



# FINAL REPORT

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## **Additional Modeling and a Synthesis of Ecosystem Process Model Performance Comparisons**

**RC-201736**

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## LIST OF ACRONYMS

ACUB	Army Compatible Use Buffer
AGB	Above-Ground Biomass
CMS	Carbon Monitoring System
CRU	Climate Research Unit
DBH	Diameter at Breast Height
DGVM	Dynamic Global Vegetation Model
DoD	Department of Defense
ED	Ecosystem Demography model
ESTCP	Environmental Security Technology Certification Program
GAEMN	Georgia Automated Environmental Monitoring Network
GCM	Global Circulation Model
GEDI	Global Ecosystem Dynamics Investigation
LANDIS-II	LANdscape DIsturbance and Succession model, variant 2
LCPF	Lower Coastal Plain and Flatwoods
LTM	Long Term Monitoring
MstMIP	Multi-Scale Synthesis and Terrestrial Model Intercomparison Project
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NECB	Net Ecosystem Carbon Balance
NECN	Net Ecosystem Carbon and Nitrogen, operates within LANDIS-II
NEE	Net Ecosystem Exchange
NEP	Net Ecosystem Productivity
NRCS	National Resources Conservation Service
PAR	Photosynthetically Active Radiation
PFT	Plant Functional Type
SOC	Soil Organic Carbon
SSURGO	Soil Survey Geographic database
USDA	United States Department of Agriculture

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## ABSTRACT

### **Introduction and Objectives:**

Land managers of forested landscapes face increased difficulty in projecting how various management techniques impact ecological processes, such as carbon sequestration potential. Given the large use of prescribed fire on DoD lands, there is a need to assess landscape carbon flux in response to different fire frequencies and management regimes. Ecosystem process models provide a robust solution to informing management decisions in an uncertain future. Model selection depends on the geographic location of interest, the overall goals and objectives of management, and the inherent biotic and abiotic disturbances that affect ecosystem dynamics (e.g., vegetation response and interactions with climate and climate-driven disturbances)..

Our *project objectives* were to 1) provide data and technical support to the ESTCP board and project performers throughout the inter-model comparison projects (Topic 5, FY17) and 2) perform an inter-model comparison at one designated performance site using different model classes to assess the impacts of fire regimes on landscape carbon projections.

### **Technology Description:**

We synthesized two forested data rich study sites (Jones Center at Ichauway in southern GA and Harvard Forest in MA) and provided them to ESTCP and the other chosen ESTCP teams, while continuing to support those teams and ESTCP. These long-term datasets included information on soil, vegetation, biomass, carbon flux, management. We also calibrated a landscape class, the Landscape Disturbance and Succession II (LANDIS-II) model, and a global class, the Ecosystem Demography (ED) model for the Jones Center at Ichauway. We assessed the strengths and weaknesses of each model including validating for Net Ecosystem Exchange with eddy-covariance flux tower data. The models are now available for any additional scenarios involving southeastern U.S. pinelands.

### **Performance and Cost Assessment:**

We found that both models predicted similar carbon projections and general species dynamics at short and long fire return intervals but differed at intermediate ranges due to inherent species representation (individual species versus Plant Functional Types (PFTs) within each model. Both models supported an aggressive prescribed fire regime in southeastern U.S. pinelands to maintain ecosystem carbon stability. We provide a detailed assessment of how, why, and when to use either model.

Our cost assessment is primarily labor based. The models are free to access and use, however, a data technician(s) and a modeling expert(s) are needed to parameterize, calibrate, and validate the models. Subsequent studies after these steps may be less labor intensive with varying costs.

### **Implementation Issues:**

We encountered no implementation issues.

### **Publications:**

Flanagan, S. A., S. Bhotika, C. Hawley, G. Starr, S. Wiesner, J. K. Hiers, J. J. O'Brien, S. Goodrick, M. A. Callahan Jr., R. M. Scheller, K. D. Klepzig, R. S. Taylor, and E. L. Loudermilk. 2019. Quantifying carbon and species dynamics under different fire regimes in a southeastern U.S. pineland. *Ecosphere* 10(6):e02772. 10.1002/ecs2.2772

Flanagan, S. A., E. L. Loudermilk, J. K. Hiers, J. J. O'Brien, S. Goodrick, M. A. Callahan Jr., G. Starr, and G. C. Hurtt. 2020. A model comparison of fire return interval impacts on carbon and species dynamics in a southeastern U.S. pineland. (*In Review. Ecosphere.*)

## Executive Summary

### Introduction

Forests impact the global carbon balance by sequestering ~30% of annual anthropogenic carbon dioxide emissions and storing ~45% of terrestrial carbon. Their ability to continue to sequester carbon and remain a sink depends on a variety of factors such as current ecosystem state, land-use history, climate change, disturbance regimes, and other interacting processes that frequently are interconnected. These interactions and their impact on future forest distribution, stability, and carbon sequestration potential are important research topics for scientists, resource managers, and policy makers.

The global process of wildland fire and climate-fire interactions are particularly critical uncertainties as emission and sequestration feedbacks are complex and multi-scalar. Methods to reduce wildfire intensity and spread, such as prescribed fire and forest thinning, compete against the goal of carbon sequestration. This is certainly important in low-intensity surface fire regimes for estimating carbon and species dynamics through time. The longleaf pine (*Pinus palustris*) ecosystem of the southeastern coastal plain of the U.S. is an archetype of a forest with a frequent surface fire regime. Through the continued use of frequent prescribed fire (1-3 yr return interval), this endangered ecosystem with many endemic flora and fauna has the potential to remain a global hotspot of diversity, maintain resilience to future droughts, and minimize large carbon emission pulses that can occur with wildfire. This ecosystem could potentially store less total carbon than if fire were excluded, but at the cost of losing endemic flora and fauna. There is a need to quantify carbon and species dynamics in longleaf pine forests and the feedbacks due to altered fire frequency and alternative stable states, namely transitions from longleaf pine to hardwood dominated stands when fire is excluded. The differences in carbon allocation and emissions between prescribed fire and wildfires are also important factors to consider given that prescribed fire is a common tool used in the southeast and wildfire risk is increasing.

