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Chapter 1

Vegetation

An essential part of rural terrains is vegetation. Available resources determine which plant species are able to grow and to what extent they strive in a given environment. Reproducing this link between species and climate is essential to determine suitable vegetation and subsequently generate plausible terrains.

To be able to determine environments suited for given plants, plant species are configured with associated resource requirement properties. Details of which can be found in *Plant Species* .
Given these properties, it is possible to automatically filter out ill-suited plants from being suggested to the user. Information about this automatic filtering feature is outlined in *Plant suitability filtering*.

Although a multitude of plants can grow in a given environment, some will naturally strive more than others. This can be because resources are more adequate or they have a faster, more aggressive growth rate. To model this intra-specie battle for resources and determine a suitable vegetative state, an ecosystem simulator is used. Details of which can be found in *Ecosystem Simulator*.

The ecosystem simulator is computationally expensive and can take some time to determine a valid distribution. The simulation time is dependent on the number of plant instances, the simulation area and the duration. To accelerate the process, the ecosystem simulator is run on a small area and the resulting distribution analysed in order to reproduce it on larger areas. A caching system is also used to prevent users from having to run the same simulation more than once. Information about these acceleration methods can be found in *Plant Distribution Analysis and Reproduction*.

Property	Value	Unit
Slope	Maximum Slope	Degrees
Growth	Maximum canopy	Centimetres
	Maximum root size	Centimetres
	Maximum height	Centimetres
Ageing	Start of decline	Months
	Maximum age	Months
Seeding	Maximum seeding distance	Metres
	Annual seed count	-
Illumination	Start of prime	hours
	End of prime	hours
	Minimum	hours
	Maximum	hours
Humidity	Start of prime	millimetres
	End of prime	millimetres
	Minimum	millimetres
	Maximum	millimetres
Temperature	Start of prime	degrees
	End of prime	degrees
	Minimum	degrees
	Maximum	degrees

1.1 Plant Species

A database is used to store all plant species and their associated properties. The associated properties are used to determine their ability to grow in given environments and, subsequently, deduce a plausible distribution using the ecosystem simulator. Details about these properties, how they can be edited and new species added is discussed in *Specie Properties* and *Storing Species* respectively.

1.1.1 Specie Properties

When configuring a new specie it is necessary to specify a set of associated properties. These are used to determine whether or not the specie is suited to a given environment and, if so, by the ecosystem simulator to determine a suitable distribution. Table summarises the properties which are associated with each specie, discussed in detail below.

1.1.1.1 Slope

Steep slopes cause essential water and soil nutrients to run-off, making them less rich and, therefore, less suited to plant growth. The slope angle also causes larger species to struggle to support their own extensive biomass. For this reason, steeper slopes often cater for smaller plant species (grass, shrub, etc.). To model the effect of slope on given plant species, when configuring a new plant specie an associated *maximum slope* must be specified.

1.1.1.2 Growth

To model the growth of a plant specie in the ecosystem simulator, it is necessary to specify: *Maximum height*, *maximum canopy width* and *maximum root size*. Using this along with the specie's ageing properties (see 1.1.1.3), it is possible to simulate the plants vertical growth (height), horizontal growth (canopy) and root coverage. Determining a plant's height and canopy width is essential in order to determined the shade it project's on other plants during the simulation. Modelling the plant's root growth is used to determine how far the plant can reach in order to fetch vital soil water.
A maximum canopy width of zero can be used to model plants with no canopy.

1.1.1.3 Ageing

Biological life-cycle varies greatly between plant species. Whereas annual and biennials have a fixed lifespan of one and two years respectively, perennial plant species can live far longer. To model the life-cycle of different plant species they must be configured with an associated *start of decline* and *maximum* age. Using these two values, it is possible to simulate a plant getting weaker and becoming more susceptible to domination from surrounding plants.

1.1.1.4 Seeding

It is necessary to replicate the spawning of offspring in the ecosystem simulator for two main reasons:

1. *Propagation*: Plants propagate on a terrain by producing new offspring which attempt to spawn and invade different areas.

2. *Succession*: New plants spawn to later succeed older and weaker plants of the same specie.

Depending on the specie, plants spawn new offspring by producing seeds or spores. Although biologically different, both can be considered identical for the sole purpose of modelling propagation and succession.
The number of seeds/spores that a given plant creates annually is specie-dependent and therefore must accompany the specie configuration.
Different species use different techniques to propagate their seeds. For example, some use fruit as a mechanism to propagate using animals digestive systems, some are coated with a sticky mucous and attach to animals fur, some use the wind and some rely solely on gravity to take the seeds to the ground straight below. The seeding mechanism used directly affects the distance which can be achieved between parent and offspring. To emulate this in the system, a *maximum seeding distance* must be configured with each specie.

1.1.1.5 Illumination

Illumination has a big impact on plant growth. Whereas some species strive in the shaded undergrowth, others require direct illumination all year round. To model this, the following illumination values must be configured with each plant specie:

- *Minimum daily illumination*: The minimum daily illumination, in hours, at which a plant of this specie can survive.

- *Prime daily illumination range*: The daily illumination range, in hours, which is optimal for the given specie.

- *Maximum daily illumination*: The maximum daily illumination, in hours, at which a plant of this specie can survive.

1.1.1.6 Humidity (rainfall)

Soil water deposited into the soil by either rainfall or existing groundwater is absorbed by plant roots and is vital to its development and survival. Whereas some species have evolved to survive in arid climates with very little water, others require frequent downpours of rain.
To simplify water requirement specifications of different plant species, it is necessary to configure the amount of rainfall necessary as if this was the plant's only source of water (i.e no groundwater). The following values must be configured to accurately grasp a species water requirements:

- *Minimum monthly rainfall*: The minimum monthly rainfall, in millimetres, at which a plant of this specie can survive.

- *Prime monthly rainfall range*: The monthly rainfall range, in millimetres, which is optimal for the given specie.

- *Maximum monthly rainfall*: The maximum monthly rainfall, in millimetres, at which a plant of this specie can survive.

1.1.1.7 Temperature

Another aspect of climates which greatly affect plant growth is temperature. To model a plant species temperature requirements, the following need to be configured:

- *Minimum temperature*: The minimum temperature, in degrees, at which a plant of this specie can survive.

- *Prime temperature range*: The temperature range, in degrees, which is optimal for the given specie.

- *Maximum temperature*: The maximum temperature, in degrees, at which a plant of this specie can survive.

1.1.2 Storing Species

All species and associated properties are stored in a database for easy retrieval and filtering. A dedicated tool can be used to interact with the database and add/remove species and edit existing ones (see figure 1.1).

