbouring components. Leaf expansion was simulated in this way by assigning numerical values to cell properties and defining a set of rules. These rules were set to reflect the interactions of neighbouring cells.

A software package was developed which performs the simulation of leaf growth using entered values of cell properties. The software package includes provisions for simulating situations such as the effect of an insect attack on a leaf.

The area expansion rates of known leaves were used to estimate the set of rules used in the simulation. The predicted linear expansion rates were found to fit closely with the measured expansion rates of the leaves.

## TABLE OF CONTENTS

	Page
Acknowledgements	ii
Abstract	iii
Table of Contents	iv
List of Figures	v
Chapter 1: Introduction	1
Chapter 2: Review of Literature	2
2.1 Cellular Automata	2
2.2 Leaf Expansion	5
Chapter 3: Method	10
3.1 Description of Leaf Expansion Model	10
3.1.1 Introduction	10
3.1.2 Complex Leaf Shapes	13
3.2 Software Developed	14
Chapter 4: Results and Discussion	18
4.1 Output of Model	18
4.1.1 Effect of Transition Rules	18
4.1.2 Initial Configuration of Model	20
4.2 Predictions of Linear Expansion Rate	20
4.3 Simulation of Complex Shapes	26
4.4 Effect of Damage to Leaf	27
4.5 General Discussion	29
Chapter 5: Conclusions	31
References	32
Appendix A - Source Code	38

## LIST OF FIGURES

	<b>Page</b>
Fig. 2.1 Main types of two-dimensional neighbourhoods	4
Fig. 3.1 Screenshot of output of software package	14
Fig. 4.1 Output using large horizontal values	18
Fig. 4.2 Output using small horizontal values	18
Fig. 4.3 Output using equal values for all directions	19
Fig. 4.4 Output using larger values for vertical direction	19
Fig. 4.5 Comparison between predicted and measured linear expansion rates for clover	23
Fig. 4.6 Comparison between predicted and measured linear expansion rates for tobacco leaf	24
Fig. 4.7 Comparison between predicted and measured linear expansion rates for pea leaf	25
Fig. 4.8 Initial complex shape used	26
Fig. 4.9 Output of complex shape simulation	26
Fig. 4.10 Output after small damage to the leaf occurred at time 35 steps	27
Fig. 4.11 Output after bordering section of leaf is destroyed at time 30 steps	28

# CHAPTER 1

## INTRODUCTION

Leaves are valuable organs of plants as they are the main collectors of sunlight for use in the photosynthesis process. Leaf growth is therefore an important biological process, since the shape and size of a leaf can greatly impact the amount of sunlight collected. The growth of leaves can be studied experimentally and can also be simulated using computer models. For the simulation process, the leaf can be thought of as a collection of small discrete sections. Mathematical rules can be devised to model the growth based on these discrete sections. Cellular automata is a system which uses this concept and can be used to produce a model of leaf growth. Further, the environmental effects can also be incorporated into the model, such as the effect of drought on the leaf. The goal of this project is to produce a simulation model of leaf growth based on cellular automata which can be used in conjunction with experimental research.

Chapter 2 of this thesis is a review of relevant literature. Chapter 3 describes the methods used. The results and discussion are presented in Chapter 4. Chapter 5 is the conclusions.

## CHAPTER 2

### REVIEW OF LITERATURE

#### 2.1 Cellular Automata

Cellular automata refers to a mathematical modelling system “in which many simple components act together to produce complicated patterns of behaviour” (Chen et al. 2002). It was first proposed by J.H. von Neumann and Burks (1966). Since then, cellular automata has had numerous diverse applications. Wang and Ruskin (2002) presented a model for traffic flow at a single-lane roundabout by using one-dimensional ring cellular automata, and even included factors such as the behaviour of drivers. Mansilla and Gutierrez (2001) applied cellular automata to the spread of disease and rumours in human populations using partial differential equations. Cellular automata have been applied to complex biological processes including DNA sequences (Chaudhuri et al. 1997). One of the most famous examples of the use of cellular automata is Conway’s Game of Life, as described by Gardner (1970), used to simulate the behaviour of living organisms. In the Game of Life, a lattice simulates the environment of the organisms and discrete sections of the lattice known as cells may only have one of two states: living and dead. Cells change to the dead state due to either isolation or overcrowding, and cells may change to the living state to simulate birth, reflecting the real situation of organisms in a community.

Cellular automata have also had applications in the modelling of plants. The development of branching patterns was simulated using cellular automata by



Ulam in 1962 (as reviewed by Mech and Prusinkiewicz 1996). Similarly, a cellular automata system was used to simulate vessel morphogenesis of leaves (Markus et al. 1999). Due to the spatial nature of cellular automata systems, they have been used for the modelling of the spread of plant epidemics and other vegetation dynamics (Pons, J. et al. 1998).

Cellular automata have been used effectively for the modelling of the surface growth of organisms, such as the development of limbs (Wilby and Ede 1976). Similarly, cellular automata could be an effective method for the representation of leaf growth.

Cellular automata systems consist of a lattice of discrete areas known as cells. The cells each store their state, which changes in discrete time-steps. The state of a cell at the next time-step is dependent on its current state and the current states of its immediate neighbours. A set of rules are defined which determine the conditions upon which the cell will change its state. The states of all cells are updated synchronously during each time-step, producing an overall change in the lattice.

Cellular automata can be classified into three types (Ermentrout and Edelstein-Keshet 1993). The first type, eulerian automata, is the classic type described above, in which the cells contain states which change according to their neighbouring cells. The second type, known as lattice gases, involves behaviour similar to gases, in which particles move around the lattice and interact according to given rules. The third type, solidification models, is

similar to the lattice gas model, with the added restriction that particles may enter a “bound” state from which they can not move.

It is possible for cellular automata to be modelled in one, two or even three dimensions (El Yacoubi and El Jai 2002). For the one-dimensional cellular automata, the cells all remain in a row. Interactions occur between a cell and the few neighbouring cells in the row. However, in the two-dimensional case, the cells are presented in a two-dimensional structure, with each cell depending on several neighbours. Some neighbourhood configurations have been defined which indicate which neighbours a cell depends on, including the Von Neumann, Moore and uniform configurations, as shown in Fig. 2.1. The Von Neumann configuration defines the neighbourhood of a cell as the four cells located directly above, below and to the left and right of the cell, while the Moore configuration defines the neighbourhood as the neighbouring cells in all eight directions. The uniform configuration is used for hexagonal lattices, and the neighbourhood is defined to be all touching hexagonal cells.

