All updates happen per timestep = 1 year.

Rules

The only reliable indicator in this world that signals if a tree is dead or alive is `stress`. If `stress ≥ 1` then and only then is a tree dead.

Initial World

- When the simulated world is first created, seedlings are planted as per predefined species composition. Then, the forest is left to grow for 300 years. The resulting old growth forest, is the starting forest that the players work with.
- Further, the forest shall be composed of 60% coniferous trees and 40% deciduous trees. (Department of Agriculture, Food and the Marine, Ireland)

Carbon Cycle

- Let a tree have grown in volume by $\Delta V_t \ \mathrm{m}^3$.
- Let density of the biomass of the tree be $D_t \ \mathrm{g/m}^3$.
- Then, the tree's weight should have increased by $\Delta W_t = D_t \times \Delta V_t$.
- Of the total weight of the tree, 57.5% is dry weight. Thus, $\Delta W_t^{dry} = 0.575 \times \Delta W_t$
- The amount of carbon in the new volume of the tree is about half it's dry weight $C_t^a = 0.5 \times \Delta W_t^{dry}$.
- This absorbed carbon will get added to the total amount of carbon in the tree and subtracted from the air. Thus, $C_t = C_t + C_t^a$ and $C_a = C_a - C_t^a$.
- All the while the tree grows, it would also need to replace biomass lost due to damage or natural shedding. Let this increase in volume for maintenance equal 1 % of its total volume $\Delta V_t^m = 0.01 \times V_t$. Just as before, $\Delta W_t^m = D_t \times \Delta V_t$, $\Delta W_t^{mDry} = 0.575 \times \Delta W_t^m$, $C_t^m = 0.5 \times \Delta W_t^{mDry}$.
- This amount of maintenance carbon is subtracted from the air and added to the soil to emulate the amount of biomass lost being added into the soil's carbon store. This, $C_a = C_a - C_t^m$ and $C_s = C_s + C_t^m$.
  Decay
- Once a tree has died and remains on the land, 15% of the carbon stored is released into the atmosphere and soil per year. (World Economic Forum) So, let amount of carbon that is lost during decay each year be fixed at $C_t^d = 0.15 \times C_t$ where $t =$ time right before the tree died. Thus, weight of the dead tree lost to decay would be $W_t^d = 2C_t^d$ and consequently, volume would be $V_t^d = \frac{W_t^d}{D_t^d}$. That is, after each year, volume of a dead tree that remains in soil, changes as $V_t = V_t - V_t^d$.

- Of the amount of carbon decayed each year, 35% end up in the soil and 65% is released back into the atmosphere. So, $C_s = C_s \times (0.35 \times C_t^d)$ and $C_a = C_a \times (0.65 \times C_t^d)$. (~ reddit, 2021)
  Soil Release
- The amount of carbon that the soil releases back into the atmosphere each year is 4.2% of the carbon in the soil $C_s^r = 0.042 \times C_s$. Thus, $C_s = C_s - C_s^r$ and $C_a = C_a + C_s^r$.

Plant Growth

For each tree,

1. If the tree is alive, then `live()`.
2. Else `decay()`. If decayed volume = 0, then remove tree entity from spot on land.
3. Growth height $GH_t = (1 - max(0, S_t - B^-)) \times GH_t^{max}$ where S_t is the stress the *stress factor* and B^- is the *biodiversity reduction factor*.
4. The relationship between height and diameter of trees in this world is assumed to be $H = D^{2/3} \Rightarrow D = H^{3/2}$ (X. Chen and D. Brockway, 2017). So, Growth diameter $GD_t = GH_t^{3/2}$.

Stress

Living trees are under stress due to environmental conditions (atmospheric $CO2$ concentration) and age. If $S_t^{env} > 0$ then $S_t = S_t + S_t^{env}$, where $S_t^{env} = S_t^{co2}$.

When conditions are favourable, plants recover from past stress. Healthier plants (those under less stress) recover faster. If $S_t^{env} \leq 0 \wedge S_t > 0$ then $S_t = max(0, S_t - S_t^{rec}(1 - S_t))$. Here, $S_t^{rec} =$ a fixed predefined recovery factor $\in [0, 1]$ and $1 - S_t$ is indicative of remaining health.

Impact of stress on very old trees (senescent ones) increase as time passes. If life stage of a tree is "senescent", after each time step some stress due to aging $S_t^{age} = 0.01$ is added to net stress of the tree $S_t = S_t + S_t^{age}$. Once maximum age of this tree is reached, $S_t^{age} = 1.0$ and the tree dies.

Cutting down a tree immediately inflicts maximum stress (1.0) on the tree, causing it to die. In this microworld, a tree dies when and only when $S_t \geq 1.0$.

