LANDIS-II Net Ecosystem Carbon and Nitrogen (NECN) Succession v8.1 Extension User Guide

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1 Introduction

This document describes the **Net Ecosystem Carbon and Nitrogen (NECN) Succession** extension for the LANDIS-II model. For information about the LANDIS-II model and its core concepts including succession, see the *LANDIS-II Conceptual Model Description* and the LANDIS-II website (www.landis-ii.org).

1.1 Purpose

We designed the NECN Succession extension to provide total ecosystem accounting of Carbon and Nitrogen and to allow species to respond dynamically to a changing climate via establishment and growth.

NECN calculates how cohorts grow, reproduce, age, and die (Scheller et al. 2011). Dead biomass is tracked over time, divided into four pools: surface wood, soil wood (dead coarse roots), surface litter (dead leaves), and soil litter (dead fine roots). In addition, three principle soil pools: fast (soil organic matter (SOM1)), slow (SOM2), and passive (SOM3) are simulated, following the Century soil model (Parton et al. 1993, Schimel et al. 1994, Parton et al. 1994, Pan et al. 1998).

For a schematic drawing of the NECN extension, see Scheller et al 2011.

1.2 Cohort Reproduction – Probability of Establishment

The probability of establishment (P_{EST}) is internally calculated at an annual time step and is dependent upon input weather data. Although calculated annually, establishment can only occur following a disturbance or at a succession time step. P_{EST} is based on the minimum of three limiting factors: 1) growing degree days (GDD), 2) drought tolerance, 3) minimum January temperature. These represent **climatic** limits to species establishment in that the requisite parameters vary by climate region. Establishment, given available light, is calculated as a function of LAI and represents the **site-scale** limits to establishment.

1.3 Cohort Growth

At each time step, cohort growth is determined by estimated leaf area index (LAI), water availability, temperature, growing space capacity and nitrogen availability. Cohort growth generally follows the algorithms found in Century, except for N uptake. In the spring, the amount of resorbed N is calculated (leaf N - litter N), which can be "used" by the cohort when conditions are conducive to growth. In hardwoods, resorbed N is used primarily in the spring; resorbed N can be utilized throughout the year in conifers. After the pool of resorbed N is depleted, the cohort takes up N from the mineral N pool. Uptake of N is proportional to above-ground net primary productivity (ANPP), with greater N uptake by faster growing cohorts. When mineral N is limiting, competition for N

between cohorts is determined by the relative amount of their coarse root biomass.

1.3.1   Water and temperature limits

NPP limitation due to soil water content (WC) and soil temperature (T) are calculated using a four-parameter curve for each species (Fig. 1), the parameters of which are user supplied (eq. 1).

$$GrowthLimit = e^{\frac{Curve3}{Curve4}(1-fraction^{Curve4})}(fraction^{Curve3}) \qquad \text{Eq. 1}$$

Where

$$fraction = \frac{Curve2 - S}{Curve2 - Curve1}$$

And S is the site variable (either soil moisture or soil temperature) of interest. If the GrowthLimit calculation in Eq. 1 is less than 0, the GrowthLimit is set to 0.

The four curve parameters (TemperatureCurve1 through TemperatureCurve4 and MoistureCurve1 through MoistureCurve4), called Curve1 thorugh Curve4 in Eq. 1, represent the optimum value of WC or T, where the GrowthLimit equals 1. Curve2 determines the maximum or minimum value past which the GrowthLimit equals 0 (whether it is a maximum or minimum depends on whether Curve1 is larger or smaller than Curve2). Curve3 and Curve4 determine the shape of the curve, particularly how quickly it asymptotically approaches 0 on the other side of the curve from the threshold.
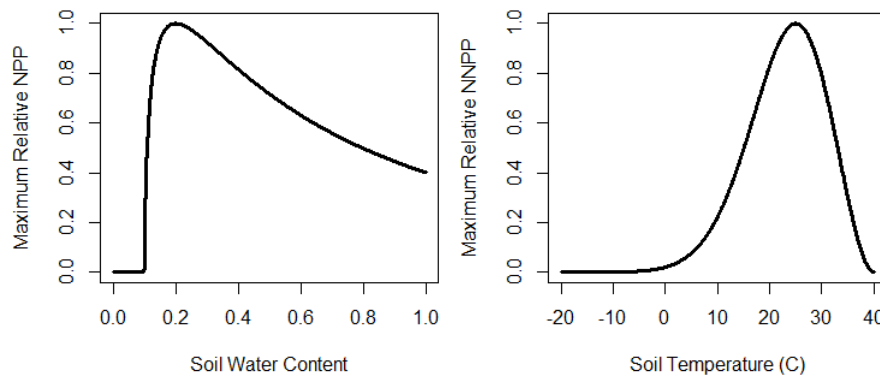
Figure 1. GrowthLimit curves for soil water content and soil temperature. Moisture curve values depicted are 0.2, 0.1, 1, and 0.3. Temperature curve values are 25, 40, 1.81, 2.03.

1.4 Soil and Dead Biomass Decay

Decay processes generally follow the algorithm and science from Century v4.5 whereby there are four litter pools (structural and metabolic material either on the surface or within the soil) and three soil organic matter (SOM) pools (SOM 1,2,3). SOM1 is further subdivided into SOM1 surface and SOM1 soil.

Decay rates of SOMsurf, SOM1soil, SOM 2 and SOM 3 are universal.

1.5 Initial Communities and Soil Properties

The initial biomass is provided by the user and therefore there is no model "spin-up".

Note: *An initial (time zero) climate stream is still required for initialization (see the climate library user's manual- LANDIS-II Climate Library v1.0 User Guide). This is an artifact of the Climate Library and this data is not used.*

1.6 Cohort Reproduction – Disturbance Interactions

Every disturbance will trigger succession at each site at the time step that the disturbance(s) occur. In succession, there is a hierarchy of reproduction options following a disturbance. The goal of this design was to give reproductive precedence to species with propagules available on site.

If planting (currently possible only through a Harvest extension) is triggered for one or more species, then no other reproduction will occur. Planting is given highest precedence as we assume that a viable cohort is generated. However, the probability of establishment must be greater than zero.

If serotiny (only possible immediately following a fire) is triggered for one or more species, then neither resprouting nor seeding will occur. Serotiny is given precedence over resprouting as it typically has a higher threshold for success than resprouting. This slightly favors serotinous species when mixed with species able to resprout following a fire.

If resprouting (which can be induced by many disturbance types) is triggered, then seeding will not occur.