This is particularly important to understand at DoD military bases as many have become key refuge and restoration sites for longleaf pine as a species and ecosystem. For example, Eglin Air Force Base, FL, represents one of the largest remaining tracts of longleaf pine in the southern U.S. Here, the long-term frequent fire history from military training and prescribed burning has maintained many endemic species populations. Fort Bragg, NC, has more than 89,000 acres of longleaf pine forest where studies on how time since burn influences vegetation type have already been conducted and have called for future research that incorporates a wider time frame. The longleaf pine ecosystems at Fort Bragg, Fort Stewart, GA, and the Savannah River Site, SC have been utilized to study how fire frequency has impacted understory plant diversity. Moreover, southeastern DoD installations have utilized programs such as the Readiness and Environmental Protection Integration Program to work with other federal agencies, state agencies, and non-profit partners to maintain and improve existing longleaf pine ecosystems and restore acreage to longleaf pine in and around military installations.

## Objectives

Our *project's objectives* were to 1) provide data and technical support to the ESTCP board and project performers throughout the inter-model comparison projects (Topic 5, FY17) and 2) perform an inter-model comparison at one designated performance site using a landscape and global class model to assess the impacts of varying fire frequency on landscape carbon projections.

The ESTCP inter-model comparison projects (FY17, Topic 5) goals were to 1) acquire knowledge of how processes (e.g., disturbances, management, climate) affect resilience and sustainability of ecosystems 2) provide carbon accounting, and 3) evaluate performance and demonstrate emerging technologies (i.e., process based models) used for 1 and 2. More specifically, #3 aimed to evaluate how well a model performed and how performance compared with other models (i.e., strengths and weaknesses) as well as evaluate if a model's performance is specialized for a particular purpose (e.g., fire, NEE, management, climate change effects). For these projects, identification of strengths and weaknesses of ecosystem process models can be achieved through multiple teams of researchers that use models to conduct model performance evaluations. As such, *for project objective 1, our overarching objectives* were to synthesize data at two data rich forested study sites (Ichauway in GA and Harvard Forest in MA), provide this information to the two other chosen teams (RC17-201702, RC17-201703) to perform their own inter-model comparisons, and provide technical support for both teams throughout their projects as well as provide technical support for ESTCP.

*For project objective 2, our overarching objective* was to perform an inter-model comparison on how fire return intervals impact the southeastern pine ecosystem. Most modeling studies select a single model to assess the impacts of management on future disturbance regimes, but the inherent strengths and weaknesses of model selection on the consequences of altered fire frequencies have not been sufficiently evaluated. In this study, we explored how various fire return intervals impacted carbon and species dynamics in a southeastern U.S. pineland (Ichauway) by using two ecosystem model classes. A landscape class, the Landscape Disturbance and Succession II (LANDIS-II) model, and a global class, the Ecosystem Demography (ED) model, were used to project how fire impacts this ecosystem. Five cases of fire return intervals were simulated: fire exclusion, and intervals of 2-(prescribed fire), 20-, 50-, and 100 years (wildfire). Through an inter-model comparison approach, the impact of each scenario on each model was evaluated by examining changes and differences in total above ground biomass (AGB), net ecosystem carbon balance (NECB), and species composition, and performing a validation of Net Ecosystem Exchange (NEE) with eddy covariance site data. The similarities and differences for each model and pros and cons of using a given model class for this type of research question are also discussed. Six performance objectives were used to evaluate the model. These are described in the Performance Assessment section below.

## Technology Description

Before model development, we synthesized data from two data rich sites: Ichauway and Harvard Forest. These long-term datasets included information on soil, vegetation, biomass, carbon flux, management, and disturbances. These data were provided to ESTCP and the other performers for the performance phase of their projects. We also supported the other performers and ESTCP

throughout the project timelines. We used the Ichauway data for our model development and inter-model comparisons.

For regional level management questions either a landscape class or global class model is often used and should be selected based on the model's ability to simulate the desired environmental change and predict the necessary ecosystem attributes one wishes to examine. As each class has relative strengths and weaknesses, a model comparison was conducted between a landscape class, the Landscape Disturbance and Succession II (LANDIS-II) model, and a global class, the Ecosystem Demography (ED) model, to explore some of these differences.

LANDIS-II (v6.2.1) integrates various ecosystem processes and disturbances that interact at the landscape scale and over longer time periods. LANDIS-II uses a gridded landscape where each cell contains species-age-cohorts of woody species whose growth and succession are governed by a species competitive ability, dispersal, and reproduction. It has been successfully implemented for understanding ecosystem dynamics, succession, insects, fire, wind, dispersal, harvesting, fuel treatment effectiveness, and climate change research. Within LANDIS-II, we used the Net Ecosystem Carbon and Nitrogen (NECN) Succession extension (v4.2) and the Biomass Harvest extension (v3.1.6). The NECN extension implements succession with above and below ground carbon and nitrogen and simulates the regeneration and growth of vegetation based on age, competition for resources (water, nitrogen, light), and disturbance. Vegetation growth and response to disturbance is determined by unique species attributes (e.g., shade tolerance). Dead biomass (woody and leaf litter) and soil organic carbon (SOC) are also tracked over time. The Biomass Harvest extension simulates the removal of aboveground live leaf and woody biomass of designated species and ages within selected areas.

The ED model was selected as the global class model. ED is a mechanistic model that approximates the first moment of the spatial stochastic ("gap") ecosystem model. The approximation relates size, age, and structure in a pseudo-spatial framework to minimize computational time when compared to spatially explicit simulations. PFTs are grouped into classes dependent on physiognomy, leaf form, photosynthetic pathway, and other characteristics, and compete for water, nutrients, and light governed by submodels of growth, soil water availability, phenology, disturbance, and biogeochemistry. The original ED model now has numerous variations that have been published. The version chosen here follows the adjustments made by Hurtt et al. (2002) for North American tree species, with the modifications made by Flanagan et al. (2016) and (2019). Previous research successfully implemented this version of ED in North America and had a harvest function similar to that of LANDIS-II added for charcoal extraction studies in Mozambique. A version running the same core code but with downscaled inputs is currently being used in NASA's Carbon Monitoring System (CMS), and the NASA Global Dynamics Investigation (GEDI) mission.