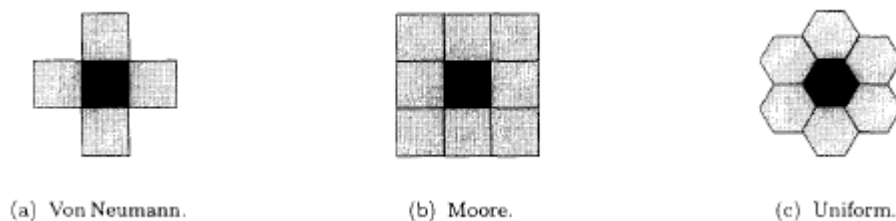


Fig. 2.1 Main types of two-dimensional neighbourhoods. (Taken from El Yacoubi and El Jai 2002)

The shapes of the individual cells can vary depending on the modelling requirements, including triangular, square and hexagonal shapes. The set of rules which govern the state of each cell, known as the transition function, may be deterministic or stochastic (El Yacoubi and El Jai 2002). An example of a type of deterministic function is the totalistic function, in which only the sum of the state values of the neighbouring cells is considered. Stochastic transition functions involve changing the states of each cell based on probabilities with the overall direction of growth also controlled by a probabilistic mechanism. (Bandini and Pavesi 2002).

The transition function is usually identical for each cell in a cellular automata structure. However, it is also possible for hybrid structures to be implemented, in which different groups of cells operate under different sets of rules (Chaudhuri et al. 1997).

Although cellular automata systems involve simple structures which only interact locally, they can successfully simulate complex systems.

## **2.2 Leaf Expansion**

The study of the expansion of leaves began as early as 1727, when Hales studied the growth of a fig leaf by measuring the displacement of points marked on the leaf (as described by Wolf et al. 1986). Avery (1933) discovered that the final shape of a leaf is a result of a differential distribution of growth

in various sections of the leaf, known as localised growth, and larger growth rates in particular directions compared to others, known as polarised growth.

The growth of a leaf is the result of cell division and cell expansion. While cell division provides the framework for leaves, the many variations in leaf shape are due to the magnitude and direction of cell expansion (Tomos 1985). Cell expansion is dependent on water absorption and cell wall yielding (Cosgrove 1986). Water movement into cells due to osmotic pressure gradients increases the pressure inside the cells, known as turgor pressure, which provides the force for expansion. This expansion is controlled by cell wall yielding properties according to the following equation proposed by Lockhart (1965).

$$r = m (P - Y)$$

where  $r$  is the growth rate,  $m$  is the elastic properties of the cell wall,  $P$  is the turgor pressure and  $Y$  is the yield threshold above which the growth occurs.

There have been several applications of cellular automata to the simulation of cell division (as reviewed by Martinez 1976).

In monocot leaves, cell division and cell expansion are spatially separated, simplifying the study of elongation of these leaves (Van Volkenburgh 1999). Cell division only occurs at the base of the leaf, at the meristem. Cell expansion occurs in the area above the meristem (Schaufele and Schnyder 2000). As more cells are produced at the meristem, older cells are moved further away from the base. These cells then go through the process of expansion, with an increasing cell length as the cells are moved further from the base. Cells reach

their maximum length at the end of the expansion zone (Tardieu et al. 1999). By the time cells have reached the visible section of grass leaves, both cell division and cell expansion have completely ceased (Dale and Milthorpe 1983).

The growth of dicot leaves differs significantly from that of monocots. Dicot leaves grow bi-directionally, with a significantly longer time of growth than monocots (Granier and Tardieu 1998). Cell division and cell expansion occur in all areas of the leaf and may overlap spatially and temporally (Van Volkenburgh 1999). However, the rates of division and expansion are not uniform over the leaf, with a higher relative expansion rate in the regions adjacent to the major veins compared to peripheral regions (Dale and Milthorpe 1983). The study of the growth of *Xanthium strumarium* leaves, performed by Maksymowych (1973), which is considered one of the key studies of the spatial distribution of dicot leaf growth, also confirmed the above localised cell division/expansion patterns.

Tardieu et al. (1999) found that the growth of a dicot leaf can be classified into three stages of development. In the first stage, the relative expansion rate and the relative cell division rate are constant and at their maximum values. There is an exponential increase in the total area of the leaf and in the number of epidermal cells. The next stage is characterised by a decrease in relative cell division rate, while the relative expansion rate remains constant. During the final stage, cell division ceases and the relative expansion rate decreases.

The decrease in expansion and division rates begins first in the tip of the leaf, and then progressively towards the base (Dale and Milthorpe 1983 and

Tardieu et al. 1999). As a result of this, the area of the base is significantly larger than that of the tip.

Arkebauer and Norman (1995 a,b,c) proposed a model for predicting the growth of monocot leaves. Since the number of cells in a leaf can be extremely large, cells were grouped into classes of similar volume. All the cells in a certain class were assumed to expand at the same rate. Arkebauer and Norman then devised several equations for the calculation of the number of cells expanding into larger volume classes at each time-step and the number of dividing cells. Cell expansion was assumed to be related to the wall extensibility and water relations of the cells, while cell division was related to the cell temperature and a daughter ratio, defined as the proportion of cells remaining after a cell division which are capable of further divisions. The model was successful in simulating the expansion of the whole leaf based on cell expansion and division and also incorporated the effects of water potential inputs and temperature.

Environmental conditions can significantly affect the growth of leaves. Factors which may influence leaf expansion include the availability of light, relative humidity, soil water potential and defoliation (Parrish and Wolf 1983). These factors have an impact on leaf expansion by affecting either the wall loosening or the water flux into expanding cells, thereby changing the cell expansion rate. Cell division and cell expansion have both been shown to be affected by water stress (Sivakumar and Shaw 1978). As water deficits increase, cell expansion rates progressively decrease, until eventually ceasing

completely. Since cellular automata deal with physical problems by using discrete sections, it may be an appropriate tool to model the complex interactions of cell division and cell expansion.

## CHAPTER 3

### METHOD

#### 3.1 Description of Leaf Expansion Model

##### 3.1.1 Introduction

Cellular automata represent complex systems in terms of discrete components. Since leaf expansion is a continuous process, it must be characterised by the behaviour of discrete components, in order to fulfil the requirements of a discrete modelling system. This enables the system to be simulated using a computer program.

A cellular automata system was developed to model the expansion of leaves. The lattice of the cellular automata represents the environment in which the leaf is growing. A two-dimensional lattice was considered to be appropriate, as only the surface leaf expansion was studied. The CA cells are representative of the cells of the leaf. In order to simplify the model, cells with similar properties were grouped together into a single unit of cells. Each CA cell represents one of these units of leaf cells.