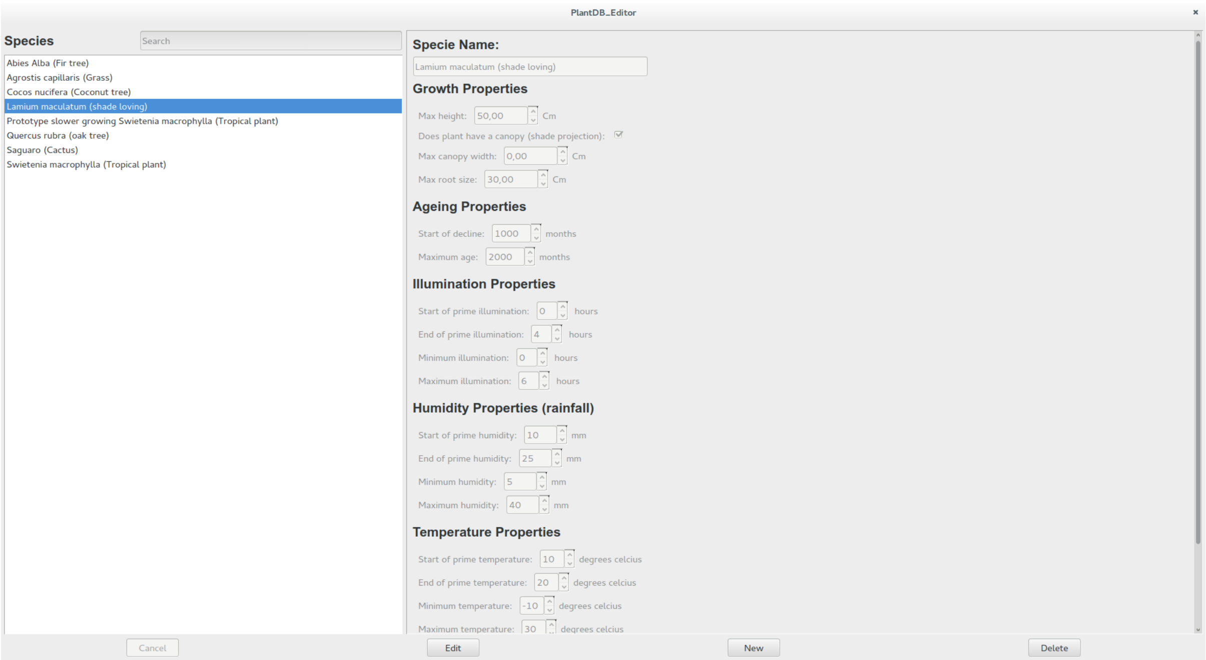

Figure 1.1: Plant database editor tool.

1.2 Ecosystem Simulator

Once the user selects the union of all species that must appear in all clusters of the terrain, it is necessary to determine a valid vegetation distribution for each cluster. To do so, an ecosystem simulator is used similarly to that in the work by Deussen et al **?** and Lane and Przemyslaw **?**. Unlike these other ecosystem simulators, however, it isn't based on L-Systems and models both resource requirements and resource availability in greater detail. The purpose of ecosystem simulator is to determine, given a vegetative state, S_t at time t, the vegetative state S_{t+n} at time $t+n$, for any value of n.

To do so, the simulation advances through time in monthly intervals and the strength of all plant instances are re-calculated at each iteration. Their strength depend not only on resource properties of the given month but also surrounding plants as they battle for these resources. Determining the set S = {P_1, P_2, P_3, ...} of plants which compete for resources with plant P_n depends on the spatial reach of P_n. Spatial awareness is therefore a key requirement of the simulation which is achieved by splitting the simulation area into a grid of cells as described in *Gridded Simulation Area*.

Within each cell of the gridded simulation area, resources must be distributed to the different plant instances present. How this is done is described in *Resource Distribution*.

Given the resources allocated to each plant instance, it is possible to calculate their strength. This is used as a representation of the plant's health and, consequentially, it's ability to survive and grow. Details about the plant's strength calculation and it's usage is discussed in *Plant Strength Calculation* and *Plant Strength Usage* respectively.

On an annual basis, new plant instances are spawned based on species seeding properties. How this is done is discussed in *Spawning Plants*.

To conclude the discussion on the ecosystem simulator, it's performance will be analysed in *Performance* and results discussed in *Results*.

1.2.1 Gridded Simulation Area

The simulation window used is one hundred by one hundred meters, accurate to the nearest centimetre. To easily model plant's interacting and battling for resources, the window is split into cells to form a grid as illustrated in figure 1.2. One hundred metres was chosen as the simulation window size it is deemed large enough to model the interaction of any type of plant specie.

The size of individual cells can be configured to increase/decrease the resolution and, therefore, the accuracy of the simulation. As the simulation progresses, plant's grow, their spatial coverage increases, and they enter new grid cells. When a plant enters a new grid cell, it becomes a member of it and cell resources must be distributed to it as well as all other plants present in the given cell. The information associated to each individual grid cell can be split into two categories: *time-dependent* and *simulation-dependent*. The time-dependent information depends only on the current month, is identical for every grid cell and is comprised of: the *soil humidity* and the *illumination*. The simulation-dependent information changes throughout the simulation as plants spawn, die and grow

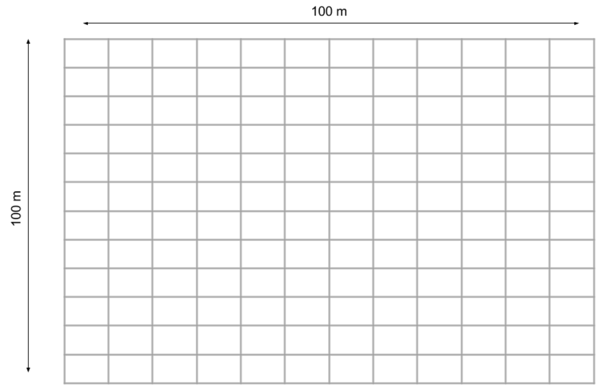

Figure 1.2: Gridded simulation area.

and is comprised of: the list of plants whose roots intersect the cell and the list of plants whose canopy intersects the cell.

1.2.2 Resource Distribution

The strength of each plant in the simulation must be recalculated on a monthly basis. To determine the strength of a given plant, it is necessary to know the illumination and humidity allocated to it along with the temperature. The temperature is not a distributable resource and is identical for all plant instance for a given month. The allocated humidity and illumination is determined by averaging the resources distributed to it in each cell it overlaps in the grid. So, before the strengths of individual plant instances can be calculated, first each cell of the grid must be iterated over and illumination and humidity distributed to the plants contained within. How these are allocated is discussed below.

1.2.2.1 Illumination Distribution

Plants which are heavily dependent on illumination will often grow a large canopy in order to maximize the leaf coverage area which receives direct sunlight. In the process this will restrict the illumination received by smaller plants in the undergrowth. To model the shade projection of larger plants, illumination is distributed in each cell depending on the plants height and canopy width.

Equation 1.1 is used to allocation illumination amongst the set $S = \{\mathrm{P}_1, \mathrm{P}_2, \mathrm{P}_3, ...\}$ of plants which canopy intersect with cell C_{xy}.

$$Illumination(P_n) = \begin{cases} C_{illumination}, & \text{if } CanopyWidth(P_n) = 0 for x \in S \\ C_{illumination}, & \text{if } Height(P_n) > height(x) for x \in S : x \neq P_n \\ 0, & \text{otherwise} \end{cases} \tag{1.1}$$

Where:

- *Illumination(P_n)* is the illumination allocated to plant P_n whose canopy overlaps with current grid cell.

- $C_{illumination}$ is the monthly illumination of the cell.
- *CanopyWidth(P_n)* is the canopy width of plant P_n.
- *Height(P_n)* is the height of plant P_n.
- S is the set of plants whose canopy intersects with the given grid cell.

Intuitively, if all plants present in the given cell are canopy-free (i.e no shade projection), the equation allocates them all the available illumination. If not all plants are canopy-free, the equation allocates illumination only to the tallest canopy plant.

1.2.2.2 Humidity Distribution

Plants grow there roots in order to access the nutrients and moisture available in the surrounding soil. As roots of different plants overlap, they start to compete for these soil resources.

When distributing the soil humidity of a given grid cell C_{xy} to the set $S = \{P_1, P_2, P_3, ...\}$ of plants which roots intersect the cell, one of three distinct scenarios can occur depending on the total available humidity of the cell: *Abundant humidity*, *sufficient humidity* and *insufficient humidity*.

The humidity is deemed abundant if the available humidity, $H_{available}$, surpasses 300 millimetres. In this situation, the humidity is deemed to be enough for there to be standing water and therefore all plants of S are allocated $H_{available}$.