Finally, if neither planting, serotiny, nor resprouting occurred, seeding dispersal into a sight will occur.

1.7 Cohort Reproduction – Initial Biomass

Cohort reproduction is the establishment of a cohort, aged 1 year and the calculation of its initial biomass.

$$InitialBiomass = 0.002 \times ANPP_{MAX} \times Exp(-1.6 \times B_{ACT}/B_{MAX})$$

where ANPP$_{MAX}$ is the maximum ANPP possible for the species*;* B$_{MAX}$ is the maximum biomass possible for the species; and B$_{ACT}$ is the current total biomass for the site (not including other new cohorts). Initial biomass must be ≥ 1 (g / m^2); if < 1, initial biomass is set equal to 1.

Note: *This initial cohort will be grouped ('binned') appropriately into a larger cohort (e.g., 1 – 10) at the next successional time step.*

1.8 Interactions with Disturbances

NECN handles the distribution of dead material for all disturbances. The biomass of cohorts killed by a disturbance to be allocated to the proper dead biomass pools. In the case of fire, a fraction of the existing litter and large woody material on the forest floor and a fraction of biomass killed during the fire is volatilized. These fractions are controlled by the user and vary by fire intensity/severity. Similarly, the user controls how much dead material is removed during a harvest operation.

1.9 Drought mortality

As of NECN v7.0, cohort mortality may be modeled as a function of climatic variables. These algorithms are entirely optional. If desired, then each species is provided with parameters relating their probability of mortality to climatic variables. Potential drivers of mortality include temperature, climatic water deficit, and soil moisture, as well as site biomass. The parameters are coefficients of a logistic model predicting the probability of decadal cohort survival, following Bradford et al. (2022).

1.10　Cohort Senescence

As a cohort nears its longevity age, there will be an increase in the loss of biomass. This is called **age-related mortality**, and the age at which this mortality begins is species-specific and controlled by the user**.** The biomass will decline to near zero at the maximum life span. If a cohort exceeds the longevity for that species, then the cohort dies.

1.11　Major Releases

1.11.1　Version 8.1 (October 2025)

- The Climate Library was updated.

- There was a major correction to the soil water balance algorithm.

1.11.2　Version 8.0 (August 2024)

- The Core was updated to Version 8

- The species CSV table and functional group tables were merged into a single species CSV table.

1.11.3   Version 7.0 (September 2023)

Version 7.0 introduces many substantial changes to the inputs and assumptions of NECN, including:

1. We updated the soil water model with these modifications:

   a. A portion of the snowpack evaporates when PET > 0. This amount is added to AET. The amount added is the same amount of PET that was used to evaporate snow (i.e., PET * 0.87). Previous versions decremented PET by the amount of evaporated snow instead. We also changed the code to stop subtracting evaporated snow from the soil water. This evaporated water is already subtracted from the snowpack, and there is no need to remove it twice. As a result, the energy budget is now balanced, and PET = AET + CWD as expected.

   b. AET can now draw soil water down to Permanent Wilting Point (PWP).

   c. Stormflow is taken out of water above field capacity (FC) before the calculation of AET. Remaining water above FC is not immediately discarded, but is available for AET.

   d. Baseflow is removed from the soil after AET, as a proportion of total soil water. At this step, it may reduce soil water below PWP. If, after baseflow is removed, soil water is above FC, then soil water is reduced to FC and excess water is added to baseflow.

   e. A bug which allowed soil water and AET to become negative under some conditions has been fixed.

   f. The Henne water mode has been removed; identical soil moisture dynamics may be replicated by setting baseflow to 0 on the input maps.

   g. Due to these changes, users should **evaluate whether their models' NPP have changed** when updating to NECN v7. Users are likely to see lower NPP than in NECN v6.x due to 1) bug fixes which change the soil moisture, and 2) slight differences in how baseflow is represented. Users should experiment with reducing baseflow, compared to NECN v6, if soil moisture or NPP is lower than empirical data. Alternatively, if the water balance is as expected, the soil moisture curve parameters in the Functional Group Table may be calibrated to increase NPP. Users are encouraged to use single-cell model runs with calibrate mode on – the relevant column is GrowthLimitSoilWater. If you previously used the Henne Water Mode, the NECN v7

model should be largely the same as the NECN v6 model, so long as baseflow and stormflow are set to 0.

2. Drought mortality was directly incorporated. Drought mortality is a probabilistic process which may vary depending on climatic water deficit, temperature, or soil water content. In previous versions, the effects of drought were realized in NECN by reduced growth rates, and reduced regeneration, but not elevated mortality rates. We added representation of this process via a mechanism-agnostic statistical model that incorporates climate-associated mortality from any proximate cause.

3. A new algorithm determines whether there is sufficient light for establishment. The previous tables of LAI and shade classes have been replaced with two species parameters that determine a Weibull distribution that directly relates LAI to the probability of light given LAI. These probability distribution functions should be estimated from empirical data consisting of the regeneration in a plot and the plot LAI. These data are used to estimate a Weibull distribution (see figure below). **Shade classes are no longer used.**
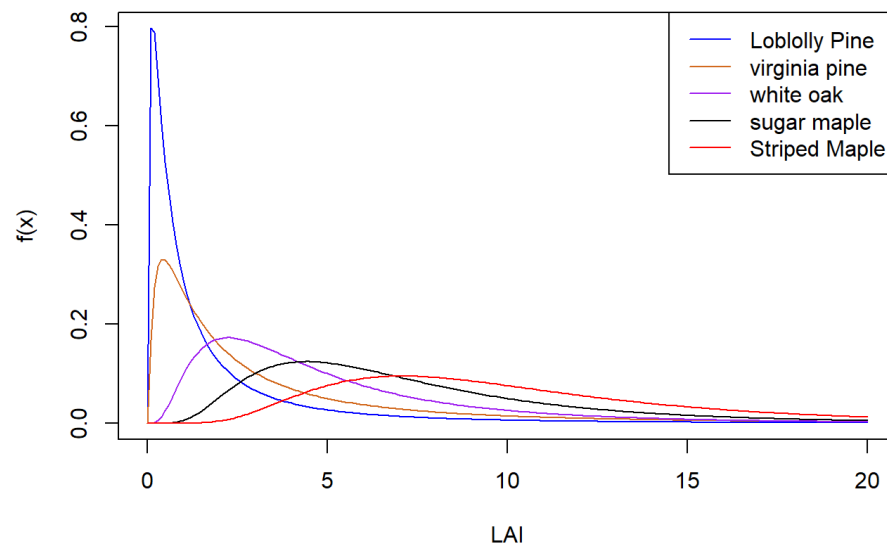
4. A new optional moisture curve is available, following DGS succession, allowing NPP to be reduced in both dry and excessively wet soils. The functional form is identical to the temperature curve. This feature allows for reduced growth of upland species in wetlands, preventing their rapid growth in unrealistic areas.