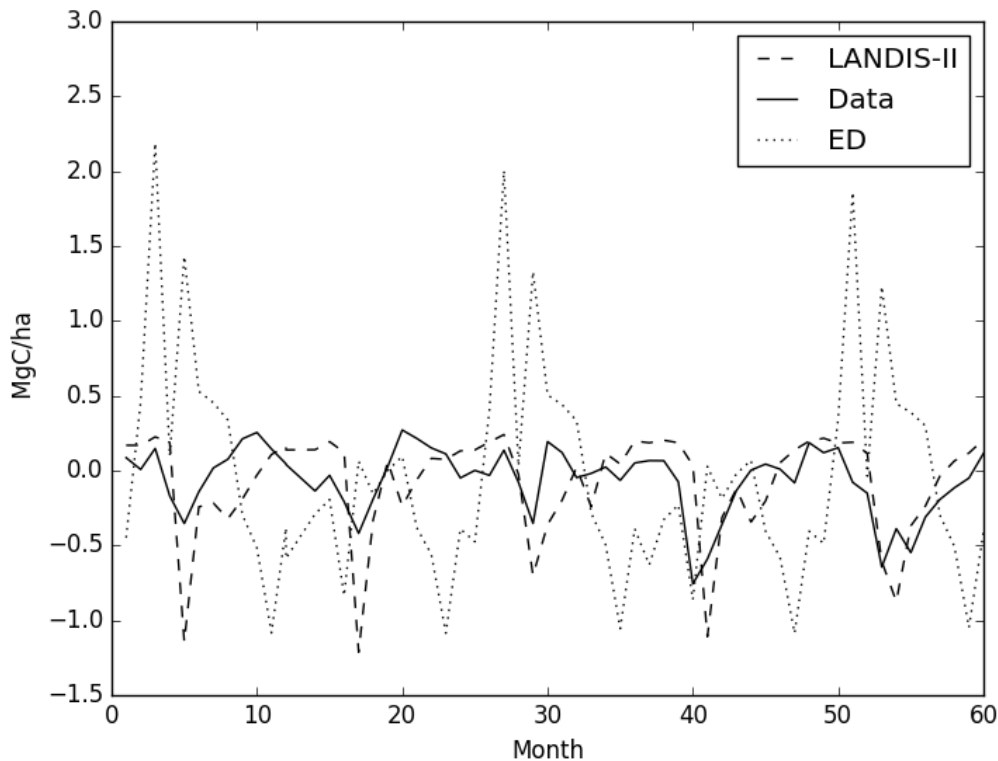
## **Performance Assessment**

We used six performance objectives to evaluate our models. The objectives were to examine model performance during the model calibration phase, development of the fire scenarios, model validation and model inter-comparison. The first four objectives were focused on assessing 1) current species abundance within each model, 2) carbon sequestration potential under a

prescribed fire regime, 3) a fire exclusion regime, and 4) three wildfire regimes. In this executive summary, we focus on the last two performance objectives, which were to 5) evaluate the models with an independent *validation dataset of carbon flux*, and 6) perform a *model inter-comparison* of AGB, NECB, and species composition.

### Carbon Flux Validation

Model validation involved comparison to flux tower measurements taken from the Jones Center at Ichauway. Three flux towers, which experienced biannual burning from January 2009-December 2013, were compared to each model's outputs. LANDIS-II requires the user to input climate variables so climate from these explicit times were used. ED's climate is precomputed so it could not be made to fluctuate yearly. Each model's predicted NEE for the prescribed fire scenario, which is the research site's standard management practice, was compared to the eddy covariance values for NEE (Figure ES1). The average net ecosystem exchange (NEE) over this five year period was -0.73 MgC/ha/yr for the data, -0.94 MgC/ha/yr for LANDIS-II, and -0.40 MgC/ha/yr for ED. This illustrates a  $\sim\pm 0.3$  MgC/ha/yr difference in mean NEE between models and data, which is quite small, especially given that the flux tower data was not used to calibrate either model.