If $H_{available}$ is less than 300 millimetres, it is necessary to determine whether the humidity is sufficient or insufficient by calculating the requested humidity $H_{requested}$ as outlined in equation 1.2.

$$H_{requested} = \sum MinHumidity(P_n) \text{ for } n \in S \tag{1.2}$$

Where:

- *MinHumidity(P_n)* is the minimum humidity requirement of the specie to which plant P_n belongs.
- S is the set of plants whose roots intersect with the given grid cell.

If $H_{requested}$ is less than $H_{available}$, the humidity is deemed sufficient and the amount allocated to each plant is calculated as described in equation 1.3. If $H_{requested}$ is more than $H_{available}$, however, the humidity is deemed insufficient and the allocation is done following equation ...

$$\begin{aligned} H_{allocated}(P_n) &= MinHumidity(P_n) + OverFlow \\ OverFlow &= H_{available} - \sum MinHumidity(P_n) \text{ for } n \in S \end{aligned} \tag{1.3}$$

Where:

- $H_{allocated}(P_n)$ is the humidity allocated to plant P_n.
- *MinHumidity*(P_n) is the minimum humidity requirement of the specie to which plant P_n belongs.
- S is the set of plants whose roots intersect with the given grid cell.

Intuitively, it allocates each plant with the minimum amount of humidity it requires to survive plus the resulting overflow.

$$\begin{aligned} H_{allocated}(P_n) &= min(MinHumidity(P_n), Vigor(P_n) \times H_{remaining}) \\ Vigour(P_n) &= \frac{RootSize(P_n)}{\sum RootSize(P_x) \text{ for } x \in S} \\ H_{remaining} &= H_{available} - (\sum H_{allocated}(P_x) \text{ for } x \in S_{processed}) \end{aligned} \tag{1.4}$$

Where:

- The plants of S **must** be iterated over in decrementing order of their vigor as this will affect the water they are allocated.
- $H_{allocated}(P_n)$ is the humidity allocated to plant P_n.
- *MinHumidity*(P_n) is the minimum humidity requirement of the specie to which plant P_n belongs.
- *Vigour*(P_n) is the vigor of plant P_n in comparison to other plants present in the cell. It is estimated based on root size.
- *RootSize*(P_n) is the root size of plant P_n.
- $S_{processed}$) is the set of plants from S whose water allocation has already been calculated.
- S is the set of plants whose roots intersect with the given grid cell.

Intuitively, this algorithm prioritises water distribution to more vigorous plant's.

1.2.2.3 Plant Humidity Allocation

To calculate the humidity allocated to plant P_n, it is first necessary to determine the set of grid cells S = {C_1, C_2, C_3, ...} which it's roots intersect. Given this, the plants humidity allocation is calculated using equation 1.5. The humidity allocated to a given plant is simply the average of the humidity allocated to it in all grid cells it's roots intersect.

$$H_n = \frac{\sum H_{allocated}(C_x) \text{ for } x \in S}{|S|} \tag{1.5}$$

Where:

- H_n is the humidity allocated to plant P_n.
- $H_{allocated}(C_n)$ is the humidity allocated to plant P_n in grid cell C_n.
- $|\ S\ |$ is the number of cells in the set S.

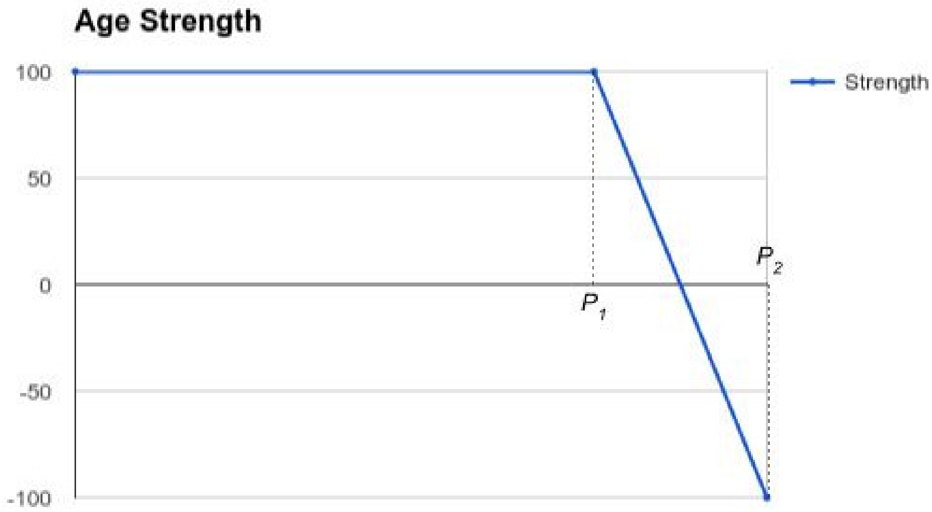

Figure 1.3: Graph used to calculate the age strength of any plant. $\mathbf{P}_1$ is the age of *start of decline* configured for the given specie. $\mathbf{P}_2$ is the *maximum age* configured for the given specie.

1.2.2.4 Plant Illumination Allocation

Calculating the illumination allocated to a plant P_n is very similar to calculating the humidity allocation only the set of grid cells $S = \{C_1, C_2, C_3, ...\}$ are those which the plants canopy intersects. Given S, the plant illumination is calculated using equation 1.6.

$$I_n = \frac{\sum I_{allocated}(C_x) \text{ for } x \in S}{|S|} \tag{1.6}$$

Where:

- I_n is the illumination allocated to plant P_n.
- $I_{allocated}(C_n)$ is the illumination allocated to plant P_n in grid cell C_n.
- $|S|$ is the number of cells in the set S.

1.2.3 Plant Strength Calculation

The strength of plant P_n is the minimum of S_{age}, $S_{temperature}$, $S_{illumination}$ and $S_{humidity}$ which represent the strength of the plant in terms of it's age, temperature, illumination and humidity respectively. Each strength is a value ranging form negative to positive one hundred. How each individual strength is calculated is discussed below.

1.2.3.1 Age Strength

A graph as illustrated in figure 1.3 is generated for each specie using it's associated ageing properties. This graph is used to determine the age strength S_{age} of any plant P_n.

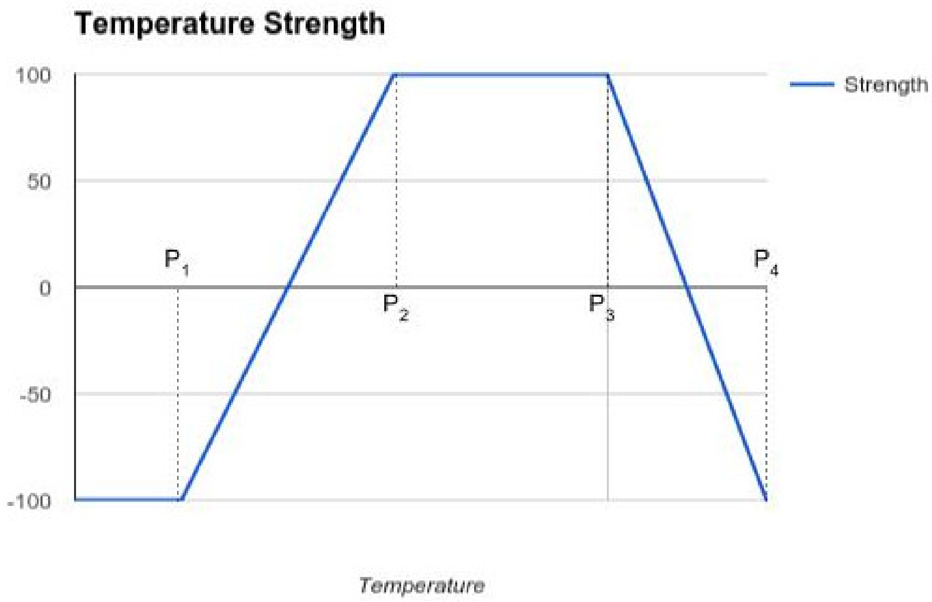

Figure 1.4: Graph used to calculate the temperature strength of any plant. $\mathbf{P}_1$ and $\mathbf{P}_4$ are the *minimum* and *maximum temperature* configured for the given specie. $\mathbf{P}_2$ and $\mathbf{P}_3$ form the *prime temperature range* configured for the given specie.