Cells in a leaf expand in all directions. Due to this behaviour, the Moore configuration was considered the most appropriate form of representation of the CA neighbourhood (see page 4). The Moore neighbourhood allows cells in all eight directions to be influenced by the centre cell. Using this configuration, cell expansion can be simulated by considering the effect of an expanding cell on the neighbouring cells in all directions.



At any given time, each cell of the cellular automata may either represent a portion of the expanding leaf or the surrounding space. Thus, two states are possible for each CA cell, either the growing state or the empty state.

To determine how the cells of the model change between these states, transition rules were devised. The cells of a leaf are influenced by surrounding cells through the transfer of water and solutes, resulting in cell expansion. This influence is included in the model by the transition function. The state of a CA cell changes to the growing state if a neighbouring cell is already in the growing state.

Dicot leaves grow in all directions and exhibit polarised growth, i.e. different rates of growth in each direction, as discovered by Avery (1933). For the simulated leaf to exhibit the same behaviour, the transition rules had to be modified to allow the rate of growth to be specified in any direction. Each cell of the simulation process was given a decimal value. The precision of this decimal value can be decided by the required accuracy of the results. If a neighbouring cell is found to be in the growing state, the decimal value of the current cell increases by a set amount. This amount is dependent on the location of the neighbour. When the value of a CA cell has increased above a given threshold value, the cell changes to the growing state.

By specifying different amounts of increase for CA cell values according to the direction of the neighbour, the modelled leaf growth can be made to exhibit the same properties of actual leaf growth. Since the threshold growth level is a constant, CA cells with growing neighbours in any particular direction

will reach the threshold value faster if the amount of increase for that direction is larger. This will result in a faster growth rate for the simulated leaf in that direction. Using this method, the rates of increase for each direction can be chosen to give the desired effect.

This system can be represented mathematically as follows:

Let  $L$  represent a lattice of cells. For each cell in  $L$  located at position  $(i,j)$ :

Let  $S_{i,j}(t)$  represent the state of the cell at time  $t$  and  $n_{i,j}(t)$  represent the numerical value of the cell at time  $t$ .

$S_{i,j}(t) \in \{0,1\}$ , where 1 = growing state, 0 = not growing.  
 $n_{i,j}(t)$  is a decimal number

*Initial conditions:*  $S_{i,j}(0) = 0, n_{i,j}(0) = 0$

*Transition rules:*

$S_{i,j}(t + 1) = \begin{matrix} 1 & \text{if } S_{i,j}(t) = 0 \text{ and } n_{i,j}(t + 1) > m, \text{ where } m \text{ is the threshold} \\ & \text{value.} \end{matrix}$

$1$  if  $S_{i,j}(t) = 1$

$0$  otherwise

$n_{i,j}(t + 1) = n_{i,j}(t) + a_{dir}$  if  $S_{x,y}(t) = 1$

$n_{i,j}(t)$  if  $S_{x,y}(t) = 0$  for all neighbours or  $S_{i,j}(t) = 1$

where the cell at position  $(x,y)$  is a neighbour of the cell at position  $(i,j)$  and  $a_{dir}$  is a value depending on the direction of cell  $(x,y)$ .

During the course of growth of an actual leaf, the growth rates change with time. Leaf growth slows and eventually ceases when the leaf reaches a certain age. By using dynamic transition rules, this behaviour can be specified for the model. When a certain number of steps have been performed, signifying a length of time, the rates of increase for the cell values are changed, to reflect the associated change in growth rate of the actual leaf.

### **3.1.2 Complex leaf shapes**

The cellular automata model described can be used to simulate simple shaped leaves with differences in dimensions, such as broader leaves. However, in nature, there is a large diversity of leaf shapes. Modelling leaves with more complex shapes requires changes to the transition rules.

The rates of growth in each direction will vary depending on the section of the leaf. Therefore, in order to simulate the growth of leaves with complex shapes, a hybrid cellular automata system can be used, where different sets of transition rules are applied to each section of the leaf.

The rules must be changed to include an additional state value that defines which section of the leaf each CA cell belongs to. This value is set to 0 for cells which are not in the growing state. If a neighbouring cell is in the growing state, the cell is assigned to the same leaf section as the neighbour, thus allowing it to follow the rules for that particular section.

Using these modifications to the original cellular automata system, the growth of a large variety of leaves was simulated.

### 3.2 Software developed

The discrete nature of cellular automata models, as well as the large number of calculations which must be performed for a lattice of appropriate size, makes cellular automata an ideal candidate for computer simulations. The use of a computer program to perform the simulation allows large size lattices to be considered with minimum additional effort.

The cellular automata lattice was represented as a grid of squares, with each square representing a single CA cell. The state of these squares is in the form of numerical values. Thus, a visual representation can be a useful aid in providing such rapidly changing information to the user. Different colours can be used to represent the different states of each cell. A software package was developed to run the leaf growth simulation, which produces such a graphical output. A user friendly menu is provided to enter required parameters. An example screenshot of the graphical display is shown in Fig. 3.1.

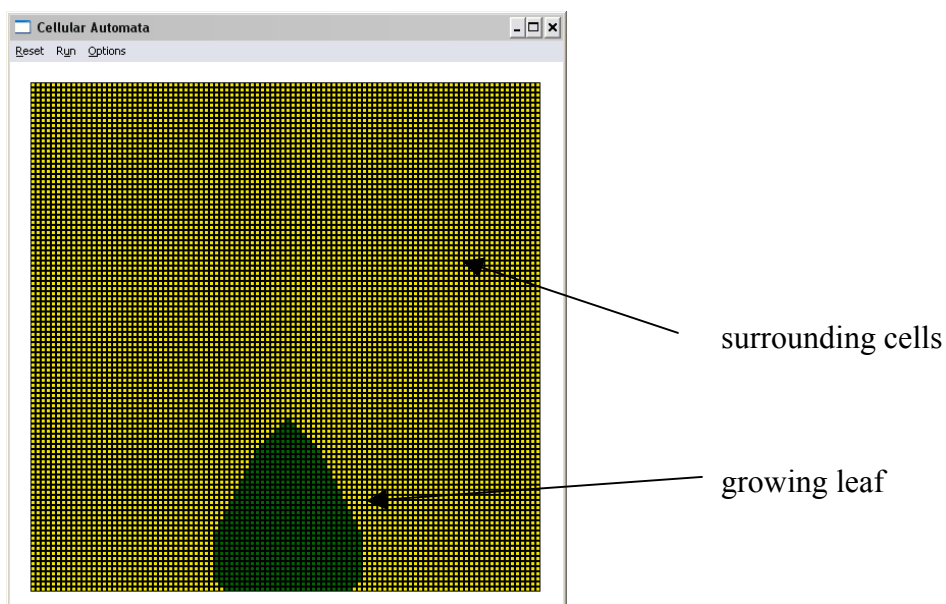


Fig. 3.1 Screenshot of output of software package

The values and states of the cells are stored in two-dimensional arrays. At each time-step, the new value of each cell is determined by examining the states of all neighbouring cells. For cells which lie on the borders of the CA lattice, the effect of their missing neighbours are taken into account by equating those cells to a non-growing state with a value of 0.