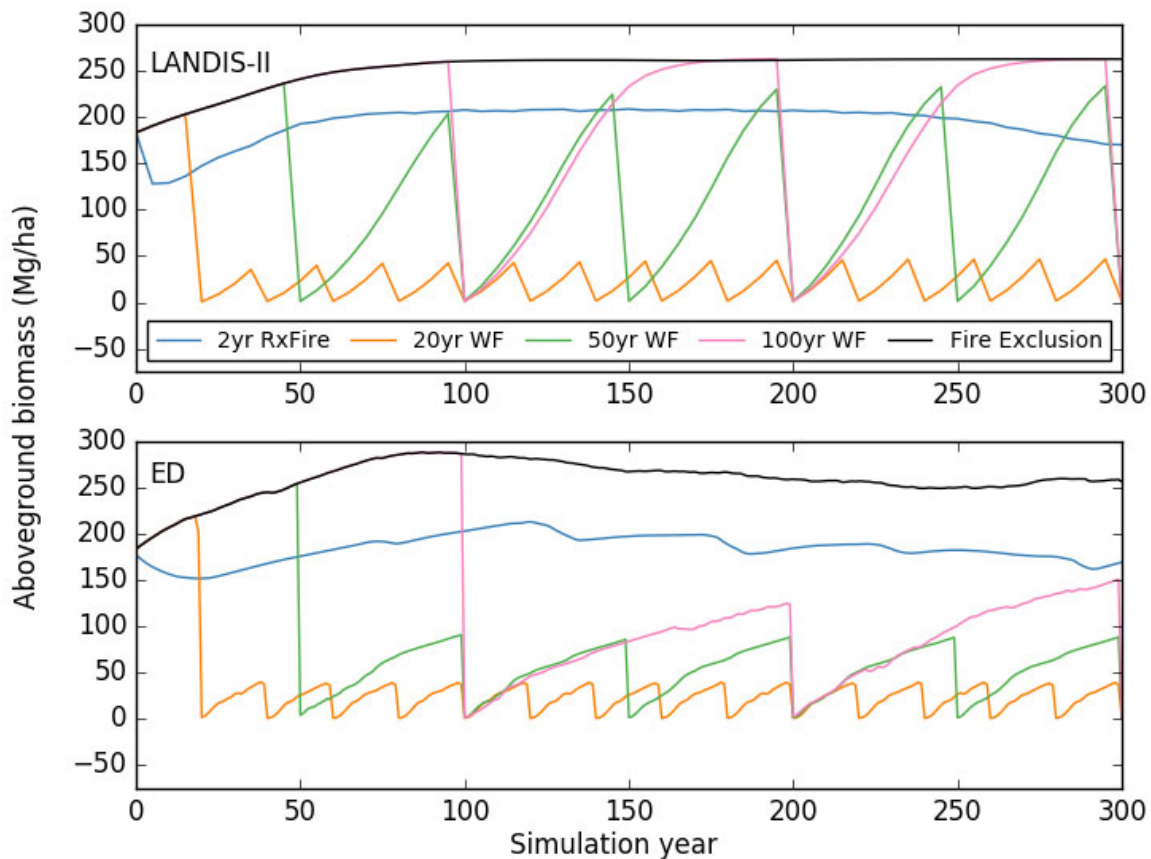
**Figure ES1:**

Monthly predicted NEE of the models and the empirical flux tower data.

### Model Inter-Comparison: Aboveground Biomass

Both models predicted maximum AGB of  $\sim 250$  Mg/ha in the fire exclusion scenario (Figure ES2). Also, both LANDIS-II and ED showed a decrease in AGB towards the end of the

prescribed fire (Rx) scenario as the landscape was essentially dominated by one species--either longleaf pine or the pine PFT, respectively. As this is a second growth forest of relatively the same age, age related mortality caused both models to predict a decline in AGB near the end of the prescribed fire scenario. By extending the scenarios past this time frame, total AGB overcame this age related perturbation and returned to the established maximum AGB, due to recruitment of new individuals into the stand. The wildfire (WF) scenarios were run with return rates of 20, 50, or 100 years and showed that LANDIS-II's representation of multiple similar species on the landscape quickly achieved maximum predicted total biomass and made for a smoother curve. In LANDIS-II this was ~80 years after a wildfire event, while ED was still not at maximum predicted AGB 100 years after a wildfire event.

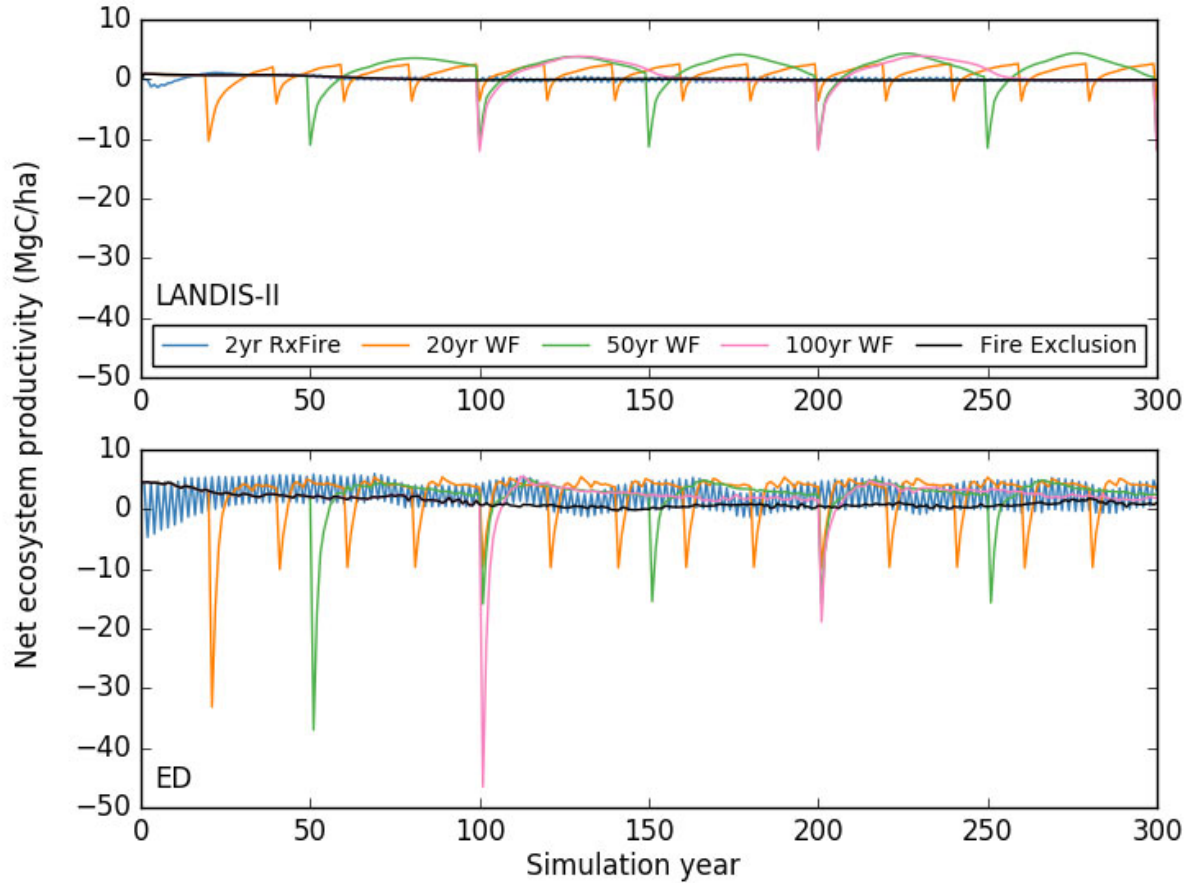


**Figure ES2.** Yearly model predicted AGB for all scenarios – 2yr prescribed fire (Rx), wildfire (WF) every 20, 50, and 100 yrs, and fire exclusion.