5. Additional optional limits to establishment were added. Establishment may now be (optionally) limited by climatic water

deficit or by soil drainage classes, preventing species from establishing in dry sites or poorly-drained sites. In combination with the above moisture curve modifications, this change prevents establishment of upland species in wetlands. CWD-based establishment is somewhat easier to parameterize than DryDays-based establishment, and both are well supported empirically.

6. Potential Evapotranspiration (PET) may be adjusted on a site level according to slope and aspect, following the ForClim model (Bugmann 1994, equation 3.74).

7. Outputs were added to better characterize the energy and water balance, including raster maps of average soil moisture and PET, and tabular monthly outputs of PET, AET, and CWD.

1.11.4   Version 6.10 (April 2022)

We added regeneration that requires dead woody material (DWM, aka 'nurse logs'). Tree species which can regenerate only on DWM (DWM dependent species) are invoked when an optional species parameter ('Nlog_depend') is present and one or more species are labeled as such. If you simulate only DWM independent species, you will get the same result as prior versions of NECN. See Hotta et al. (2021) for details.

1. The new species parameter, *Nlog_depend*, identifies whether the species is dead woods dependent species or not.

2. The ratio of the area occupied by DWM in a state of advanced decay (decay classes 3, 4, and 5; those that can be regarded as nurse logs) is calculated. If light and environmental conditions are favorable and the ratio of the area occupied by nurse logs is larger than the random number, DWM dependent species can establish.

3. If you simulate grass species, the establishment of DWM dependent species is determined by following 3 steps.

   A) Can cohorts establish in forest floor with grass species?

   B) Is there a sufficient amount of downed logs? (determination based on the area occupied by well decayed downed logs)

   If step (A) is TRUE, cohorts establish on the forest floor. If cohorts cannot establish in step (A) and the shade class of the site is darker than the most suitable shade class for the species, the model checks whether the cohorts can establish if they are not shaded by grasses. If step (B) is FALSE, cohorts cannot establish. If step (B) is TRUE, there are sufficient amounts of well decayed downed logs for establishment.

Additionally, we modified the calculation of the initial decay value of DWM. The initial decay value is now the mean value of wood decay rate of all woody plants.

1.11.5   Version 6.8 and 6.9 (January 2022)

A new optional parameter, GrowthLAI was added to the Species table; this allows the user to override the previous default value of 0.47. We also added an optional Minimum LAI to the functional group table allowing users to override the previous default of 0.10. **Both Species and Functional Group parameters now require input as a CSV file.**

1.11.6   Version 6.7 (May 2021)

We added a new type of species: Grass. Grasses are invoked when an optional species parameter ('Grass') is present and one or more species are labeled as such. We added a competitive relationship between grass and woody plants if grasses are present. If you simulate only woody plants, you will get the same result as prior versions of NECN.

1. The new species parameter, *Grass*, identifies whether the species is grasses or woody plants.

2. New cohorts can be limited by shade from both grass species (if present) and woody species cohorts.

3. If grass species are present, the algorithm of NPP limiting factor (*calculate_LAI_Competition*) is altered: First, the NPP of the newly established Juvenile will be limited by both 1) older aged woody species cohorts and 2) grass species cohorts on the site. If AGB of the Juvenile cohort exceeds the total AGB of grass species on the site, the NPP of the Juvenile will be limited by only 1) the older aged woody cohorts.

In addition, the climate library was updated to v4.2.

1.11.7   Version 6.6 and Earlier

Documentation for earlier version can be found on GitHub: https://github.com/LANDIS-II-Foundation/Extension-NECN-Succession/tree/master/docs

1.12 Minor Releases (this major release)

1.12.1   8.0.4. Update to Fine Fuel calculation timing

Fine Fuel impacts from fire are now recalculated after each fire and harvest, rather than following the NECN timestep. Other impacts on fine fuel load, such as due to decomposition, are still calculated at the NECN timestep. This means that fires and harvests can affect fine fuel loads in the next timestep, rather than delayed until the next NECN timestep.

1.12.2   8.0.3. Bugfix in postfire regeneration

Postfire regeneration (sprouting and serotiny) was inadvertently not being called after fires. This has been fixed, and it should operate as expected from NECN v7.

1.12.3   8.0.2. Bugfix in initial biomass calculation.

1.12.4   8.0.1. Bugfixes in ANPP calculation.

1.13 References

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1.14 Acknowledgments

2 Succession Input File

Many of the input parameters for NECN are specified in the main input file. Additional files are required for species and functional group parameters. This text file must comply with the general format requirements described in section 3.1 *Text Input Files* in the *LANDIS-II Model User Guide*.

2.1 LandisData

This parameter's value must be `"NECN Succession"`.

2.2 Timestep

This parameter is the time step of the extension. Value: integer > 0. Units: years.

Note: When changing the timestep of this extension (e.g., from a 5-year time step to a 1-year time step), you may need to adjust the probability of establishment adjustment factor (ProbEstablishAdjust) to retain the same regeneration rates (see section 2.13 below).

2.3 SeedingAlgorithm

This parameter indicates the seeding algorithm. Valid values are `"WardSeedDispersal"`, `"NoDispersal"` or `"UniversalDispersal"`. The algorithms are described in section 4.5.1 *Seeding* of the *LANDIS-II Conceptual Model Description*.

2.4 InitialCommunitiesCSV (file name)

This parameter is the CSV file with the definitions of the initial communities at the active sites on the landscape (see section 4).

IMPORTANT NOTE: The first data row (immediately beneath the header row) determines the data type (int, double, Boolean, or string) for all subsequent rows. Therefore, the first data row MUST have the intended data types.

2.5 InitialCommunitiesMap (file name)

This parameter is the input map indicating the initial communities at the active sites on the landscape. Each cell value for an active site on the landscape must be one of the map codes listed in the initial communities input file (see section 4).

2.6 ClimateConfigFile (file name)

The climate configuration file contains required climatic inputs.   The format of that file and its contents are described in the climate library user's manual (LANDIS-II Climate Library v1.0 User Guide).