The new values for cells are stored in a temporary array while calculations are taking place. This ensures that all cells are using the previous states of neighbours for calculations, as defined by cellular automata systems, and not the new states. After the new values for all the cells have been calculated, these values are copied back to the original array.

An excerpt of the code for this section follows. The array “cell” stores the current values for each cell, the array “temp” temporarily stores the new values and the array “isleaf” stores the current state of each cell (1 or 0). The function “getNextState” is the function which performs the transition rule calculations for each cell and returns the new values.

```
for(i = 0; i < max; i++){ // for each row
    for(j = 0; j < max; j++){ // for each column
        temp[i][j] = getNextState(i,j); // calculate new value and store in
                                        temp array.
    }
}

for(i = 0; i < max; i++){ // for each row
    for(j = 0; j < max; j++){ // for each column
```

```

cell[i][j] = temp[i][j];    // update values
if(cell[i][j] > threshold){ // if new value is larger than threshold
    isleaf[i][j] = 1;      // change state of cell to growing state
}
}
}

```

The new values for each cell are calculated using a separate function, in which the transition rules are specified. The function examines the state of each neighbour until one is found which is in the growing state. The new value for the current cell is then determined by the addition of its previous value and the  $a_{dir}$  value, depending on the direction of the chosen neighbour. The pseudo-code for the basic transition rules follows. The variables “a1” and “a2” represent the  $a_{dir}$  values for two of the neighbour directions. The new value for the cell is returned as the “result” variable. Using this method, rules for any of the eight directions can be specified.

```

if (the cell is not in the growing state){
    if (the neighbour in the downwards direction is growing){
        result = cell[row][column] + a1;    // increase cell value by a1
    }else if (the neighbour in the left direction is growing){
        result = cell[row][column] + a2;    // increase cell value by a2
        ... etc. ...
    }
}else{ // cell is already in the growing state - no change
    result = 0;
}

```

By using a computer program, the output after large numbers of time steps can be easily calculated. The program can be used to internally calculate the results of intermediate steps and only display the results of steps relevant to the user, such as the output after every 20 steps. This simplifies experiments involving the CA model and allows users to view the entire process of leaf growth in a short period of time.

The program options allow the user to specify the transition rule parameters or to use established transition functions based on measured data for different species. The leaf shape can be modified at any time, allowing different leaf varieties to be simulated. Similarly, portions of the leaf can be destroyed, to simulate the impact of damage to the leaf due to insect attacks. The user can also choose to run a pre-defined simulation of a more complex leaf shape.

The program was aimed at producing outputs of linear and area expansion rates for variable input conditions. The relative area of the simulated leaf at any time is calculated by counting the number of cells that are in the growing state. Similarly, the length is a count of the longest column of cells in the growing state. These values are displayed to the user as message boxes when requested, allowing quantitative predictions of leaf growth to be made using the model. Using these outputs, a user can calculate linear and area expansion rates of a particular leaf to investigate the mechanisms of such growth interactions.

## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 Output of model

##### 4.1.1 Effect of transition rules

The behaviour of the model under variations to the transition rules was observed. The step increment amounts of the transition rules were found to have a large impact on the resulting simulated leaf shape and rates of growth, as was expected. Increasing these parameters led to an increase in the growth of the leaf in the corresponding direction.

This concept is illustrated by Figs. 4.1, 4.2. Fig. 4.1 shows an example output of the model using larger values for the growth rates in the horizontal directions, while Fig. 4.2 shows the effect of smaller values in the horizontal directions.

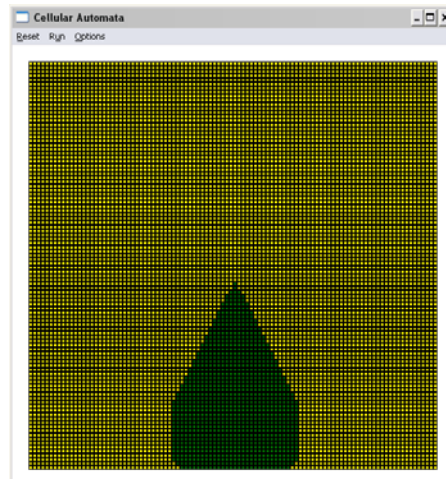
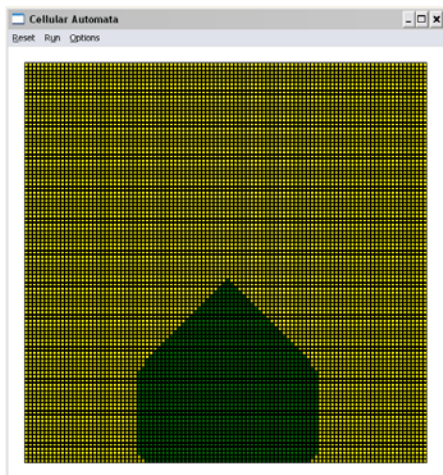


Fig. 4.1 Output using large horizontal values

Fig. 4.2 Output using small horizontal values



Since the chosen step increment amounts define the produced output, the values had to be chosen to correspond with the growth rate distributions of actual leaves. For example, if the values are equal for all directions, the output eventually becomes square shaped, even if the simulation began with a different shape. This can be seen in Fig. 4.3. However, the output in Fig.4.4 can be produced by specifying greater growth rates in the vertical direction, similar to the actual growth distribution of leaves.