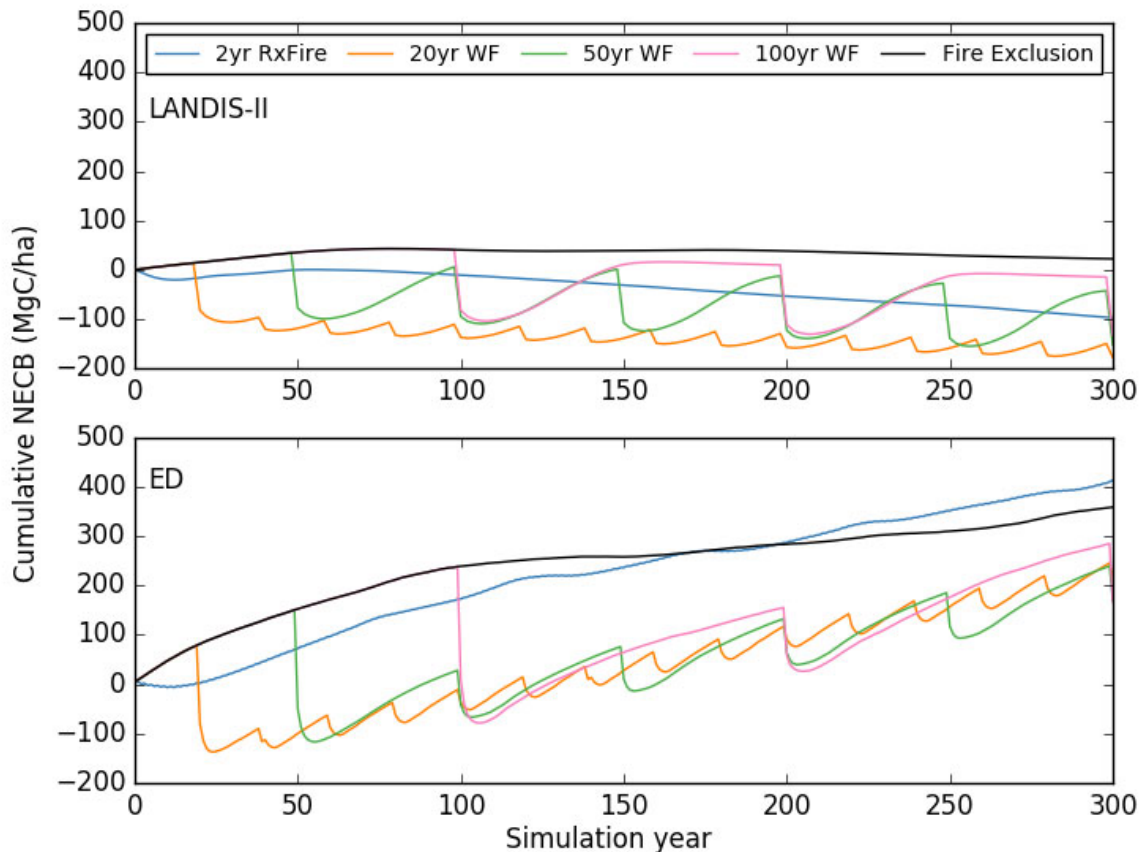
**Model Inter-comparison: Net Ecosystem Productivity and Carbon Balance**

Net ecosystem productivity (NEP), which does not account for biomass removed by fire, also showed the impact of ED not reaching maximum biomass. Both models predicted emissions after a fire event (negative values) and then sequestration (positive values) a few years later. However, as LANDIS-II had reached maximum potential AGB by the end of the 100yr wildfire return scenario, and reached near-maximum values (~80-90% of maximum) in the 50yr wildfire scenario (Figure ES2), predicted NEP was zero or near zero (Figure ES3) for these scenarios. As ED did not reach maximum potential AGB in any of the wildfire scenarios (Figure ES2), it

continued to predict positive NEP until the next fire event (Figure ES3). As with the flux validation, ED had greater peaks and valleys in its predicted response. To calculate NECB, NEP was combined with the loss of biomass from fire. This was tracked through time cumulatively, with ED predicting slight net carbon gains (sequestration) for all scenarios, whereas LANDIS-II predicted slight net losses of C (emissions) (Figure ES4). ED predicted prescribed fire to be the ideal scenario in terms of NECB while LANDIS-II predicted it as the ideal scenario except for the fire exclusion scenario.



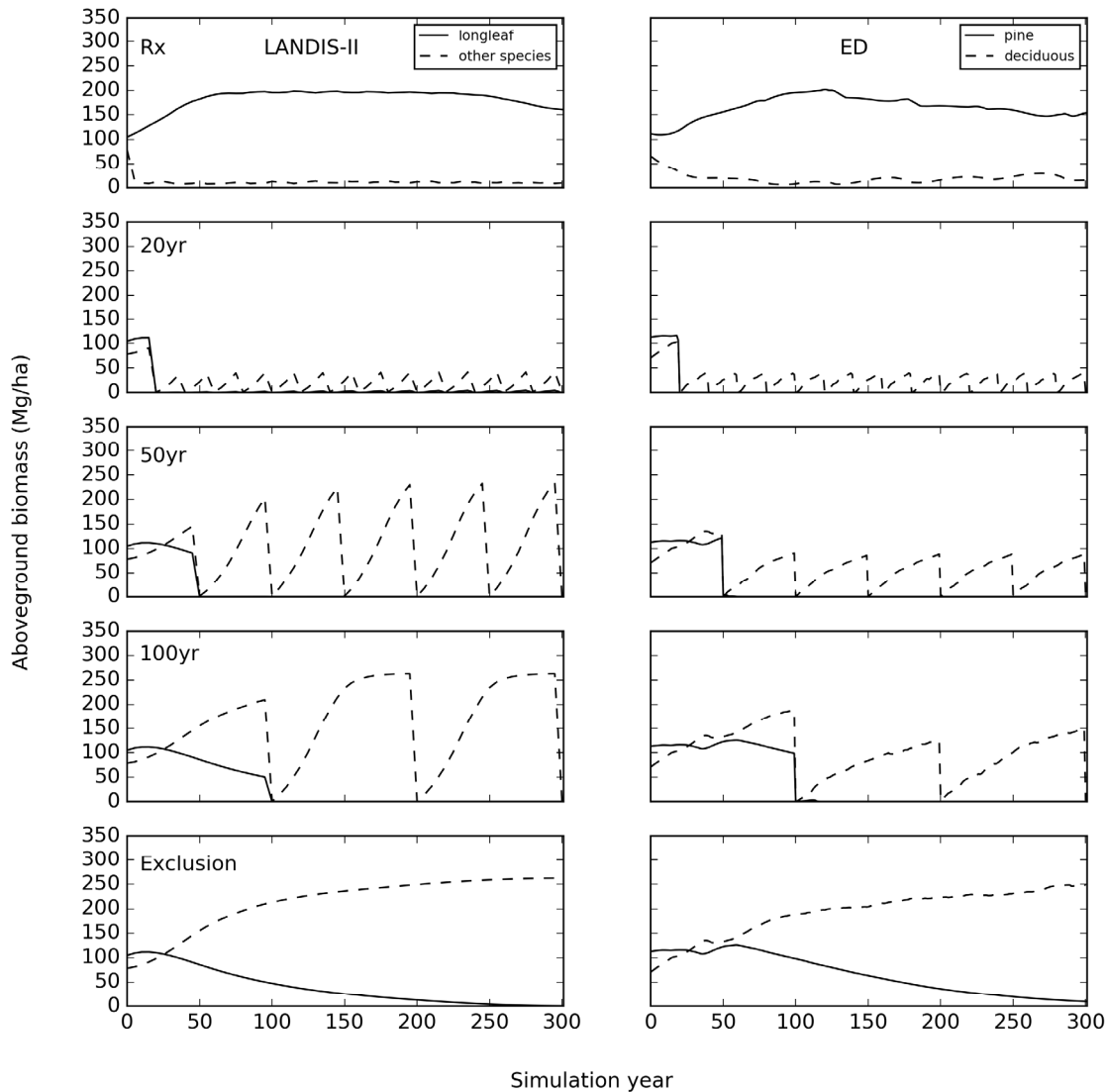
**Figure ES3.** Yearly model predicted NEP for all scenarios – 2y prescribed fire (Rx), wildfire (WF) every 20, 50, and 100 yrs, and fire exclusion.