1.2.3.2 Temperature Strength

A graph as illustrated in figure 1.4 is generated for each specie using it's associated temperature requirement properties. This graph is used to determine the temperature strength $S_{temperature}$ of any plant P_n.

1.2.3.3 Illumination Strength

A graph as illustrated in figure 1.5 is generated for each specie using it's associated illumination requirement properties. This graph is used to determine the illumination strength $S_{illumination}$ of any plant P_n.

1.2.3.4 Humidity Strength

A graph as illustrated in figure 1.6 is generated for each specie using it's associated humidity requirement properties. This graph is used to determine the humidity strength $S_{humidity}$ of any plant P_n.

1.2.4 Plant Strength Usage

The strength of each plant is recalculated on a monthly basis as available resources change and other plants spawn and grow. The strength of a plant is used to determine its growth potential and probability of death as discussed below.

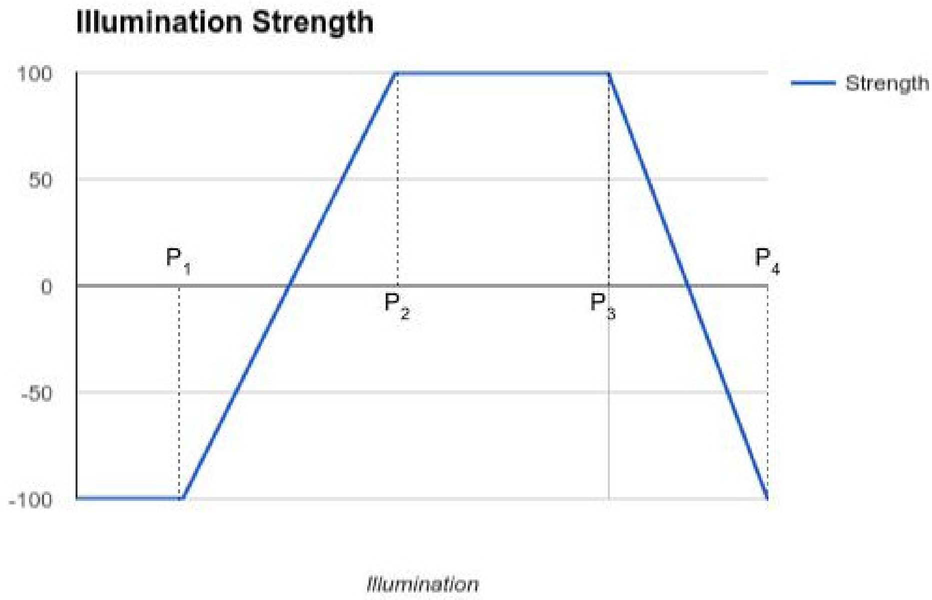

Figure 1.5: Graph used to calculate the illumination strength of any plant. $\mathbf{P}_1$ and $\mathbf{P}_4$ are the *minimum* and *maximum illumination* configured for the given specie. $\mathbf{P}_2$ and $\mathbf{P}_3$ form the *prime illumination range* configured for the given specie.

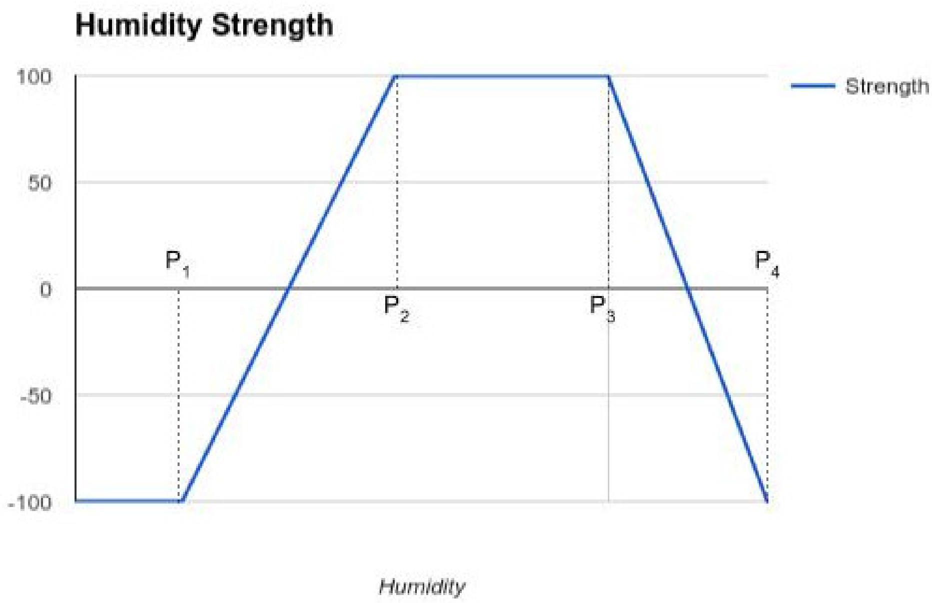

Figure 1.6: Graph used to calculate the humidity strength of any plant. $\mathbf{P}_1$ and $\mathbf{P}_4$ are the *minimum* and *maximum humidity* configured for the given specie. $\mathbf{P}_2$ and $\mathbf{P}_3$ form the *prime humidity range* configured for the given specie.

1.2.4.1 Growth Potential

In the simulation, each plant P attempts to grow its roots, its canopy and it's height on a monthly basis. Each specie has a maximum root growth $MaxGrowth_{root}$, canopy growth $MaxGrowth_{canopy}$ and height growth $MaxGrowth_{height}$ which is calculated based on the growth and ageing properties using equations 1.7, 1.8 and 1.9 respectively.

$$MaxGrowth_{root}(S) = \frac{MaxRoot(S)}{Age_{StartOfDecline}(S)} \tag{1.7}$$

Where:

- $MaxGrowth_{root}(S)$ is the maximum monthly root growth of specie S.
- $MaxRoot(S)$ is the configured maximum root size of the specie S.
- $Age_{StartOfDecline}(S)$ is the age of start of decline configured for specie S.

$$MaxGrowth_{canopy}(S) = \frac{MaxCanopy(S)}{Age_{StartOfDecline}(S)} \tag{1.8}$$

Where:

- $MaxGrowth_{canopy}(S)$ is the maximum monthly canopy growth of specie S.
- $MaxCanopy(S)$ is the configured maximum canopy size of specie S.
- $Age_{StartOfDecline}(S)$ is the age of start of decline configured for specie S.

$$MaxGrowth_{height}(S) = \frac{MaxHeight(S)}{Age_{StartOfDecline}(S)} \tag{1.9}$$

Where:

- $MaxGrowth_{height}(S)$ is the maximum monthly height growth of specie S.
- $MaxHeight(S)$ is the configured maximum height of specie S.
- $Age_{StartOfDecline}(S)$ is the age of start of decline configured for specie S.