Forests with more biodiversity, grow faster and can better cope with stress.

Biodiversity

Larger more mixed forests boast higher biodiversity b.

- If no trees then biodiversity score $B = 0$.
- For each coniferous tree, if there exists a deciduous tree then $B = B + 3$.

- For each remaining coniferous or deciduous tree for which there is another tree of the same type $B = B + 2$.
- For each remaining coniferous or deciduous tree for which there is no tree of any type $B = B + 1$

Forests with more old growth and mature trees harbour greater biodiversity. Even dead trees (dead wood) contribute towards increased biodiversity (fungi, insects, etc.).

- $B = B + (0.5 \times \text{no. of seedlings})$
- $B = B + (0.8 \times \text{no. of saplings})$
- $B = B + (2 \times \text{no. of mature trees})$
- $B = B + (3 \times \text{old growth trees})$
- $B = B + (1 \times \text{no. of dead trees})$

Ecosystems are more biodiverse than new forests or plantations.

- Biodiversity percent $B\% = \frac{B}{B_{max} - Bmin}$ where $B_{max} = 3 \times \text{no. of land positions}$ and $B_{min} = 0$.
- $0 \leq B\% < 0.25 \Rightarrow$ Biodiversity category $B_{cat} = \text{unforested}$
- $0.25 \leq B\% < 0.5 \Rightarrow B_{cat} = \text{plantation}$
- $0.5 \leq B\% < 0.75 \Rightarrow B_{cat} = \text{forest}$
- $0.75 \leq B\% < 0.1 \Rightarrow B_{cat} = \text{ecosystem}$

Forests with more biodiversity, grow faster and can better cope with stress.

- $B_{cat} = \text{unforested} \Rightarrow B^{-} = 0.0$
- $B_{cat} = \text{plantation} \Rightarrow B^{-} = 0.01$
- $B_{cat} = \text{forest} \Rightarrow B^{-} = 0.1$
- $B_{cat} = \text{ecosystem} \Rightarrow B^{-} = 0.3$

Reproduction

Trees may reproduce every R_t no. of years only if there is a free space adjacent to the tree and the tree is mature/old growth with $S_t \leq 0.5$.

Volume

For simplicity, the volume of a tree here is assumed to be same as that of a cylinder with the tree's height and diameter. When decaying, it is assumed that only height decreases until 0, after which the tree no longer exists.

Funds

Influx

There are two main types of income sources.

1. **Timber:** Income from timber is obtained as a result of felling trees. User's generate this income by including the "fell action" in their plans.
2. **Non-Timber:** There is more than one type of income from the forest that does not come from timber. This includes the following.
   1. **Non-Timber Forest Products**
   Income is generated from harvesting and selling mushrooms, berries or honey.
   Harvesting of NTFP leads to a drop in biodiversity score.
   Availability of this resource peaks when biodiversity score is high or when amount of deadwood is high (mushrooms).
   *1. **Hunting & Fishing***
   Income is generated from selling permits to hunt or fish on land.
   The mean of the normal distribution associated with this income source is dependent on biodiversity. When biodiversity score is more, the mean is higher.
   Both these income types are less dependable and fluctuate from year to year.
   ***Availability** associated with each of these income streams is modelled using a normal distribution with some predefined mean and standard deviation. This means that most of the time, income from these resources amount to a similar value but occasionally, it may be much higher or lower.*
   Outflux*

- Executing management actions (plant/fell) costs a certain amount (F_{plant}, F_{fell}).
- Also, every year, a fixed amount F_m is deducted to reflect living/maintenance costs.

Constants

Age
In the simulated world, the maximum life expectancy of a conifer tree is 100 years while that of a deciduous tree is slightly lower at 80 years. On average conifer trees are more long lived than deciduous ones. [(F. Biondi et. al., 2023)]

Stage	Coniferous Age At Start	Coniferous Duration	Coniferous Age At End	Deciduous Age At Start	Deciduous Duration	Deciduous Age At End
Seedling	0	4	4	0	3	3
Sapling	4	22	26	3	18	21
Mature	26	34	60	21	26	47
Old Growth	60	30	90	47	23	70
Senescent	90	10	100	70	10	80

Air Volume $= 4.2 \times 10^{18}\ \mathrm{m}^3$ (Quora, 2024)

Biodiversity

- Biodiversity Categories from Biodiversity Scores
  - $unforested = [0, 0.25)$
  - $plantation = [0.25, 0.5)$
  - $forest = [0.5, 0.75)$
  - $ecosystem = [0.75, 1.01)$
- Biodiversity Stress Reduction Factor (BD^{-})
  - $\mathrm{unforested} = 0.0$
  - $\mathrm{plantation} = 0.01$
  - $\mathrm{forest} = 0.1$
  - $\mathrm{ecosystem} = 0.3$