**Figure ES4.** Cumulative NECB predictions for all scenarios – 2y prescribed fire (Rx), wildfire (WF) every 20, 50, and 100 yrs, and fire exclusion.

### Model Inter-comparison: Species Distribution

Under a frequent prescribed fire regime, both models approached max AGB of a longleaf pine stand similar to literature values, with proportions of biomass from longleaf versus all other species (Figure ES5 Rx). In the absence of fire, both models predicted a switch to a hardwood dominated forest (Figure ES5 Exclusion) with a higher maximum total biomass. The 20 yr scenarios showed similar results for both models as well. The major difference was between the 50- and 100 year scenarios. For example, in the 100 year scenario, hardwoods were predicted to dominate in both models, but these hardwood forests were predicted to reach maximum biomass between fire events only in the LANDIS-II simulations. However, it is important to note that this result does not imply forest stability. When LANDIS-II was separated by species, the eight simulated oaks had outcompeted the other species on the landscape, but were still on various and divergent trajectories as the forest matured. The addition of similar species that did not outcompete one another predicted a shorter time to maximum total biomass but not a stable ecosystem state regarding species dynamics.



**Figure ES5.** Yearly model predicted AGB for longleaf vs. other species (LANDIS-II) and pine vs. deciduous (ED).

**Discussion**

In this model comparison, two classes of models, a landscape scale and DGVM, both illustrated the benefits of a prescribed fire regime to promote carbon sequestration and stable AGB in a southeastern U.S. pineland (Figure ES4). Given the large discrepancies between resolution, independent core model development, inherent processes, and species dynamics, the model outputs were remarkably similar, particularly when fires occurred either very frequently or were excluded for the entire timeframe (Figure ES5 Rx, 20yr, Exclusion). Model similarities were also supported by their validation against an independent dataset of NEE (Figure ES1), where only

minor temporal differences were found, and time series of both models tracked well with the validation dataset. This supports the use of either model for illustrating the changes in carbon flux due to fire regime changes within this ecosystem type. Consideration should be given at longer time-scale fire intervals (here, 50, 100 yr intervals, Figures ES2 and ES5), where inherent species representations (individual species versus PFTs) and dynamics within each given model illustrated more significant discrepancies.

Although general simulations of NEP and NECB were similar between models, there were also distinct differences. For instance, cumulatively (Figure ES4) ED predicted slight net carbon sequestration while LANDIS-II predicted slight net carbon emissions. As such, conclusions on determining which fire regime showed *maximum* carbon sequestration potential were different; ED predicted maximum carbon sequestration potential under a prescribed fire regime, while LANDIS-II predicted maximize sequestration potential to occur under the fire exclusion scenario; i.e. no fire on the order of centuries, which is unrealistic given this fire-prone landscape. The next best scenario for LANDIS-II to *minimize* carbon emissions was the prescribed fire regime. Interestingly, though the slopes were in opposite directions, the yearly difference between the models NECB was plus or minus  $\sim 1\text{Mg/ha/yr}$ , a relatively small amount. These values, but not the slope or the ranking order of the simulations, are influenced by the amount of AGB converted to detrital carbon after a fire. With the inherent differences in these models, the relative similarity of their outputs vis-à-vis frequent prescribed fire argues in favor of the carbon sequestration benefits provided by this regime in southeast U.S. pinelands.

The two models generally agreed with AGB, NEP, and species distribution results for prescribed fire, fire exclusion, and the 20 yr wildfire return (Figures ES2, 3, and 5). Differences primarily occurred in the predictions for the 50 and 100 y wildfire scenarios because of the underlying species dynamics (Figure ES5). In these scenarios, where LANDIS-II had eight similar species growing on the landscape versus one for ED, LANDIS-II was able to reach maximum potential AGB at  $\sim 80\text{y}$  while ED did not reach maximum AGB until after 100y. Both models showed the dominance of hardwoods in the absence of fire, but the underlying species dynamics impacted their time to reach maximum potential AGB. Even though in ED the deciduous PFT had less competition for resources, growth was still limited by the number of new individuals the PFT could produce in a year. With only one dominant PFT per scenario, and one soil and climate type for the entire domain, ED's response to disturbance events was not as smooth (Figures ES2 and 5) as LANDIS-II's response after fire where more species reproduced in multiple ecoregions. Ultimately, the inherent discrepancies between models were only notable when the heterogeneity or lack thereof was simulated for enough time (here, more than 20 y) to see their respective differences in growth responses after a disturbance. Here, at short fire return intervals, the growth potential of multiple species is not different enough between models to see notable discrepancies, and at extremely long intervals or no disturbance at all, the growth patterns converged.