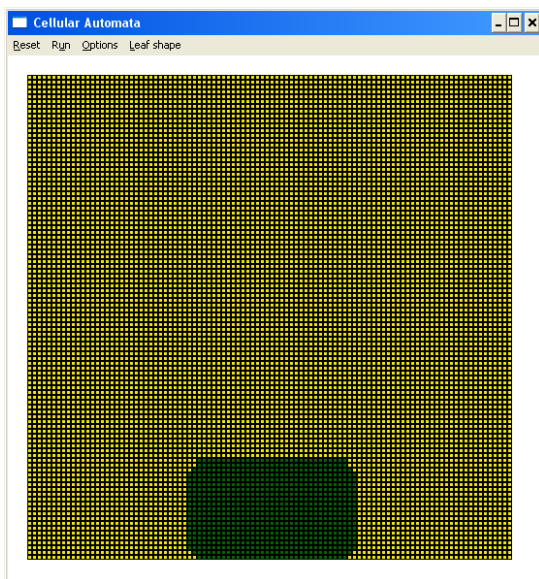


Fig. 4.3 Output using equal values for all directions

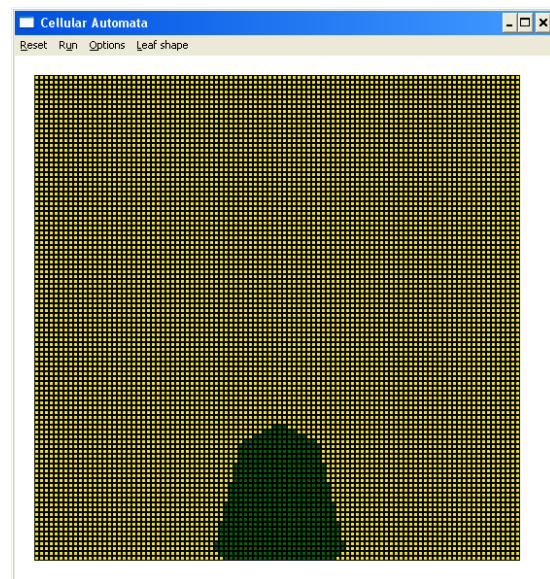


Fig.4.4 Output using larger values for vertical direction

This effect enables the model to be used to simulate different species with variations in leaf shape, by changing the transition rule parameters. Although dicot leaves were the primary target of the simulations, the model could also be used to simulate the growth of monocot leaves, by restricting the transition rules to growth in only one direction.

#### 4.1.2 Initial configuration of model

The initial configuration of the model had an impact on the output. Starting the simulation with a single cell in the growing state occasionally led to shapes which were not representative of actual leaf shapes, such as rectangular blocks of cells. Since the transition rules do not specify the required shape of the leaf, it is possible for these other shapes to occur. This situation was resolved by only considering the expansion of a leaf after the initial shape has already been established. By allowing the model to expand from an initial young leaf shape, the result of the simulation is more accurate, as the final leaf shape produced is similar to shapes found in nature.

#### 4.2 Predictions of linear expansion rate

To evaluate the effectiveness of the cellular automata model in simulating the growth of leaves, this software was used to predict the corresponding linear expansion rates for known area expansion rates.

Area expansion rates over time for three plant species: White clover, tobacco and pea, were obtained from Denne (1966), Hannam (1968) and Lecoeur et al. (1995), respectively. This data was used to obtain the step increment amounts ( $a_{dir}$ ) of the transition rules. The parameters were adjusted until the simulated area expansion rate corresponded with the measured area expansion rate as closely as possible. If the area expansion rates obtained through the simulation were larger than the measured data, the transition rule

parameters were reduced. Similarly, if the simulated area expansion rates were lower than measured rates, these parameters were increased.

After the transition rule parameters were selected, the model was used to predict the linear expansion rates of the leaf over time. These predicted rates were compared with measured linear expansion rates, to determine the accuracy of the simulation. The comparisons between predicted values and measured linear expansion rates are shown in Fig. 4.5-4.7.

The predicted rates correspond well with the measured data for clover and tobacco leaf. A relationship of  $y = 0.9416x - 0.1857$  with an  $r^2$  value of 0.94 was found for the clover leaf data and a relationship of  $y = 1.25x - 24.69$  with an  $r^2$  value of 0.85 was found for the tobacco leaf data. The gradient of the graphs are close to 1, indicating that the model is an accurate representation of leaf growth.

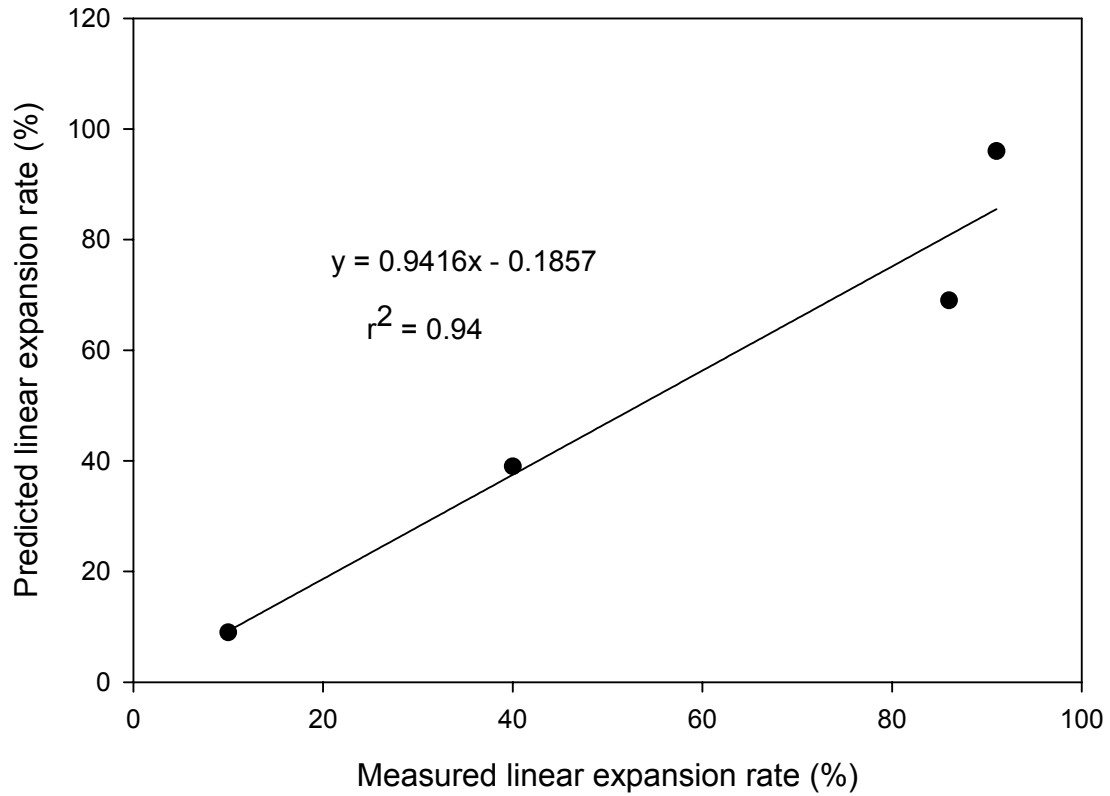
However, for the third set of data, pea leaf, the predicted rates had a larger deviance from measured values, with a relationship of  $y = 0.7739x + 7.525$  and an  $r^2$  value of 0.56. The variations can be attributed to the choice of transition rules of the CA. The shape of the simulated leaf is dependent on the emphasis on growth placed on each direction, which is determined by the transition rules. Therefore, there may be several combinations of transition rule parameters which will result in similar areas, but have different lengths.