The actual root growth $Growth_{root}$, canopy growth $Growth_{canopy}$ and height growth $Growth_{height}$ is directly dependent on the plant's strength, however, and this maximum is achieved only if the plant is at its full strength. The actual monthly root, canopy and height growth is calculated using equations 1.10, 1.11 and 1.12 respectively. Note that no plants grow if there current strength is negative as they are deemed in a *survival state*.

$$Growth_{root}(P, S) = max(0, Strength(P) \times MaxGrowth_{root}(S) \tag{1.10}$$

Where:

- $Growth_{root}(S)$ is the monthly root growth of plant P of specie S.
- *Strength(P* is the current strength of P.

- *$MaxGrowth_{root}$(S)* is the maximum monthly root growth calculated for specie S.

$$Growth_{canopy}(P, S) = max(0, Strength(P) \times MaxGrowth_{canopy}(S) \tag{1.11}$$

Where:

- *$Growth_{canopy}$(S)* is the monthly canopy growth of plant P of specie S.
- *Strength(P* is the current strength of P.
- *$MaxGrowth_{canopy}$(S)* is the maximum monthly canopy growth calculated for specie S.

$$Growth_{height}(P, S) = max(0, Strength(P) \times MaxGrowth_{height}(S) \tag{1.12}$$

Where:

- *$Growth_{height}$(S)* is the monthly height growth of plant P of specie S.
- *Strength(P* is the current strength of P.
- *$MaxGrowth_{height}$(S)* is the maximum monthly height growth calculated for specie S.

1.2.4.2 Probability of Death

On a monthly basis, the probability of death of each plant is calculated based on it's strength using equation 1.13 and the plant killed with the said probability. Note that a plant P will only be susceptible to be killed off if it's strength is negative.

$$Probability_{death}(P) = max(0, \frac{-1 \times Strength(P) + counter}{100}) \tag{1.13}$$

Where:

- *Probabilitydeath(P)* is the probability of death of plant P.
- *Strength(P* is the current strength of P.
- *counter* is a value which increases by ten each month the plant's strength is negative and resets to zero when it becomes positive. This is to prevent plant's from surviving with a continuous negative strength for too long.

1.2.5 Spawning Plants

In nature, the spawning of new plants ensures specie *succession* and *propagation*. In order to accurately model the evolution of an ecosystem it is essential to replicate this spawning mechanism. To do so, seeds are produced annually for each specie and are positioned either randomly or at predefined positions. The number of seeds that are produced for a given specie is determined by the specie's *annual seed count* configuration.

Different seeding mechanisms are used in the simulator depending on the number of plant's of the given specie present in the simulation, S_{count}, and it's illumination properties.
If S_{count} is greater than zero, existing plant instances are used to determine the location of new plants, irrespective of it's illumination requirements, as described in *Spawning from Existing Plants*.
If S_{count} is zero, the seeding mechanism depends on the specie's illumination requirements. If the specie is shade loving, *canopy seeding* is employed, else *random seeding*. Both are discussed below.

1.2.5.1 Spawning from Existing Plants

To ensure specie propagation, when plant's of the given specie are already present in the simulation window, they are used to determine the location for new plant instances. To do so, n of these plants are selected at random and seeds placed at random within an annular radius r of each. The value of n is the *annual seed count* configured for the current specie. The value of r is the configured *maximum seeding distance* of the specie. Note that if the number of plants of the given specie is less than the number of seeds to produce, a single plant is used to produce multiple seed locations.

This technique effectively ensures *propagation* until the number of plant instances present is larger than the number of seeds to produce. At which point, the *propagation* potential decreases as the plant count increases. This is because as the selection pool for the random plants increases in size, the probability of selecting a plant at a location which will permit propagation decreases. To overcome this and ensure the initial seeding plants that are selected span a wide area of the simulation window, they are selected at from individual simulation grid cells.

1.2.5.2 Canopy Seeding

Shade-loving plants strive in the shaded undergrowth. If shade-loving plants are spawned at random locations in the simulation, the probability of them landing under the canopy of an existing plant is extremely low. To overcome this, shade-loving plants are not spawned at random but under the canopy of randomly selected plants.

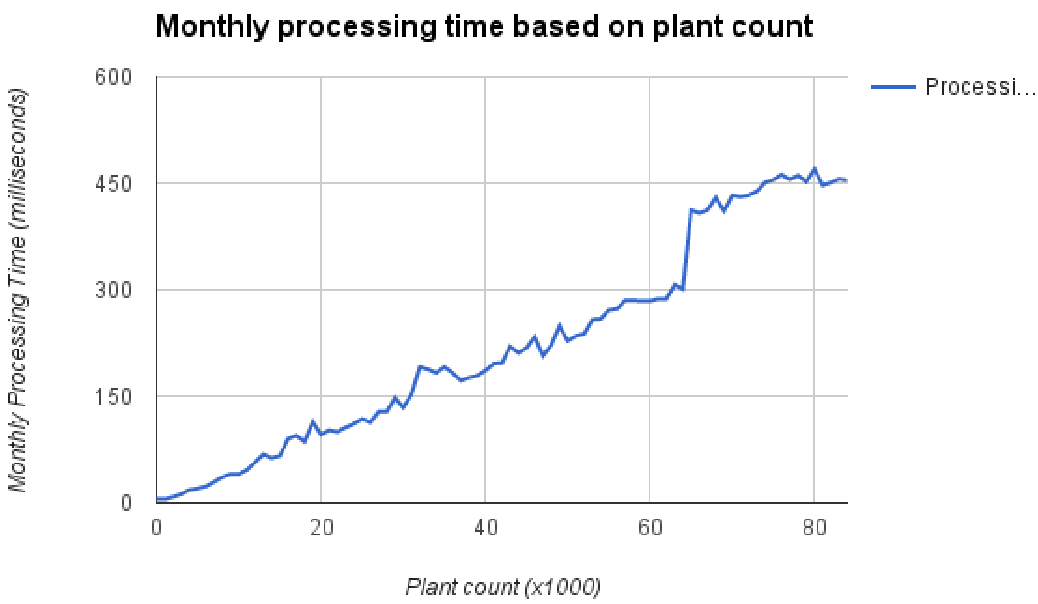

Figure 1.7: Processing time based on plant count. Total simulation time for 100 years: 271 seconds

1.2.5.3 Random Seeding

This is the most simple form of seeding and is used when no plants of the given specie are present in the simulation and the specie is not shade-loving. The set of locations for new plants to spawn is selected at random within the simulation window.

1.2.6 Performance

The number of plants present in the simulation will heavily influence it's performance as the strength of each plant needs to be recalculated on a monthly basis. To test the influence of plant count on simulation time, a simulation is run with a single specie of plant and the monthly processing time analysed alongside the number of plants present. The plant used is grass at is has no canopy and very minimal root coverage, permitting a large number of instances to grow simultaneously (see appendix **??** for properties of specie). The resources were set to be optimal for maximizing plant count and minimizing intra-plant competition. The simulation is started with only a single instance and, as the simulation progresses and seeding is performed, the number of instances increase. The results are summarized in Figure 1.7 and show that the processing time increases linearly with plant count.