When choosing a model, there is a tradeoff between input requirements and time needed for model parameterization and the affect on desired model realism to address research questions. ED has high transportability because many inputs are pre-computed but is limited in how it can be modified and lacks individual species. LANDIS-II contains this information but requires a longer parameterization, which also provides greater flexibility in 'scenario' design (climate

change, fire regimes, insects outbreaks, harvesting regimes, etc). If uncertain about what level of detail is needed, one approach is to start with an already constructed DGVM, such as ED, which has high transportability, then examine the initial outputs. If the results recommend a more in-depth analysis, take the time to build the more complex landscape class. These decisions should always be informed by what the model was needed for in the first place – the specific management question(s) of interest. Based on our expertise, if and where LANDIS-II has been implemented on DoD lands (e.g., Ft. Benning, Ft. Bragg), they should continue to use this model because it is ‘ready to use’, has higher site realism, and is more flexible (as described above) than ED or another similar coarse-scale model. For sites that have not been parameterized by a stand or landscape scale process-based ecosystem model, ED could be considered as an initial model, based on ease of use for initial assessment (again, described above). On the other hand, as LANDIS-II has many developed parameters for longleaf pine ecosystems, many DoD installations in the southeast could develop their site specific model with less effort than what was made by this work.

### **Cost Assessment**

Our cost assessment is primarily focused on labor, both models used are open-source. There were no data costs. The literature values data are also publicly available or found from federal, regional, or local sources.

The primary labor expenses are a GIS technician with some scripting skills and a modeling expert. We found our funding breakdown that was used for this project to be accurate and necessary. We utilized a fulltime GS-12 post-doc and a GS-09 data technician at 0.33 FTE for 2.5 years. This was for the execution of two ecosystem process models with involved research questions, while providing other teams with data and supporting them with questions about data and various modeling needs. Dr. Scheller, one of the research teams we supported and the creator of LANDIS-II, estimated 8 months of a GIS technician and 2 months of a modeling expert for his LANDIS-II project. We similarly estimated 1 year of support to build LANDIS-II over a much larger area. Given this, we could estimate that it takes ~1yr of 1 FTE of a GS-12 to build LANDIS-II at any given site. However, once the model is developed for an area the costs could be considerably less if you were looking to address a specific research question with the developed model. In addition, there are various extensions (e.g. wind damage, harvesting, insect outbreaks, etc.) that can be added, and we estimate 3-6 months of FTE effort needed per extension. The ED model would be similar as it is already built for the U.S., but it does not have many pre-existing extensions. As such, the modeling expert would have to write code to add an extension, taking 3-6 months of FTE per extension. In the end, the main cost would be the initial construction of the model for a given site.

### **Implementation Issues**

We encountered no implementation issues.



## 1.0 INTRODUCTION

### 1.1 BACKGROUND

Forests impact the global carbon balance by sequestering ~30% of annual anthropogenic carbon dioxide emissions and storing ~45% of terrestrial carbon (Canadell et al. 2007, Bonan 2008). Their ability to continue to sequester carbon and remain a sink depends on a variety of factors such as current ecosystem state, land-use history, climate change, disturbance regimes, and other interacting processes that frequently are interconnected (Denslow 1980, Emanuel et al. 1985, Prentice and Fung 1990, Bachelet et al. 2001, Hurtt et al. 2002, Bonan 2008, Xu et al. 2009, Dale et al. 2011, Pan et al. 2011, Millar and Stephenson 2018). These interactions and their impact on future forest distribution, stability, and carbon sequestration potential are important research topics for scientists, resource managers, and policy makers.

The global process of wildland fire (Bond and Keeley 2005, Bowman et al. 2009) and climate-fire interactions (Kang et al. 2006, Goetz et al. 2012, Liu et al. 2014) are particularly critical uncertainties as emission and sequestration feedbacks are complex and multi-scalar (Hurteau and North 2009, Wiedinmyer and Hurteau 2010). Methods to reduce wildfire intensity and spread, such as prescribed fire and forest thinning, compete against the goal of carbon sequestration (Hurteau et al. 2008, Loudermilk et al. 2014). This is certainly important in low-intensity surface fire regimes (Mitchell et al. 2009, Hurteau and Brooks 2011) for estimating carbon and species dynamics through time. The longleaf pine (*Pinus palustris*) ecosystem of the southeastern coastal plain of the U.S. is an archetype of a forest with a frequent surface fire regime (Mitchell et al. 2009). Through the continued use of frequent prescribed fire, this endangered ecosystem with many endemic flora and fauna (Hardin and White 1989, Walker 1993, Kirkman et al. 2016) has the potential to remain a global hotspot of diversity, maintain resilience to future droughts, and minimize large carbon emission pulses that can occur with wildfire (Hurteau and North 2009, Starr et al. 2015, Gonzalez-Benecke et al. 2015). This ecosystem could potentially store less total carbon than if fire was excluded, but at the cost of losing endemic flora and fauna. There is a need to quantify carbon and species dynamics in longleaf pine forests and the feedbacks due to altered fire frequency and alternative stable states, namely transitions from longleaf pine to hardwood dominated stands when fire is excluded (Provencher et al. 2001, Varner et al. 2007, Kirkman et al. 2016). The differences in carbon allocation and emissions between prescribed fire and wildfires are also important factors to consider given that prescribed fire is a common tool used in the southeast and wildfire risk is increasing (Bachelet et al. 2001, Mitchell et al. 2014, Krofcheck et al. 2017, Schoennagel et al. 2017).