The results indicate that the cellular automata model can be used to predict linear expansion rates based on known area expansion rates. The accuracy of the predicted values is dependent on the chosen transition rules. However, the

model can be calibrated to produce accurate simulations for a chosen species, and can then be used for further calculations.

The process of selecting transition rule parameters based on area expansion rates was automated in the software package. A dialog box is displayed for the user to enter the required area expansion rate. The program iteratively adjusts the transition rule parameters and compares the simulated area expansion rate with the required rate. When the closest possible area expansion rate is obtained, the program runs the simulation. The predicted linear expansion rate and the visual model of the growing leaf are displayed to the user.

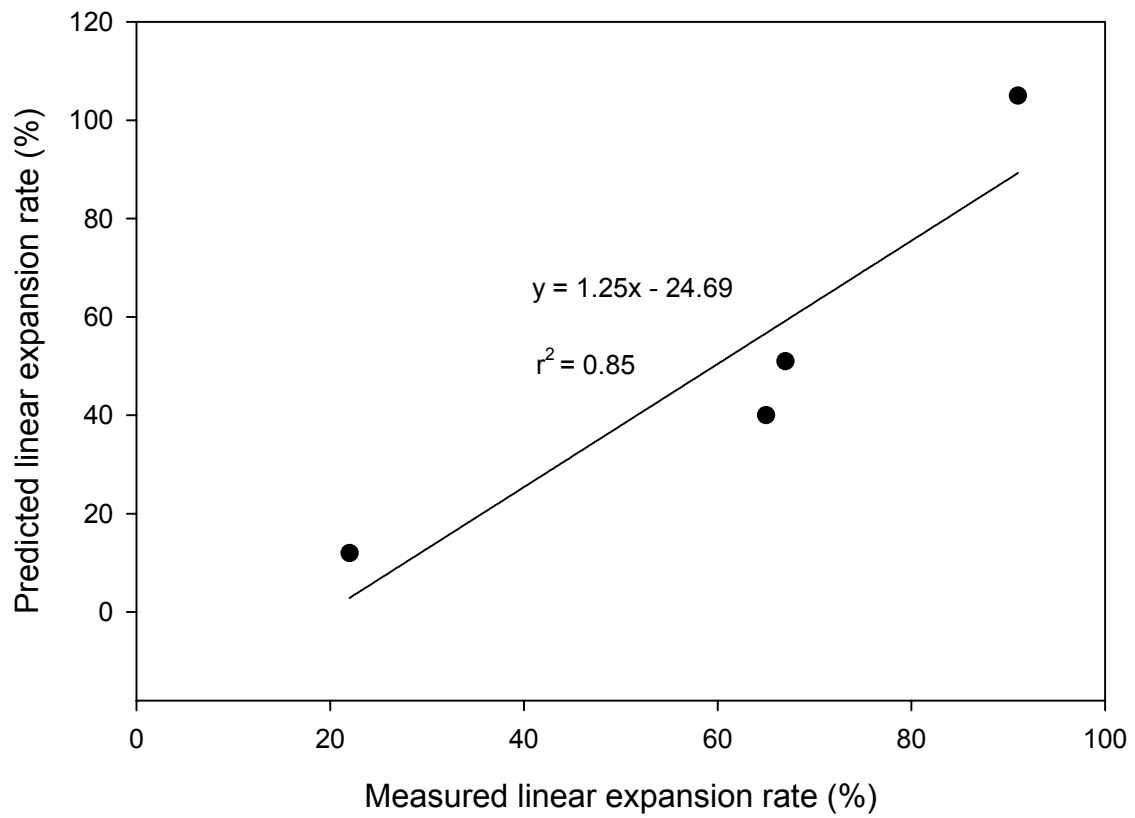
Predicted vs. Measured linear expansion rates  
for clover \*



\* Measured data obtained from Denne (1966).

Fig. 4.5 Comparison between predicted and measured linear expansion rates for clover

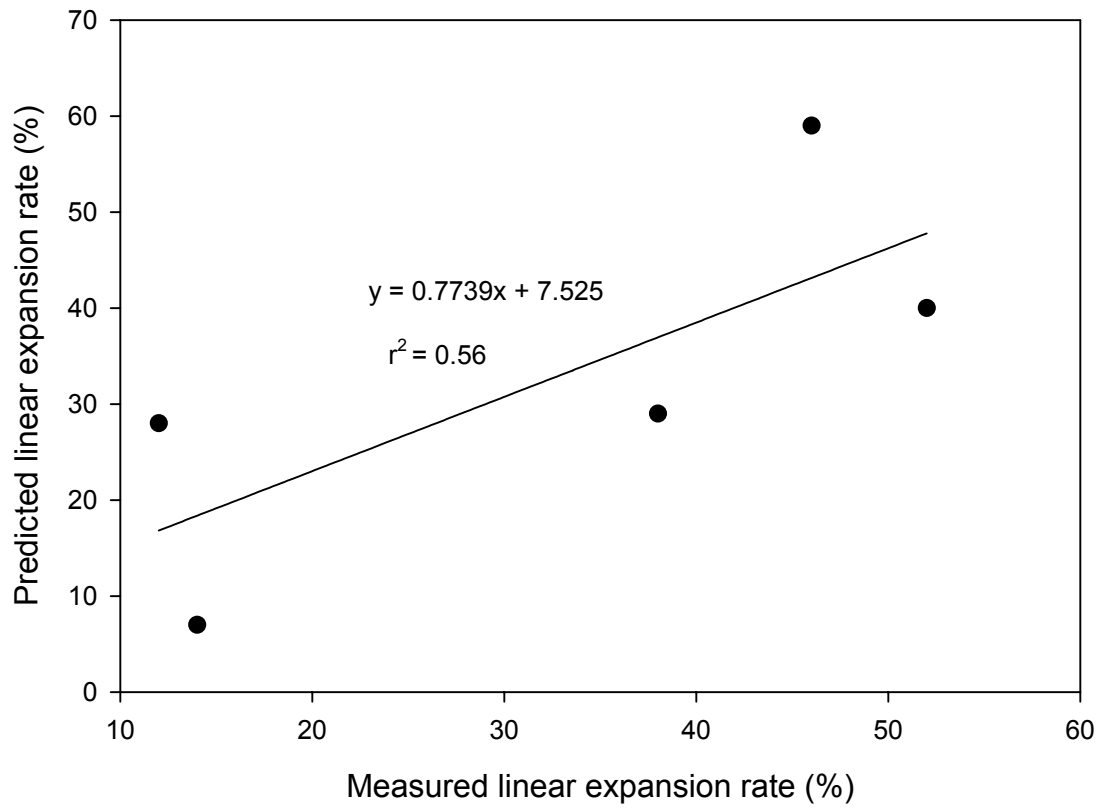
Predicted vs. Measured linear expansion rate  
for tobacco \*



\* Measured data obtained from Hannam (1968).