Another simulation property which heavily impacts performance is the root and canopy growth of plant species present. The reason for this is that, as plant's roots and canopy grow, they will cover more simulation grid cells and more calculations will be required per individual cell when the contained resources are distributed. To analyse

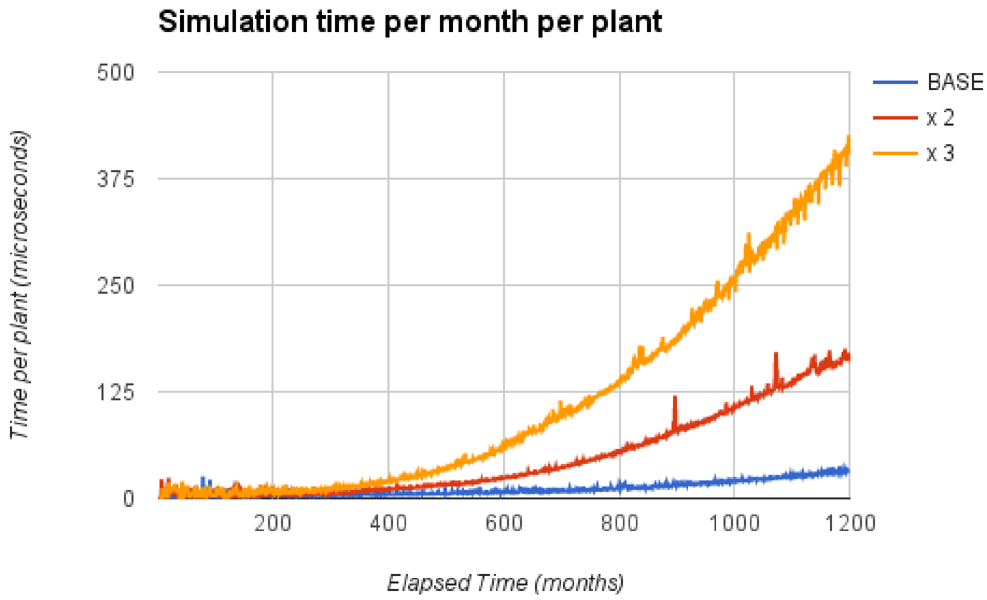

Figure 1.8: Evolution of the monthly processing time normalised based on plant count. The processing time increases as the plant's grow larger as they cover more grid cells. Total simulation time for one hundred years: 49 seconds for S_{base}, 122 seconds for S_{X2} and 166 seconds for S_{X3}

the impact of plant growth, a base specie S_{base} is created with a given root and canopy growth rate. Then, two species are created S_{X2} and S_{X3} with twice and thrice the growth rates of S_{base} respectively (see appendix **??** for specie details). An identical simulation is run on each specie in terms of available resources and, on a monthly basis, the number of plants present in the simulation along with the monthly processing time analysed. Given this information, it is possible to track the average monthly processing time per plant throughout the simulation. It is important to normalise based on the number of plants as the faster growing plants will permit less plants to survive for the simple reason that they will require and be able to access resources from a larger amount of grid cells. As can be seen in the results plotted in figure 1.8, the processing times are similar to start and then increase proportionally to the species growth rate.

1.2.7 Results

To test the resulting spatial distribution of plant communities in their work, Lane and and Przemyslaw **?** attempt to reproduce three important properties of nature: *Self-thinning*, *succession* and *propagation*.
As plants grow, their resource requirements increase and, as a direct consequence, inter-plant competition for resources increases. Eventually, the competition becomes too intense and resources too scarce leading to more vigorous plants starving smaller plants. At this point, *self-thinning* begins and plant densities decrease.
Given plant specie A with a fast growth rate and specie B with a slower growth rate but

Simulation	Simulation time (years)	Humidity	Illumination	Temperature
1	100	25	10	15
2	100	30	10	15
3	100	35	10	15

Table 1.1: Self-thinning test simulation configurations. For simplicity, monthly resources are kept constant.

higher shade tolerance. At first, the faster growing specie A will dominate and flourish but, with time, the slower growing but more shade tolerant specie B will flourish and dominate. This is the *succession* property.
Plants *propagate* in clusters surrounding the seeding plant.

To test the ecosystem simulator, we will first employ the same methodology as Lane and and Przemyslaw **?** and attempt to reproduce *self-thinning*, *succession* and *propagation*.

To ensure a given plant specie strives better in its optimal environment, the same simulation will be run using a single plant specie with varying resource properties and the resulting plant distribution analysed. This test is discussed in *Varying Resources Test* below.

A *shade-simulation test* is performed to ensure plants which depend on direct illumination strive less in the shaded undergrowth of larger plants.

To ensure shade-loving plants are able to propagate and strive under the canopies of larger plants, a *shade-loving plant test* is also performed.

1.2.7.1 Self-thinning Test

Self-thinning occurs when the plant biomass surpasses a given tipping point where available resources become insufficient to permit further plant growth. At this point, larger plants start to kill off smaller, weaker plants by stealing their resources.

To test whether self-thinning is successfully modelled in the ecosystem simulator, three simulations are run as described in table 1.1 and the plant count tracked throughout. As described previously, self-thinning occurs because of insufficient resources. By modifying only available humidity in each simulation, it's effect on self-thinning becomes apparent. As can be seen in the results summarized in figure 1.9, the plant count increases at first, reaches a maximum and decreases thereafter. This is the exact behaviour of self-thinning. Furthermore, it is apparent that the maximum plant count increases with the humidity available, therefore showing that self-thinning is sensitive to available resources.

1.2.7.2 Succession Test

Succession occurs in an ecosystem due to the different growth rates of the species it contains. To test *succession* in the ecosystem simulator, two plant species S_{fast} and S_{slow}

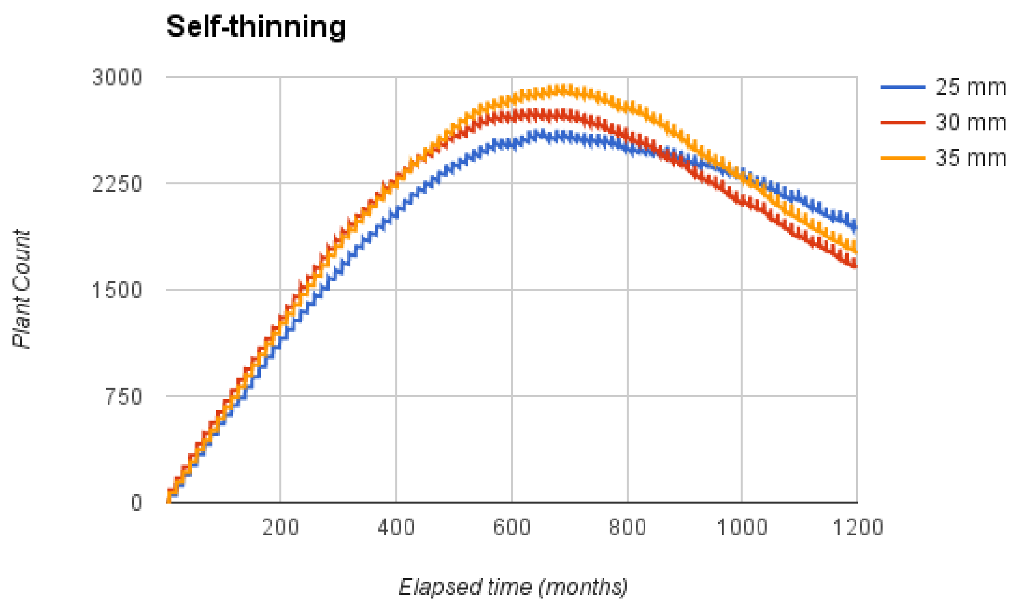

Figure 1.9: Plant count tracked throughout three separate simulations differing only in available humidity.

are created differing only in their growth rate and illumination properties (see appendix **??** for details) and a simulation run with these two species under optimal conditions. During the simulation, the appearance and average size of the two plant species are monitored to determine the dominating specie. The analytical results illustrated in figure 1.10 along with the appearance at ten year intervals displayed in figure 1.11 shows that S_{fast} dominates at first (300 months in) followed by S_{slow} (500 months in). A balance is found thereafter.

1.2.7.3 Propagation Test

To ensure propagation is modelled in the ecosystem simulator a simulation is run with a single starting grass seed (see appendix **??** for specie details) and it's evolution tracked throughout. Figure 1.12 shows that iterative propagation through annual seeding enables a single seed plant to colonize the entirety of the terrain.