2.7 Soil Physical Parameters

NECN is highly sensitive to soil physical characteristics. These values must be provided as input maps. These values are **static**: They are fixed for the duration of a scenario. Each input is on a separate line.

All data must be supplied as **double**.

Table 1. Input keywords and descriptions for soil properties.

Variable Name	Description
SoilDepthMapName	The depth of the soil, cm. ***User Tip:*** *The depth specified here has a large influence on soil water holding capacity.*
SoilDrainMapName	This influences the amount of water runoff and leaching. This affects the amount of N leaching (N loss) which, in turn, affects the amount of mineral N. It also has a large impact on the anaerobic effect on denitrification; lower values of SoilDrain lose less N to volatilization. The soil drainage factor allows a soil to have differing degrees of wetness (e.g., DRAIN=1 for well drained sandy soils and DRAIN=0 for a poorly drained clay soil).
SoilBaseFlowMapName	Base Flow is the fraction (range from 0.0 to 1.0) per month of subsoil water going into stream flow. Influences the amount of water runoff and leaching. Baseflow is removed from the soil after evapotranspiration. Baseflow may draw down soil moisture below permanent wilt point. If baseflow proportion is set to 0, then the water balance model replicates the behavior of NECN v6 water balance with the Henne watermode, which prevents the water balance from being reduced to below Permanent Wilt Point by baseflow.
SoilStormFlowMapName	Storm Flow is the fraction (range from 0.0 to 1.0) of the soil water content lost as fast stream flow. Stormflow is taken from the amount of soil moisture that exceeds Field Capacity, before soil water is made available to plants. Stormflow input values are often calculated as a function of topography and soil texture.

SoilFieldCapacityMapName	Field capacity and wilting point expressed as a fraction (range from 0.0 to 1.0). In the model algorithms, field capacity and wilting point are calculated as this fraction multiplied by soil depth.
SoilWiltingPointMapName	Field capacity and wilting point expressed as a fraction (range from 0.0 to 1.0). In the model algorithms, field capacity and wilting point are calculated as this fraction multiplied by soil depth.
SoilPercentClayMapName	Percent clay is expressed as a fraction (0.0 – 1.0).
SoilPercentSandMapName	Percent sand is expressed as a fraction (0.0 – 1.0).

2.8 Initial Soil and Dead Wood Inputs

NECN requires that users input initial C and N values for all soil and dead wood pools. (Fine fuels are currently calculated separately, see below.) These are provided as input maps. These values will change over time.

Each input is on a separate line. All data must be supplied as **double**.

Table 2. Input keywords and descriptions for initial soil and dead wood quantities.

Variable Name	Description
InitialSOM1CsurfMapName	The initial (time 0) amount of C in the soil surface, typically assumed to include the humus layer (g C m^{-2}).
InitialSOM1NsurfMapName	The initial (time 0) amount of N in the soil surface (g N m^{-2}).
InitialSOM1CsoilMapName	The initial (time 0) amount of C in the soil sub-surface; SOM1 indicates that this is the most labile C (g C m^{-2}).
InitialSOM1NsoilMapName	The initial (time 0) amount of N in the soil sub-surface (g N m^{-2}).
InitialSOM2CMapName	The initial (time 0) amount of C in the 'slow' soil pool (SOM2) (g C m^{-2}).
InitialSOM2NMapName	The initial (time 0) amount of N in the 'slow' soil pool (SOM2) (g N m^{-2}).
InitialSOM3CMapName	The initial (time 0) amount of C in the 'passive' soil pool (SOM3) (g C m^{-2}).
InitialSOM3NMapName	The initial (time 0) amount of N in the 'passive' soil pool (SOM3) (g N m^{-2}).

InitialDeadWoodSurfaceMapName	The initial (time 0) amount of surficial dead woody material, e.g., logs (g Biomass m^{-2}).
InitialDeadWoodRootsMapName	The initial (time 0) amount of belowground dead woody material, e.g., dead roots (g Biomass m^{-2}).

2.9 SlopeMapName (double, optional)

Optional. Slope steepness in degrees (0-90). Used to adjust PET for steep slopes.

2.10 AspectMapName (double, optional)

Optional. Slope aspect in degrees (0-360). Used to adjust PET for steep slopes.

2.11 NormalSWAMapName (double, optional)

Optional, required for drought mortality if using SWA as a drought variable. Normal (reference period) annual average soil water availability in cm.

2.12 NormalCWDMapName (double, optional)

Optional, required for drought mortality if using CWD as a drought variable. Normal (reference period) annual average climatic water deficit in cm.

2.13 NormalTempMapName (double, optional)

Optional, required for drought mortality if using SummerTemp as a drought variable. Normal (reference period) mean temperature from April through September.

2.14 CalibrateMode (Boolean, optional)

A Boolean input (Y or N). Determines whether the model is run in calibrate mode whereby additional parameters are added to a log file ("NECN-calibrate-log.csv"). **The calibrate mode should only be used when simulating a single site due to the volume of model output in the calibrate log file.** The intention is to view output of additional parameters, such as what factors are limiting growth at each time step.

2.15 SmokeModelOutputs (Boolean, optional)

A Boolean input (Y or N). These are outputs specific to subsequent (external) calculations of smoke emissions. If true, maps of conifer needle biomass, surface dead wood, and SOM1-surface (litter) are produced.

2.16 Write_SWA_Maps (Boolean, optional)

A Boolean input (Y or N). Should maps of soil water availability be written each year? This is useful for calculating NormalSWA for each site, as an input for drought mortality.

2.17 Write_CWD_Maps (Boolean, optional)

A Boolean input (Y or N). Should maps of climatic water deficit be written each year? This is useful for calculating NormalCWD for each site, as an input for drought mortality.

2.18 Write_Temperature_Maps (Boolean, optional)

A Boolean input (Y or N). Should maps of mean supper temperature be written each year? This is primarily useful for calculating NormalSummerT for each site, as an input for drought mortality.

2.19 Write_Species_Drought_Maps (Boolean, optional)

A Boolean input (Y or N). Writes maps of drought mortality for each species for each timestep.

2.20 WaterDecayFunction

The WaterDecayFunction parameter determines the effect of moisture on decay rate can be either linear or based on a ratio. The Century 4.0 Help file states that linear option is to be when only the relative water content in the top 15 cm affects decay rates. If ratio, the ratio of rainfall to potential evaporation rate determines the effect of moisture on decay rates.

Options: "Linear" or "Ratio"

User Tip: Linear is generally appropriate for sandy soils; ratio for more mesic soils.