Fig. 4.6 Comparison between predicted and measured linear expansion rates for tobacco leaf

Predicted vs. Measured Linear expansion rates  
for pea leaf \*



\*Measured data obtained from Lecoeur et al. (1995)

Fig. 4.7 Comparison between predicted and measured linear expansion rates for pea leaf

### 4.3 Simulation of Complex Shapes

The cellular automata model was modified to simulate shapes with varied distributions in growth rate, using the method described in section 3.1.2. The leaf was divided into three sections, with different transition functions defined for each section. The simulation was performed using the initial leaf shape shown in Fig.4.8. The output of the simulation after several time-steps is shown in Fig.4.9. The leaf correctly expanded along the three directions specified. This indicates that the method used is effective for simulating leaves with varying growth behaviour in different sections.

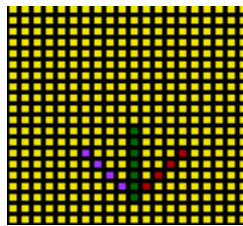


Fig.4.8 Initial complex shape used (scale expanded for ease of viewing)  
(different colours represent different sections)

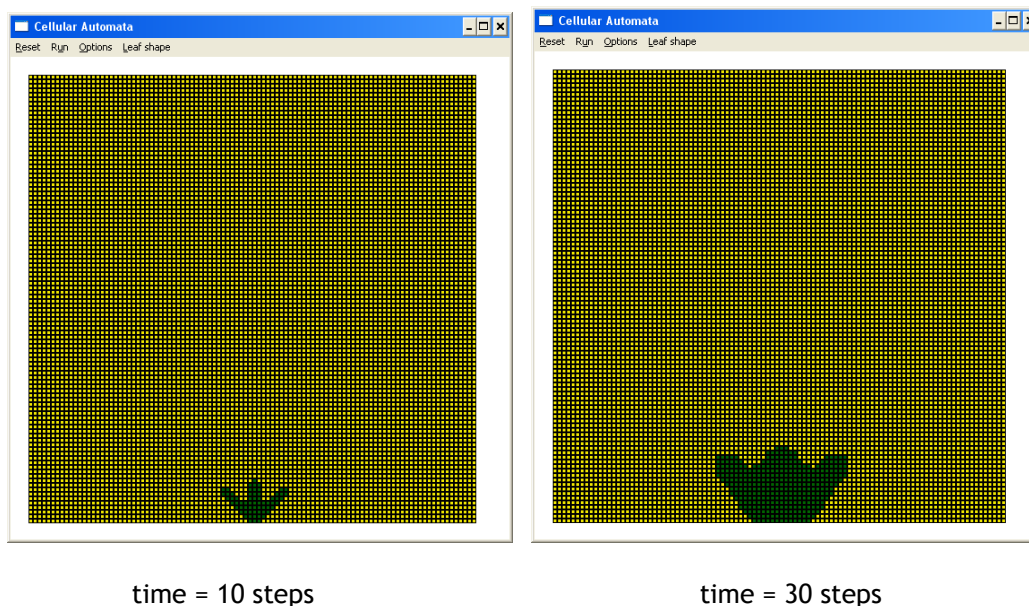


Fig.4.9 Output of complex shape simulation



#### 4.4 Effect of damage to leaf

The growth of a leaf can be affected by numerous factors, such as insect attacks. Therefore, it is of interest to model leaf growth under these different conditions. The effect of different conditions on leaf growth has been studied by several sources, including Wolf et al. (1986), in which the relative growth rates of different sections of a normal and a malformed leaf were compared.

The cellular automata model was extended to incorporate the effects of insect attacks and other damage to the leaf surface, by modifications to the states of the CA cells. The states of affected cells were set to a permanent non-growing state, representing sections of the leaf which were damaged. The values of the affected cells were set to 0. The simulation was then allowed to proceed, using the normal transition rules. The result of the simulation after a small section of the leaf was damaged is shown in Fig.4.10.

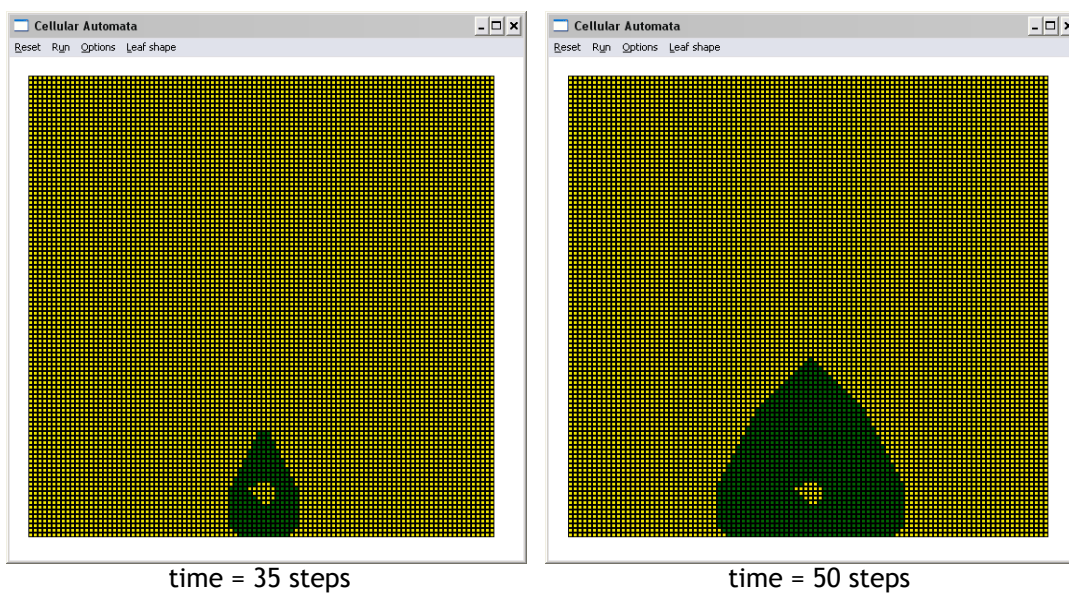


Fig. 4.10 Output after small damage to the leaf occurred at time 35 steps

The result of the simulation after a bordering section of the leaf was damaged is shown in Fig.4.11. Initially, the damage results in abnormal growth, similar to an actual leaf. However, after some time, the leaf forms a new border, which is not as would be expected of actual leaf behaviour. This is due to the localised properties of cellular automata, in which cells in different areas are unaware of damage to non-neighbouring cells. Therefore, the cellular automata system proposed seems appropriate for the simulation of the effect of small damages to the leaf surface, but not for larger damages involving the leaf border.