1.2.7.4 Varying Resource Test

To ensure a given plant specie strives better when it's habitat is more suited, multiple simulations are run with only specie S_{base} (see appendix **??** for specie properties) present. As outlined in table 1.2, the simulations vary only in their configured humidity. As seen by the results plotted in figure 1.13, illustrating the average canopy width for a single plant instance throughout the simulations, plants strive better in environments better suited to their resource requirements.

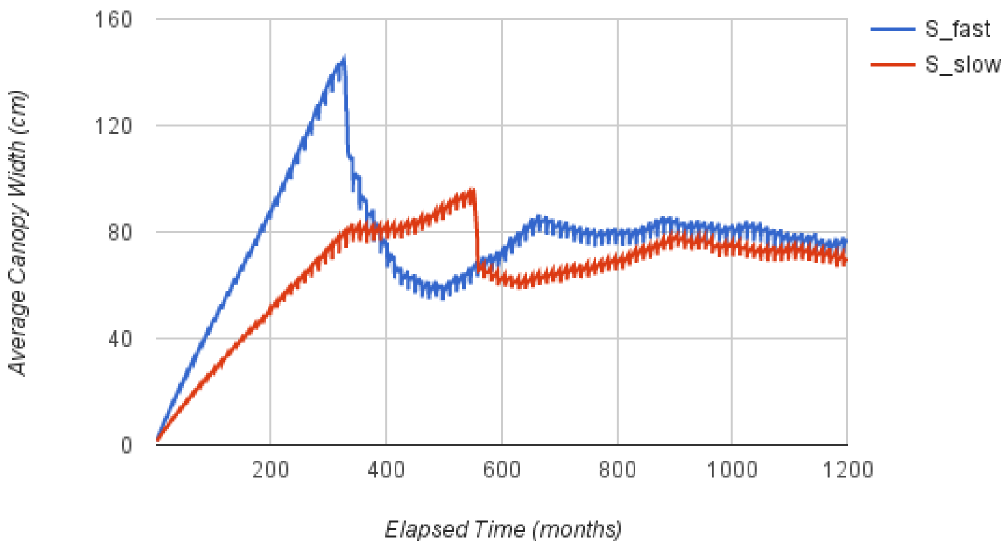

Figure 1.10: Succession Test: Average size of the slow growing S_{slow} (red) and fast growing S_{fast} (blue) throughout a simulation run in optimal conditions.

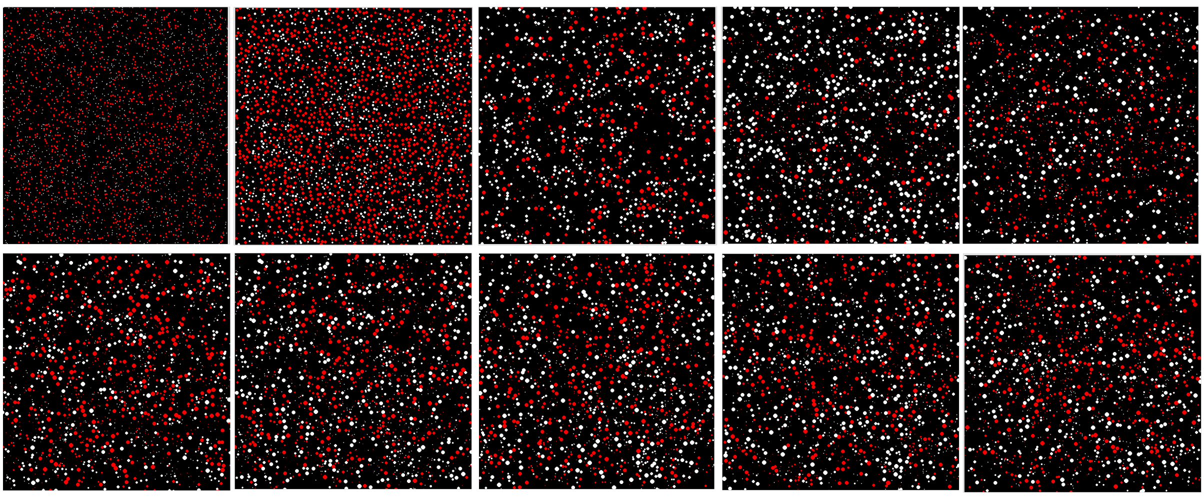

Figure 1.11: Succession Test: Appearance of the slow growing S_{slow} (white) and fast growing S_{red} (blue) at different times during the simulation. From left-to-right, top-top-bottom: 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 years.

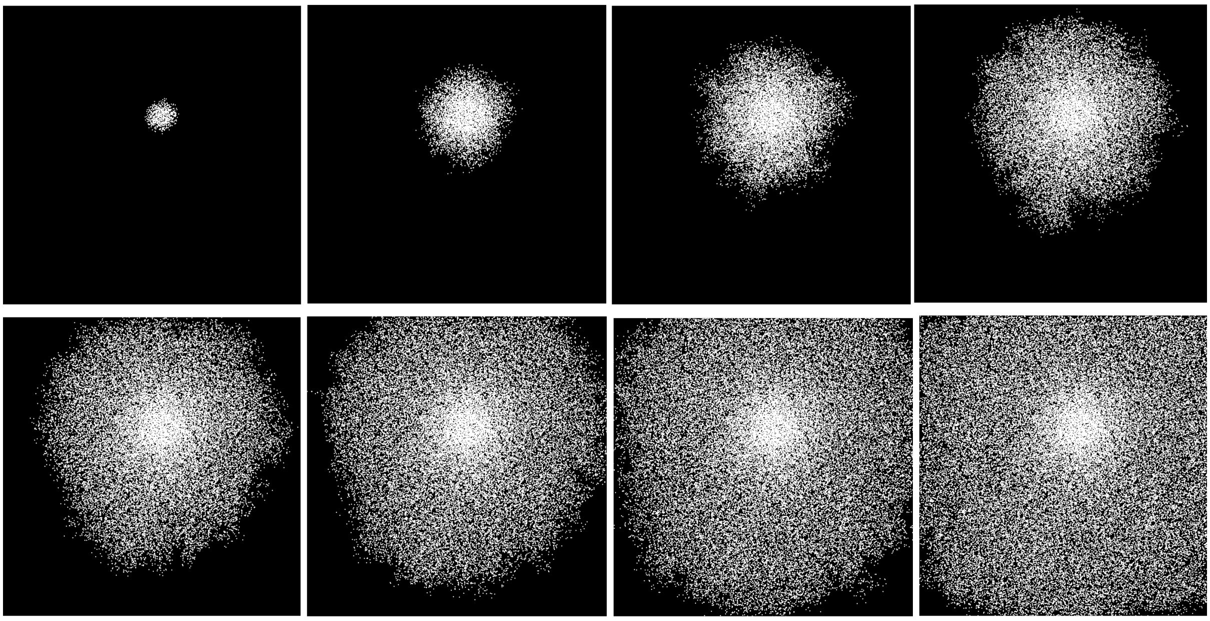

Figure 1.12: Propagation Test: Evolution through time of a simulation starting from a single seed plant of grass. From left-to-right, top-to-bottom: 2, 10, 20, 30, 40, 50, 60, 70 years in.

Simulation	**Simulation time (years)**	**Humidity**	**Illumination**	**Temperature**
1	100	22	10	20
2	100	24	10	20
3	100	26	10	20
4	100	28	10	20
5	100	30	10	20
6	100	32	10	20
7	100	34	10	20
8	100	36	10	20
9	100	38	10	20

Table 1.2: Varying resource rest simulation configurations. For simplicity, monthly resources are kept constant.