2.21 ProbabilityEstablishAdjust (double)

This optional parameter adjusts the probability of establishment. The default value is one.

User Tip: This value can be reduced (<1) if overall regeneration rates are too high. Keep in mind that p-est is dependent on the successional time step. For example, you might want to lower the adjustment factor if you shift from a 5-year time step to a 1-year time step.

2.22 InitialMineralN (double)

The amount of mineral N (g m^{-2}).

2.23 InitialFineFuels (double)

The amount of fine fuel biomass (internally, the SoilStructural and SoilMetabolic layers) as a fraction of initial dead wood. This accounts for recent disturbance that may have deposited large volumes of both dead wood and fine fuels. Ranges from 0.0 to 1.0.

2.24 Nitrogen Inputs: AtmosphericNSlope and AtmosphericNIntercept

Determines N deposition rates (including wet deposition, dry deposition, non-symbiotic fixation and N fertilization) using simple regression:

Total N deposition = (AtmosNslope*precipitation) + AtmosNinter

The AtmosNslope parameter controls how the amount of wet deposition, i.e. how much N is deposited during rain events, with higher slopes generating more N deposition. Dry deposition is controlled by the N intercept parameter, which is constant and is not a function of precipitation.

User Tip: *Adjust the slope and intercept until the monthly or annual N deposition in the NECN-succession-monthly-log.csv is similar to literature values.*

2.25 Latitude (double)

The latitude of the study site (°).

2.26 DenitrificationRate (double)

The fraction of mineral N lost through ammonia volatilization and denitrification **per month**. This fraction is not fire related; fire related volatilization is modeled separately. Ranges from 0.0 to 1.0.

User Tip: *This parameter should be adjusted so that Nvol (output parameter of N volatilization) ranges from 0 to ~0.3 for uplands and 0.3 to 1 g m^{-2} year^{-1} for wetlands (Seitzinger et al. 2006).*

2.27 Decay Rates of SOM1, SOM2, and SOM3 soil pools (double)

The decay rates for SOM1-surface, SOM1-soil, SOM2, and SOM3 determine the **maximum** decomposition rate (k) of the four soil organic matter pools. Ranges from 0.0 to 1.0.

User Tip: *In most landscapes, the relative changes in the soil pools are higher in the upper than the lower horizons. Therefore, the maximum decay rates should be higher in the surficial than the deeper pools (i.e. DecayRateSurf>DecayRateSOM1> DecayRateSOM2>DecayRateSOM3). Also, the total amount of C in soil should slowly increase over time in the absence of disturbance.*

2.28　GrassThresholdMultiplier (double, optional)

The parameter that adjusts the competitive relationship between grasses and trees (positive number, double). The competitive relationship between tree species cohort i is calculated by the following algorithm.

if (AGB of tree cohort i)<(AGB of grasses)×grassThresholdMultiplier)

　　　　Total site LAI =Total LAI of trees+Total LAI of grasses

else

　　　　Total site LAI =Total LAI of trees

Finally, the competition limit of tree cohort i = exp(k×Total site LAI)

2.29　Optional Maps

There are many additional maps that NECN can provide that are not produced by default. Each is activated by invoking the keywork **XXXMapName** followed by a file name.

File names should follow the format: "NECN\ANPP-{timestep}.tif", where timestep will be replaced with the model simulation year.

If any optional map is requested, the frequency of output must also be indicated using a matching keyword. For example, if ANEE map names are given, the variable **ANEEMapFrequency** (in years), is required. All of these maps are OPTIONAL.

Table 3. Optional maps and their keywords and descriptions.

Variable Name	Description
ANPPMapName	Aboveground Net Primary Productivity. g B m^{-2} year^{-1}
ANEEMapName	Aboveground Net Ecosystem Exchange g C m^{-2} year^{-1}. **Note:** The value of 1000 is added to ANEE output maps because most map types do not accept negative numbers; ANEE typically ranges from -500-500. To use the data, subtract 1000 from the final analysis.
SoilCarbonMapName	Soil Organic Carbon in g C m^{-2}.
SoilNitrogenMapName	Soil Nitrogen in g N m^{-2}.
TotalCMapName	Total Carbon including living C, detrital C, and soil C. g C m^{-2}.

2.30 CreateInputCommunityMaps (Boolean, optional)

This Boolean keyword will create maps necessary for generating new initial conditions in a separate model run. Maps include: SOM1, SOM2, SOM3, DeadRoots. Other necessary inputs are provided elsewhere. This will output all cohort data in the style of an input community map and text file. This allows the user to capture the state of cohorts and use that data to start a separate model run. The default value is FALSE.

2.31 Variable overrides (double, optional)

Several internal NECN parameters may be overridden using optional parameters. This replaces their default value with user input values. **Their use is not recommended except for special circumstances.** Parameters with overrides available include Stormflow, WaterFactor1, WaterFactor2, AnaerobicFactor1, AnaerobicFactor2, AnaerobicFactor3.

2.32 SpeciesParameters (CSV file name)

This table contains species' physiological parameters. Each row in the table has the parameters for one species. Every active species must have an entry.

A CSV file of species parameters MUST be provided; the older style text inputs are no longer supported. Every column must have a heading, spelled and with capitalization exactly as listed below. The type (integer, double, Boolean, or string) of the data must match the expected type, indicated in parentheses. The order of the columns does not matter.

NOTE: The first data row (immediately beneath the header row) determines the data type (int, double, Boolean, or string) for all subsequent rows. Therefore, the first data row MUST have the intended data types.

Table 4. Optional maps and their keywords and descriptions.