Carbon in the world. (S. Rackley, Science Direct, 2023)

- $\mathrm{soil} = 1400\ \mathrm{GtC} = 1400 \times 10^{15}\ \mathrm{gC}$ (initially 0 GtC)
- $air = 750\ \mathrm{GtC} = 750 \times 10^{15}\ \mathrm{gC}$ (initially 2700 GtC)
- $vegetation = 550\ \mathrm{GtC} = 550 \times 10^{15}\ \mathrm{gC}$ (initially 0 GtC)
- $\mathrm{fossil\ fuels} = 10,000\ \mathrm{GtC} = 10,000 \times 10^{15}\ \mathrm{gC}$
- C % in in plants $= 50\% = 0.5$
- Annual emissions from fossil fuels starting $= 37.15\ \mathrm{GtCO2} = 37.15 \times 10^{15}\ \mathrm{gCO2}$ (initially $0\ \mathrm{gCO2}$). (H. Ritchie and M. Roser, 2024)

CO2 ppm	**<200**	**200 - 350**	**350 - 430**	**430 - 700**	**700 - 1200**	**1200 - 1800**	**>= 1800**
Human Life	Impossible	Best	Good	Ok	Bad	Very Bad	Impossible
Photosynthesys Efficiency	Impossible	Bad	Bad	Ok	Best	Good	Very Bad

Cost of Management Actions

- $\mathrm{plant} = \mathrm{Bc}\ 900$ (A. Nita, 2024)
- $\mathrm{fell} = \mathrm{Bc}\ 1400$ (Kelly O, 2024)

Funds Starting Amount $= \mathrm{Bc}\ 10,000$

Income Sources

- $\text{timber} = \text{starting dependency} = 0.6, \text{unit} = \text{kg}, \text{price per unit} = \text{Bc } 0.3$ (B. Korchinski, 2020)
- $\text{ntfp} = \text{starting dependency} = 0.3, \text{unit} = \text{kg}, \text{price per unit} = \text{Bc } 14.0$ (Tesco Ireland)
- $\text{hunting and fishing} = \text{starting dependency} = 0.1, \text{unit} = \text{permit}, \text{price per unit} = \text{Bc } 27.0$ (Texas Parks & Wildlife Department, 2023)
- $\text{ecosystem services} = \text{starting dependency} = 0.0, \text{unit} = ?, \text{price per unit} = \text{Bc } ?$

Land Size $=$ 6 rows, 6 columns

Rotation Starting no. of Years $= 40$ (H. V. Hensbergen, K. Shono and J. Cedergren, 2023)

Timber Usage (University of Wisconsin, 2020)

- $\text{energy} \approx 0.5$
- $\text{lumber} \approx 0.5$

Time Max $= 300$ years

Maximum Growth Height (1 year) GH_t^{max}

- $\text{coniferous} \approx 0.3 \text{ m}$ (Conifers, Ardcarne Garden Centre)
- $\text{deciduous} \approx 1.8 \text{ m}$ (BBC Gardeners' World Magazine, 2024)

Height

- Starting Height of a Seedling $= 16 \text{ to } 25 \text{ cm} \Rightarrow 20.0 \text{ cm} = 0.2 \text{ m}$ Tree Time Services
- Max Height
  - $\text{coniferous} \approx (112 + 20)/2 \approx 70 \text{ m}$ (Encyclopedia Britannica)
  - $\text{deciduous} \approx (112 + 20)/2 \approx 40 \text{ m}$ (N. Moran, 2023)

Diameter

- Although subject to significant variability, a simple good estimate of a relationship between Height and Diameter of a tree is $H \propto D^{2/3}$. (X. Chen and D. Brockway, 2017) (D. Brockway, 2017) Accounting for a proportionality constant, this may be written as $H = kD^{2/3}$. For simplicity, k may be set to 1, implying a direct relationship without any scaling effect due to the environment, species of tree, etc. Thus, in this microworld the relationship between tree height and diameter is, $H_t = D_t^{2/3} \Rightarrow D_t = H_t^{3/2}$.

Reproduction Interval

- $\text{coniferous} \approx 2.5 \text{ years}$ Wikipedia, Conifer
- $\text{deciduous} \approx 1 \text{ year } ?$

Wood Density Density of wood – the ultimate guide

- coniferous $\approx 600\ \mathrm{kg}/m^3$
- deciduous $\approx 700\ \mathrm{kg}/m^3$