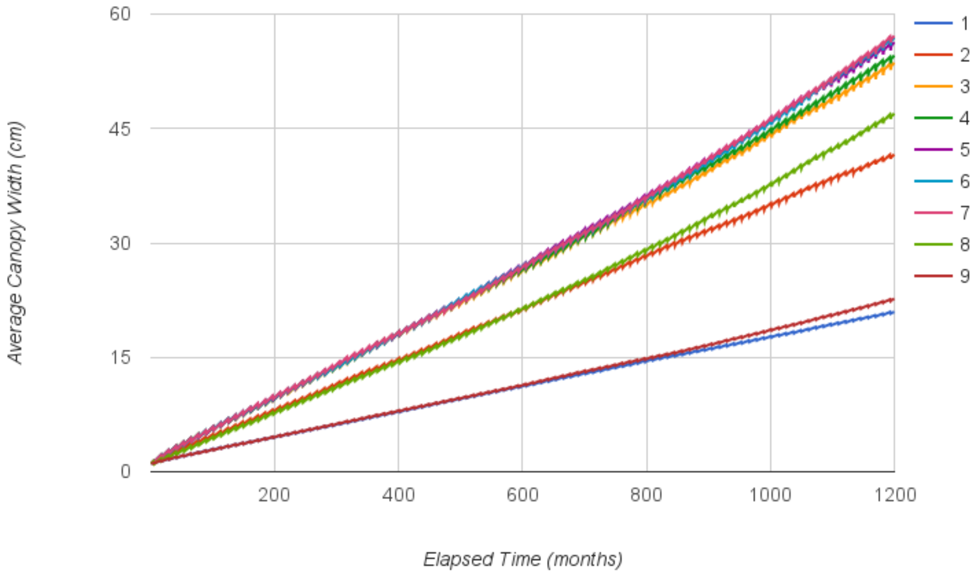

Figure 1.13: Varying Resource Test: Average canopy width of a single plant throughout the simulations outlined in table 1.2.

1.2.7.5 Shade Test

Plant's that are heavily dependent on illumination struggle to grow in areas shaded by the canopy of larger plants. To test this is modelled in the ecosystem simulator, a simulation is run with two species: $S_{smallroots}$ and grass (see appendix **??** for specie details). $S_{smallroots}$ is a custom specie created for the purpose of this test which has very small roots growth. This is important so as to focus on the effects of illumination and minimize the influence of drought. Figure 1.14, which illustrates the state of the simulation after fifty years, shows the grass struggling to grow in areas directly below the canopies of $S_{smallroots}$.

1.2.7.6 Shade-loving Test

Species which strive in shaded areas and struggle to survive in open spaces directly illuminated by the sun are deemed to be shade-loving. The shade can be caused by the terrain relief or by the shadow cast by the canopy of taller plants. To test whether the ecosystem simulator successfully caters for such plant species, a simulation is run identical to that done in the shade test (section 1.2.7.5) but with shade-loving specie $S_{shadeloving}$ added (see appendix **??** for specie details). As seen by the snapshot of the simulation after fifty years illustrated in figure .., instances of $S_{shadeloving}$ only appear in areas directly covered by the canopies of $S_{smallroots}$.

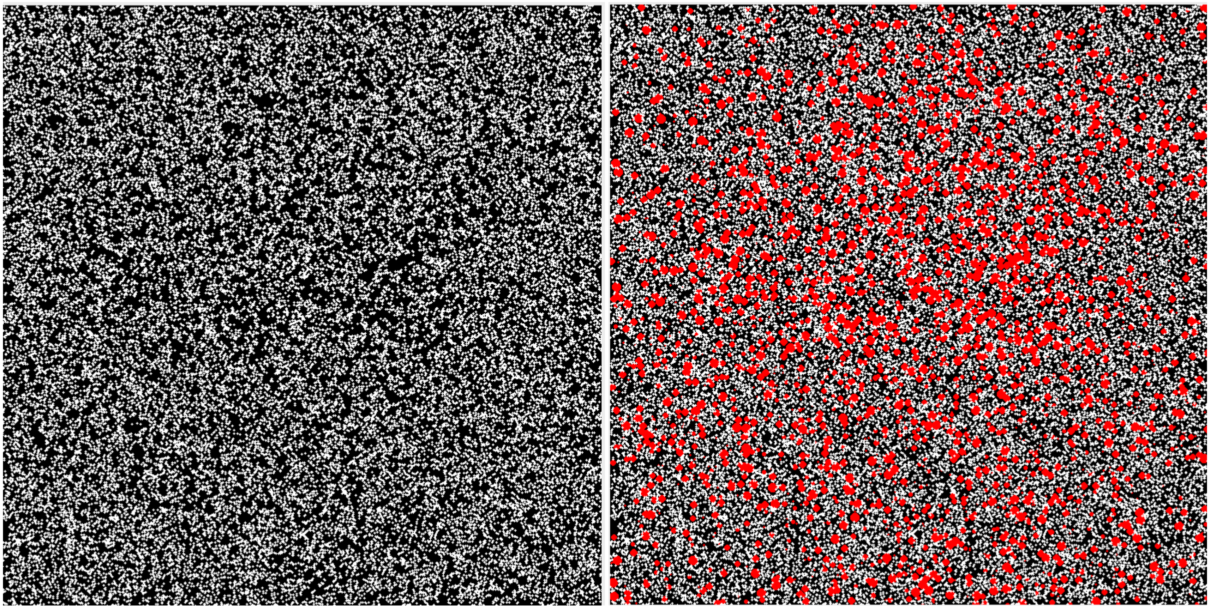

Figure 1.14: Shade Test: Simulation with $S_{smallroots}$ (red), grass (white) after fifty years. Left without rendering instances of $S_{smallroots}$ to visualise the effects of the shade

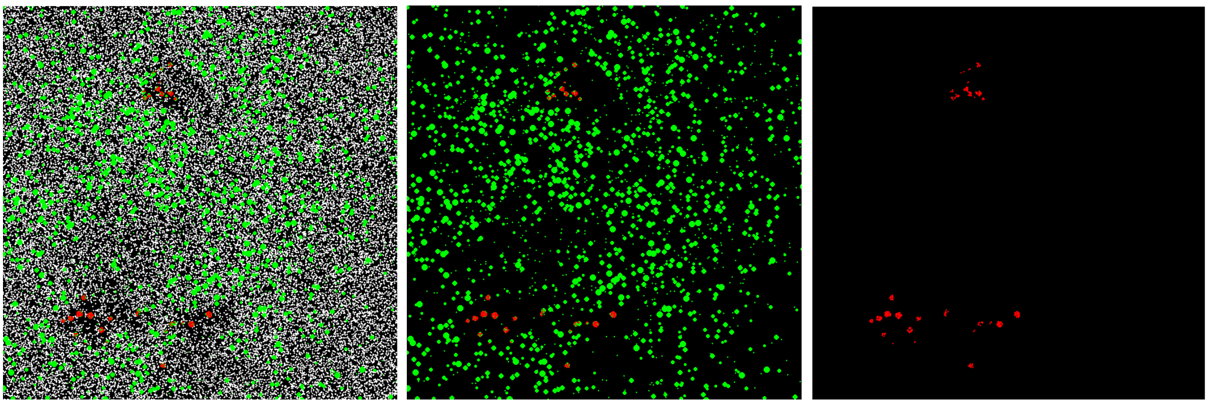

Figure 1.15: Shade Loving Test: Simulation with $S_{smallroots}$ (green), grass (white) and $S_{shadeloving}$ after fifty years. From left-to-right: All species, excluding grass and only $S_{shadeloving}$. As can be seen, $S_{shadeloving}$ strive under the canopies of $S_{smallroots}$.