Column Name	Data type	Description
SpeciesCode	string	The species code must be defined in the species input file. Species code may appear in any order.
NitrogenFixer	boolean	This should be either TRUE or FALSE, depending on whether the species can fix N. An N fixing tree or shrub is never N limited and its N components fertilize following mortality. Must be TRUE or FALSE.
GDDMinimum	integer	Growing Degree Day (GDD) minimum are used to define a species climatic envelope following the algorithm by Botkin (1973). GDD is calculated on a 5°C base. *Only applies to establishment.*

GDDMaximum	integer	Growing Degree Day (GDD) maximum are used to define a species climatic envelope following the algorithm by Botkin (1973). GDD is calculated on a 5°C base. *Only applies to establishment.*
MinJanuaryT	integer	A species has a minimum tolerable January temperature (the mean of January nights). If the stochastically generated January minimum temperature is below the minimum, a species cannot establish. Units: degrees Celsius. *Only applies to establishment.*
MaxDrought	double	If available water falls below zero for a percent of the growing season greater than this value, a species cannot establish. Units: fraction of the growing season (0.0 – 1.0). Lower values indicate species whose establishment is more sensitive to drought. *Only applies to establishment.*
LeafLongevity	integer	This parameter is the average longevity of a leaf or needle. Value: 1 ≤ integer number ≤ 10. Units: years.
Epicormic	boolean	Does the species resprout via epicormic branching following a fire? Must be TRUE or FALSE.
LeafLignin	Double	The fraction of lignin in each plant component (leaf, fine root, wood, and coarse root) per species. Value: 0.0 ≤ decimal number ≤ 1.0.
FineRootLignin	Double	The fraction of lignin.
WoodLignin	Double	The fraction of lignin.
CoarseRootLignin	double	The fraction of lignin.
LeafCN	Double	The carbon to nitrogen ratios for leaf, fine root, wood, coarse root, and litter components. The difference between leaf and litter CN ratios represents the amount of N that is resorbed (i.e. retranslocated) prior to leaf mortality.
FineRootCN	Double	The carbon to nitrogen ratio.
WoodCN	Double	The carbon to nitrogen ratio.
CoarseRootCN	Double	The carbon to nitrogen ratio.

FoliageLitterCN	double	The carbon to nitrogen ratio. **Note**: *For retranslocation to work properly, litter CN **must be** higher than leaf CN for each species.*
MaximumANPP	integer	The maximum **monthly** aboveground net primary productivity (ANPP) for each cohort of each species. The value is specified as the ANPP in the month of the year with maximum growth (e.g., June). Value: $0 \leq integer \leq 100{,}000$. Units: g biomass m-2 month-1. Default value: 0. **Note:** This is the maximum monthly ANPP during peak growing season, not the annual ANPP often reported in the literature.
MaximumBiomass	integer	This parameter defines the maximum allowable aboveground biomass (AGB) for each species. This is a life history attribute and determines the overall growth form of a species (shrub vs. understory vs. overstory) as determined by evolutionary history. This parameter interacts with KLAI and ANPP to determine the growth rate and maximum biomass of each species. Value: $0 \leq integer$. Units: g biomass m^{-2}. Default value: 0.
GrowthLAI (optional)	double	Determines the LAI growth limit, i.e., the relationship between LAI and growth limits, using the equation: LAI_Growth_limit = Maximum(0.0, 1.0 - e(GrowthLAI * LAI)) The default value is 0.47.
Grass	boolean	Determines whether the species is grass species or not. If users include grass species in their simulation, there will be competition between grasses and trees (see Introduction). If users simulate only tree species, this parameter should be set to FALSE for all species. Must be TRUE or FALSE.
Nlog_depend	boolean	Determines whether the regeneration of species depends on nursery logs. If users include nursery log dependent species in their simulation, the establishment of these species cohorts is determined by environmental conditions, light probabilities, and the amount of well decayed

		downed logs. See Hotta et al. (2021) for details. Must be TRUE or FALSE.
LightLAIScale	double	The mean ('Scale') LAI of a Weibull distribution, determined from empirical data for each species. Must be > 0.0.
LightLAIShape	double	The dispersion ('Shape') of a Weibull distribution, determined from empirical data for each species. These parameters use actual LAI to estimate the probability of light establishment from a probability distribution function.
LightLAILocation	double	The y-intercept ('Location') of a Weibull-like distribution, determined from empirical data for each species.
LightLAIAdjust	Double	A scaling parameter that multiplies probability of light establishment for that species. This may be used to increase the probability of establishment to better replicate previously calibrated parameters from NECNv6 or v7, or to represent species with greater fecundity. Note that using either LightLAILocation or LightLAIAdjust will create a distribution that is no longer a probability density function: that is, the area under the curve will no longer sum to 1. However, it may better represent empirical data.
TemperatureCurve1	double	These four parameters define how growth will respond to temperature and are used to define a Poisson Density Function curve. See the CENTURY references for a full explanation.\n\nCurve1: The optimum temperature for growth.
TemperatureCurve2	double	Curve 2: The maximum temperature for growth.
TemperatureCurve3	double	Curve 3: The left curve shape parameter.
TemperatureCurve4	double	Curve 4: The right curve shape parameter.
MoistureCurve1	double	Curve1: The optimum volumetric soil water content (in %) for growth.
MoistureCurve2	double	Curve2: The minimum volumetric soil water content where growth may occur.
MoistureCurve3	double	Curve3: the left curve shape parameter
MoistureCurve4	double	Curve4: the right curve shape parameter

FractionANPPtoLeaf	double	The fraction of aboveground net primary productivity that is allocated to leaves. Units: fraction of ANPP (0.0 – 1.0).
LeafBiomassTOLAI	double	These four parameters determine how LAI is calculated which subsequently limits growth. Therefore, these parameters help determine the initial rate of growth in the landscape. LeafBiomassTOLAI determines LAI as a function of leaf biomass. If MaximumLAI = 0.0, then only leaf biomass determines LAI and the growth limits.
KLAI	double	KLAI and MaximumLAI determine LAI as a function of wood biomass. The large wood mass (g C/m^2) at which half of theoretical maximum leaf area is achieved.
MaximumLAI	double	The theoretical maximum leaf area index for a cohort.
MinimumLAI	double	The minimum LAI for any given cohort. The default value is 0.1. An overly low minimum LAI may create the situation where a cohort is permanently suppressed under a closed canopy.
WoodDecayRate	double	This parameter defines the maximum fraction of the species' dead wood that decomposes. Value: 0.0 ≤ number ≤ 1.0. Unitless.
MonthlyWoodMortality	double	A monthly fraction of wood mortality, *constant through time and regardless of successional stage*. This mortality is in addition to growth-related mortality as a function of ANPP. Units: fraction of wood biomass (0.0 – 1.0).
LongevityMortalityShape	double	Determines how quickly longevity-related mortality begins and operates as in Biomass Succession. Value: 5.0 ≤ decimal number ≤ 25.0. If the parameter = 5, then age-related mortality will begin at 10% of life span. If the parameter = 25, then age-related mortality will begin at 85% of life span.
FoliageDropMonth	integer	Determines when the leaves will drop and become part of the litter pool. This parameter only applies to deciduous (Leaf longevity = 1.0 vegetation); evergreen species drop an equal amount of foliage across all months.