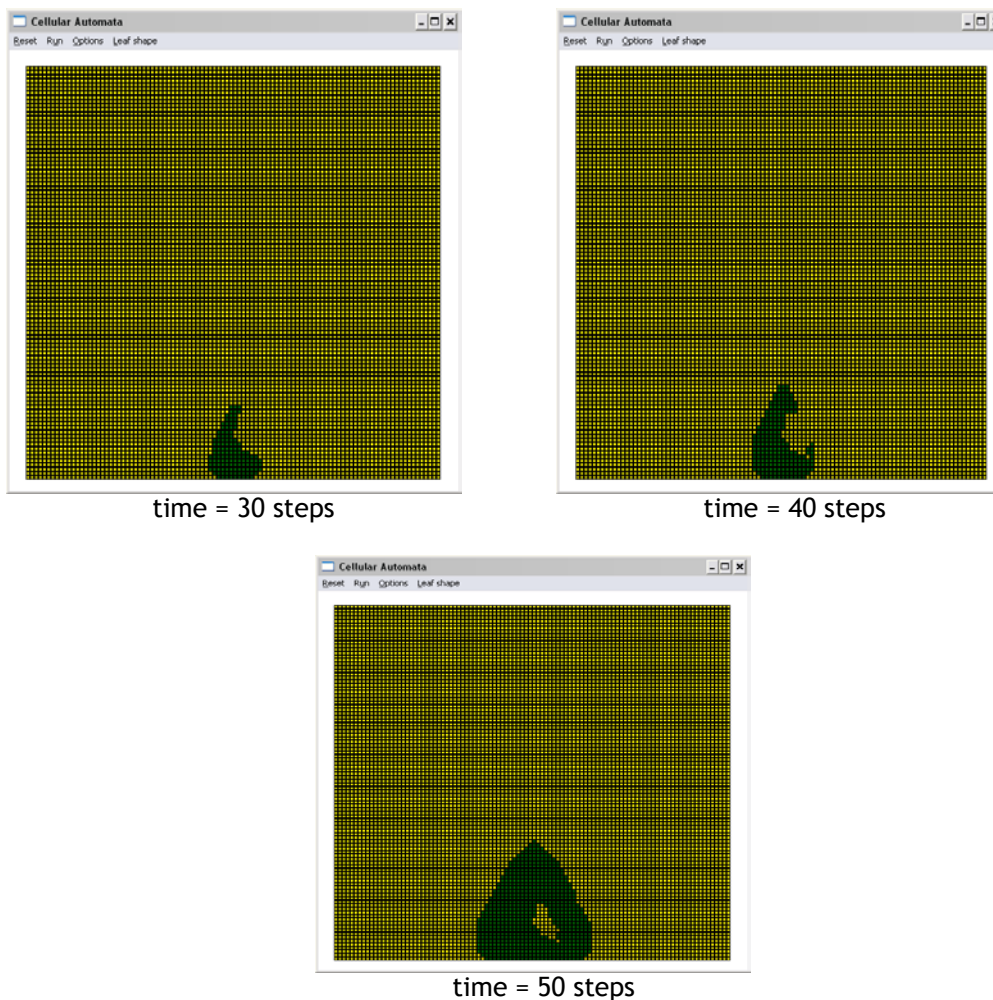


Fig. 4.11 Output after bordering section of leaf is destroyed at time 30 steps.

## 4.5 General Discussion

The results of the simulations performed using the cellular automata model indicate that the model is a good representation of leaf expansion. The linear expansion rates predicted using the model corresponded closely with measured data. This indicates that the growth rates and leaf shapes produced by the model are similar to the properties of growing leaves. The growth of leaves is a physical system, whereas simulation methods are numerical systems. This poses inherent difficulties associated with fitting numerical values to the physical entities. An example of such a difficulty is the precision of the step increment amounts for the values of the CA cells, which can affect the behaviour of the simulation. A low degree of precision results in an inaccurate representation of leaf growth, whereas high precision can lead to oscillating effects inherent in numerical systems. This indicates that an appropriate level of precision must be found to match the physical system with a numerical system. The results obtained in this study indicate that the representation of some properties of physical systems, such as of a growing leaf, can be made possible with numerical values.

The expansion of leaves of different species with variations in shape can be simulated by modifications to the model transition rules. Similarly, the effect of small damages to the leaf surface can be simulated by changes to the CA states of the affected cells. However, the model was unable to accurately simulate the effects of larger damages. Overall, the cellular automata model can effectively simulate the expansion of leaves.

The cellular automata system developed is capable of representing the spatial and temporal behaviour of the expansion of leaves. The model would therefore be beneficial for agricultural purposes requiring outputs of yield to be produced for continuously varying inputs. Crop growth models, such as GRASSMAN (Scanian and McKeon 1990) and PLANTGRO (Hackett 1991) produce such outputs. To be used in such systems, the model could be calibrated to perform simulations of ideal leaves for a particular species, using field measurements. The growth of leaves in the field could then be compared to the output of the simulation, enabling modifications to be made to improve the final leaf properties. Using a model for leaf expansion allows improvements to be made at earlier stages of leaf growth.

The system developed would be beneficial for precision farming techniques. Precision farming requires a large number of decisions to be continually made over time, based on environmental, economic and growth factors (Clark and McGuckin 1996). An automated system is essential for such a system. The cellular automata model could be easily integrated into a precision farming system, to aid in decisions involving leaf expansion.

Further studies on the application of cellular automata to leaf expansion could involve improvements to the states and transition rules used in the system, to further reflect the measured properties of leaves in the field. The effect of different conditions to the growth of the leaf, such as drought, could be incorporated into the model, allowing the model to aid in studies of these situations.

## CHAPTER 5

### CONCLUSIONS

The physical system of leaf expansion can be effectively simulated using the cellular automata method. The model developed in this study was able to accurately simulate the growth of leaves, by assigning numerical values to leaf properties. By appropriately selecting the precision of the step increment values, the calculated output can further be improved to reflect the natural leaf growth patterns. The cellular automata system developed would be beneficial for use in precision farming systems, where an automated system is necessary to provide continuous results for varying inputs. As the cellular automata model can simulate rapidly changing behaviour of leaves, this system can be an appropriate tool for performing such system integrations. Future studies in this area could involve the inclusion of the impact of environmental effects on the leaf.

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## APPENDIX A - SOURCE CODE

The source code for the software package developed can be downloaded from the Innovation Expo 2003 website:

<http://innovexpo.itee.uq.edu.au/2003/exhibits/s363324>