		Note: *Note that FoliageDropMonth=9 means that half the leaves will drop in October (one month offset) and the other half drop in November.*
CoarseRootFraction	double	The fraction of aboveground net primary productivity that is used to compute the ANPP of coarse roots. Units: fraction of ANPP (0.0 – 1.0).
FineRootFraction	double	The fraction of aboveground net primary productivity that is used to compute the ANPP of fine roots. Units: fraction of ANPP (0.0 – 1.0).

2.33 DroughtMortalityParameters (CSV file name, optional)

This file gives parameters for drought mortality for each species. There are two methods to specify mortality: with thresholds of climatic water deficit (CWD), or with multiple regression with potential predictor variables including Age, Temperature, Soil Water Anomaly, Biomass, Climatic Water Deficit, Normal Climatic Water Deficit, and the interaction between CWD and Biomass. Each predictor variable also has a user-specified "lag" which indicates how many of the most extreme of the preceding 10 years of weather to use. For example, CWD with a lag of 10 would use the mean CWD of the entire preceding decade; a lag of 3 would use the mean of the CWD of the three years with the highest CWD. Multiple regressions currently predict **probability of decadal survival**, and the predictions are converted to annual mortality internally. The parameters should be on the log-odds scale. Predictions are back-transformed internally using an inverse logit function.

The CWD Threshold mode and Multiple Regression Mode cannot be used simultaneously for a given species. The parameters for the other model type should be filled with zeroes (i.e., if using CWD Threshold for a species, all the columns from "Intercept" to "IntxnCWD_Biomass" should be zero).

Table 5. Optional drought parameters and their keywords and descriptions.

Column Name	Input type	Description
SpeciesCode	String	The species code must be defined in the species input file.
CWDThreshold	integer	First threshold for mortality. Above this threshold of annual CWD (in cm), species have a probability of mortality given by MortalityAboveThreshold.
MortalityAboveThreshold	double	Probability of cohort mortality if annual CWD exceeds CWDThreshold.

CWDThreshold2	integer	Second threshold for mortality. Above this threshold of CWD, cohorts have a probability of mortality given by MortalityAboveThreshold2. Note: if you are only interested in one threshold, then set CWDThreshold and CWDThreshold2 to the same value and set MortalityAboveThreshold and MortalityAboveThreshold2 to the same value.
MortalityAboveThreshold2	double	Probability of cohort mortality if annual CWD exceeds CWDThreshold2.
Intercept	double	Intercept for drought survival regression method
BetaAge	double	Parameter for the effect of cohort age on log-odds of decadal survival. Calculated for each cohort.
BetaBiomass	double	Parameter for the effect of site aboveground biomass on log-odds of decadal survival
BetaTemp	double	Parameter for the effect of the average of lagged summer Temperature (in degrees C) on log-odds of decadal survival. Summer temperature is calculated from the sum of temperatures of July-October of the preceding year and May-June of the current year.
BetaSWAAnom	double	Parameter for the effect of lagged annual soil water anomaly (in cm) on log-odds of decadal survival; calculated for each site using soil water availability and input maps of normal SWA
BetaCWD	double	Parameter for the effect of lagged annual Climatic Water Deficit (in cm) on log-odds of decadal survival
BetaNormCWD	double	Parameter for the effect of Normal CWD on log-odds of decadal survival, generated from the Normal CWD input maps.
IntxnCWD_Biomass	double	Parameter for the interactive effect of CWD and site biomass, calculated by multiplying those variables.
LagTemp	integer	Range 0-10. The consecutive number of the preceding 10 years to use to calculate temperature for the regression method. E.g., a value of 5 would specify the value for Temperature should be the mean summer monthly temperature of the 5 hottest consecutive years of the preceding 10 years. Setting this value to 10
LagSWA	integer	Range 0-10. The number of the preceding 10 years to use to calculate Soil Water Anomaly for the regression method. E.g., a value of 3 would specify

		the value for SWA should be the mean soil water anomaly of the 3 driest consecutive years of the preceding 10 years.
LagCWD	integer	Range 0-10. The number of the preceding 10 years to use to calculate Climatic Water Deficit for the regression method. E.g., a value of 9 would specify the value for CWD should be the mean annual CWD of the 9 driest consecutive years of the preceding 10 years.

2.34 Fire Reduction Parameters

The `FireReductionParameters` table allows users to specify how much dead wood and litter will be removed as a function of fire severity, and what proportion of cohort biomass is volatilized when a cohort is partially or completely killed. Coarse debris reduction, fine litter reduction, and Organic Horizon Reduction reduce, control what proportions of dead wood, dead litter biomass, and surface soil C pools are volatilized by a fire of a given severity class. Cohort Wood and Cohort Leaf Reductions control how much of cohort wood and leaf biomass are consumed by fire. The remainder of the biomass is deposited into the dead wood and dead leaf carbon pools.

Note: This table is required even if fire extensions are not being used.

2.34.1   Fire Severity (integer)

The first column is fire severity, classes 1 – 10. Severity should be listed in ascending order.

The number of fire severity classes that you should use is dependent on the fire extension selected.

2.34.2   Coarse Debris Reduction (double)

The second column is the proportion (0.0 – 1.0) of dead wood biomass that is volatilized. The proportion will be applied to both C and N components.

2.34.3   Fine Litter Reduction (double)

The third column is the proportion (0.0 – 1.0) of dead litter biomass that is volatilized. The proportion will be applied to both C and N components.

2.34.4   Cohort Wood Reduction (double)

The fourth column is the proportion (0.0 – 1.0) of cohort wood biomass that is volatilized. The proportion will be applied to both C and N components.

2.34.5   Cohort Leaf Reduction (double)

The fifth column is the proportion (0.0 – 1.0) of cohort leaf biomass that is volatilized. The proportion will be applied to both C and N components.

2.34.6   Soil Organic Matter (SOM) Reduction (double)

The last column is the proportion (0.0 – 1.0) of SOM1-surface (the O-Horizon) that is volatilized. The proportion will be applied to both C and N components.

2.35 Harvest Reduction Parameters

The `HarvestReductionParameters` table specifies how much dead wood and litter will be removed as a function of harvest activity **and how much cohort wood and leaf biomass is moved off site during harvesting**. Live cohort wood is typically removed from the site during harvesting. After a harvest event kills a cohort, pre-existing dead biomass can be removed from the forest. If a prescription is not listed (or is not spelled identically to the name used in the harvest prescription file), the defaults are zero for all values.

2.35.1   Prescription Name

The first column is prescription name. Each prescription name must be identical to the prescription names in the Harvest file (see "LANDIS-II Base Harvest v2.0 User Guide"). Prescriptions can be in any order; they do *not* need to appear in the same order as in the Harvest input file.

2.35.2   Dead Wood Reduction (double)

The second column is the proportion (0.0 – 1.0) of dead wood biomass – **existing before the harvest begins** - that is removed due to the associated harvest prescription. The proportion will be applied to both C and N components.

2.35.3   Dead Litter Reduction (double)

The third column is the proportion (0.0 – 1.0) of dead litter biomass – **existing before the harvest begins** - that is removed due to the associated harvest prescription. The proportion will be applied to both C and N components.

2.35.4   Cohort Wood Removal (double)

The fourth column is the proportion (0.0 – 1.0) of cohort *living* wood biomass that is removed from the site due to the associated harvest prescription. *The remainder is typically regarded as slash and is left on site.* The proportion will be applied to both C and N components.

2.35.5   Cohort Leaf Removal (double)

The fifth column is the proportion (0.0 – 1.0) of cohort *living* foliar biomass that is removed from the site due to the associated harvest prescription. *The remainder is typically regarded as slash and is left on site.* The proportion will be applied to both C and N components.

3 Output Files

The NECN Succession extension produces a number of outputs. The maps of soil C, ANPP, and NEE are described above.

In Version 5+, additional maps have been added to track water:

- Annual Water Budget: Excess soil moisture after evapotranspiration. Defined as water inputs (precipitation + irract) – actual evapotranspiration (AET)

- Available water: amount of water available to trees

In version 7, the following output maps were added:

- AnaerobicEffect: average value of the anaerobic effect variable, which reduces soil respiration in wet sites

- SoilWater: now represents the average soil water content (in cm)

- PET: annual total potential evapotranspiration

In addition to the maps, there are five primary log files and one optional log file. These are all comma delimited (*.csv) files that are typically read using Excel.

3.1 Output Metadata

When you run NECN, xml files are created for all text outputs in the Metadata folder**. Users can open these xml files in any internet browser and will list all the output parameters, their description and units.**

3.2 NECN-succession-log

The primary log file that outputs a snapshot of data at every successional time step. These data are averaged by climate region and are most useful for analyzing variation over time and across climate regions.

3.3 NECN-succession-log-short

An abbreviated version of the NECN-succession-log file. This reduced set of parameters was chosen for display in the LANDVIZ tool.

3.4 NECN-succession-monthly-log

This log file contains an abbreviated set of data that are useful at a monthly time step. These include NPP, heterotrophic respiration, N deposition and NEE. These data can be compared to monthly flux tower data. Also included are monthly temperature and precipitation. These allow a quick cross-reference to your input data.

3.5 NECN-prob-establish-log

This log file contains the data used to calculate the probability of *seeding* establishment for each climate region at each succession time step. The probability of establishment is the minimum of all limiting factors. However, these values do not take shade and presence of seed sources into account and therefore do not reflect the cumulative probability of establishment in a given site. These also do not reflect reproduction from planting, serotiny, or resprouting.

Note: The probability of establishment is calculated annually and averaged over the succession time step.

3.6 NECN-reproduction-log

This log file summarizes all reproduction events, including from planting, serotiny, resprouting, and seeding.

3.7 NECN-calibrate-log (Optional)

A detailed monthly output for **every cohort at each month**. *Note: **Due to the volume of data, this file should ONLY be used with single cell runs.***

3.8 Drought mortality maps and tabular data

If enabled (see 2.17), a raster will be written for each species for each timestep containing biomass killed by drought.

4 Initial Communities

4.1 Initial Communities Map

This is the input map indicating the initial communities at the active sites on the landscape. Each cell value for an active site on the landscape must be one of the map codes listed in the initial communities input file (see section 5, below).

Each initial community has an associated map code and a list of species present at sites in the class. There is **now only one input format**, a CSV file, described below.

4.2 Initial Communities Input CSV File

This file contains the definitions for each initial community. Each active site on the landscape is assigned an initial community. The initial community specifies the cohorts that are present including species, age, biomass (g m^{-2}), leaf biomass, and wood biomass.

Each initial community has an associated map code that corresponds to the accompanying map, as well as information about the cohorts present, including species, ages, biomass (g m^{-2}), woody biomass, and leaf biomass. Note: ANPP (g m^{-2} yr^{-1}) is initialized with a value of 0 and is assigned a value during the first time step.

4.2.1   FileName

The file name must point to a CSV file with format described next.

4.2.2   CSV file format

NOTE: The first data row (immediately beneath the header row) determines the data type (int, double, Boolean, or string) for all subsequent rows. Therefore, the first data row MUST have the intended data types.

The CSV format requires a header row with the following names in bold, below.

MapCode: This parameter is the code used for the community in the input map (see section 2.5). Value: $0 \leq$ integer $\leq 65,535$. Each communities' map code must be unique. Map codes do not have to appear in any order, and do not need to be consecutive.

SpeciesName: These must match the names found in the scenario species file.

CohortAge: A cohort age is an integer and must be between 1 and the species' Longevity parameter. The ages do not have to appear in any order.

CohortBiomass: Biomass must be entered as an integer (no significant digits).

WoodBiomass: Wood biomass must be entered as an integer (no significant digits).

LeafBiomass: Leaf biomass must be entered as an integer (no significant digits).

MineralNallocation, **MineralNfraction**, **Nresorption: DO NOT INCLUDE.** *You will notice a warning during initialization that these data are missing.* This is intentional and you can ignore this warning.

4.2.3   Unvegetated (aka empty) Map Codes

For Empty Map Codes: If there is an active map code that does not have any vegetation, the data should be represented as: *TheActualMapCode*, NA, 0, 0 (where *TheActualMapCode* is the code without data, e.g. 1968).

Example:

5, NA, 0, 0

4.2.4   Grouping Species Ages into Cohorts

The list of ages for each species is grouped into cohorts based on the succession extension's timestep. This timestep determines the size of each cohort. For example, if the timestep is 20, then the cohorts are ages 1 to 20, 21 to 40, 41 to 60, etc.

Suppose an initial community class has this species in its list (biomass left out here for simplicity):

```
acersacc  10  25  30  40  183  200
```

If the succession timestep is 10, then the cohorts for this species initially at each site in this class should be:

```
acersacc  10  20  30  40  190  200
```

Note that biomass values will be totaled when cohorts are grouped.

If the succession timestep is 20, then the cohorts for this species initially at each site in this class will be:

```
acersacc  20  40  200
```