This is particularly important to understand at DoD military bases as many have become key refuge and restoration sites for longleaf pine as a species and ecosystem. For example, Eglin Air Force Base, FL, represents one of the largest remaining tracts of longleaf pine in the southern U.S. Here, the long-term frequent fire history from military training and prescribed burning has maintained many endemic species populations (Loudermilk et al. 2016, Dell et al. 2017). Fort Bragg, NC, has more than 89,000 acres of longleaf pine forest where studies on how time since burn influences vegetation type have already been conducted (Sasmal et al. 2017) and have called for future research that incorporated a wider time frame. The longleaf pine ecosystems at

Fort Bragg, Fort Stewart, GA, and the Savannah River Site, SC have been utilized to study how fire frequency has impacted understory plant diversity (Veldman et al. 2014). Moreover, many other southeastern DoD installations have utilized programs such as the Readiness and Environmental Protection Integration Program to work with other federal agencies, state agencies, and non-profit partners to maintain and improve existing longleaf pine ecosystems and restore acreage to longleaf pine in and around military installations.

## 1.2 OBJECTIVE OF THE DEMONSTRATION

Our *project's objectives* were to 1) provide data and technical support to the ESTCP board and project performers throughout the inter-model comparison projects (Topic 5, FY17) and 2) perform an inter-model comparison at one designated performance site using a landscape and global class model to assess the impacts of varying fire frequency on landscape carbon projections.

For these ESTCP inter-model comparison projects (FY17, Topic 5), identification of strengths and weaknesses of ecosystem process models can be achieved through multiple teams of researchers that use models to conduct model performance evaluations. As such, *for project objective 1, our overarching objectives* were to synthesize data at two data rich study sites (Ichauway and Harvard Forest), provide this information to ESTCP and the two other chosen teams (RC17-201702, RC17-201703) to perform their own inter-model comparisons, and provide technical support for both teams throughout their projects as well as provide technical support for ESTCP.

*For project objective 2, our overarching objectives* were to perform an inter-model comparison on how fire return intervals impact the southeastern pine ecosystem. Ecosystem process models are used to aid management decisions by predicting how various environmental changes may influence an ecosystems composition, structure, and distribution. A wide range of models have been developed and often with a tradeoff between the complexity of biophysical and biogeochemical processes simulated and the spatial scale of the model. Ecosystem processes must be simplified to increase the spatial and temporal resolution of a model due to the computational demands of simulating succession, disturbance, competition, and other processes, such as soil respiration and nutrient dynamics (D. P. Turner et al. 2004, K. G. Turner et al. 2015, De Bruijn et al. 2014). Ecosystem process models simulated at the stand, or gap level class, emphasize biogeochemical and biophysical processes of individual trees or a small group of trees at fine spatial (meters) and temporal scales (~yrs). The forest landscape model class simulates spatially explicit processes, such as dispersal, nutrient cycling, and disturbance over larger areas (~1000ha) and larger time steps (~centuries) (Lischke et al. 2006, Syphard et al. 2011, Xu et al. 2012, Jin et al. 2017, Wang et al. 2017), at the loss of some finer scale attributes like explicit tree location. The dynamic global vegetation model (DGVMs) class operates globally with spatial resolutions on the order of degrees, with temporal resolutions similar to landscape models, and can often be coupled with Global Circulation Models (GCMs) to allow feedbacks to climate (Woodward et al. 1995, Cox 2001, Krinner et al. 2005, Sitch et al. 2008, Fisher et al. 2018). This class of models require even more simplification of the fine scale attributes such as using plant functional types (PFTs) rather than individual tree species. Scaling strategies create cross-over between the various classes but it is typical to trade complexity of the inherent simulated

processes for increased spatial and temporal resolution (Sato et al. 2007, Sato and Ise 2012, Snell 2014, Snell et al. 2014, Flanagan et al. 2019).

Most modeling studies frequently select a single model to assess the impacts of management on future disturbance regimes, but the inherent strengths and weaknesses of model selection on the consequences of altered fire frequencies have not been sufficiently evaluated (McGuire et al. 2012). In this study, we explored how various fire return intervals impacted carbon and species dynamics in a southeastern U.S. pineland by using two ecosystem model classes. A landscape class, the Landscape Disturbance and Succession II (LANDIS-II) model, and a global class, the Ecosystem Demography (ED) model, were used to project how fire impacts this ecosystem. Five cases of fire return intervals were simulated: fire exclusion, and intervals of 2-(prescribed fire), 20-, 50-, and 100 years (wildfire). Through an inter-model comparison approach, the impact of each scenario on each model was evaluated by examining changes and differences in total above ground biomass (AGB), net ecosystem carbon balance (NECB), and species composition, and performing a validation of Net Ecosystem Exchange (NEE) with eddy covariance site data. The similarities and differences for each model and pros and cons of using a given model class for this type of research question are also discussed in detail.

### **1.3 REGULATORY DRIVERS**

Regulations and directives that support the need for the development and enhancement of ecosystem process models to inform management decisions include:

- Relevant federal law includes the following: Endangered Species Act of 1973, Clean Water Act of 1972, National Environmental Policy Act of 1970, Clean Air Act of 1963.
- Relevant DoD programs include the following: Army Regulation 200-1 Environmental Protection and Enhancement, Army Compatible Use Buffer (ACUB) Program, DoDI Natural Resources Conservation Program, Air Force Policy Directive 32-70 Environmental Quality

## 2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

### 2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

For *project objective 1*, a comprehensive synthesis of large amounts of data from two data rich sites were completed. A total of 234 datasets were compiled, and extensive metadata written, that included information on soils, carbon nitrogen, biomass, debris, species, weather, topography, historic disturbances, management, and eddy covariance flux tower data. These data, summarized in Appendix B (Ichauway), C (Harvard Forest), and D (Overview and Comparison), were provided to the two other performers (RC17-201702, RC17-201703) to use for the model performance phase of their projects. We provided technical support for these teams in terms of LANDIS-II model parameter sharing, feedback on project issues, including help with the ED model, as well as many discussions over conference calls and emails. We also provided extensive support to the ESTCP board providing written reviews of over a dozen documents, including demonstration plans, video production, white papers and tasks, and final reports of these two projects. Please refer to the final report for each of the other project's performers (RC17-201702, RC17-201703) for further details on individual model development and inter model comparisons within their respective projects. This is the end of any details regarding project objective 1.

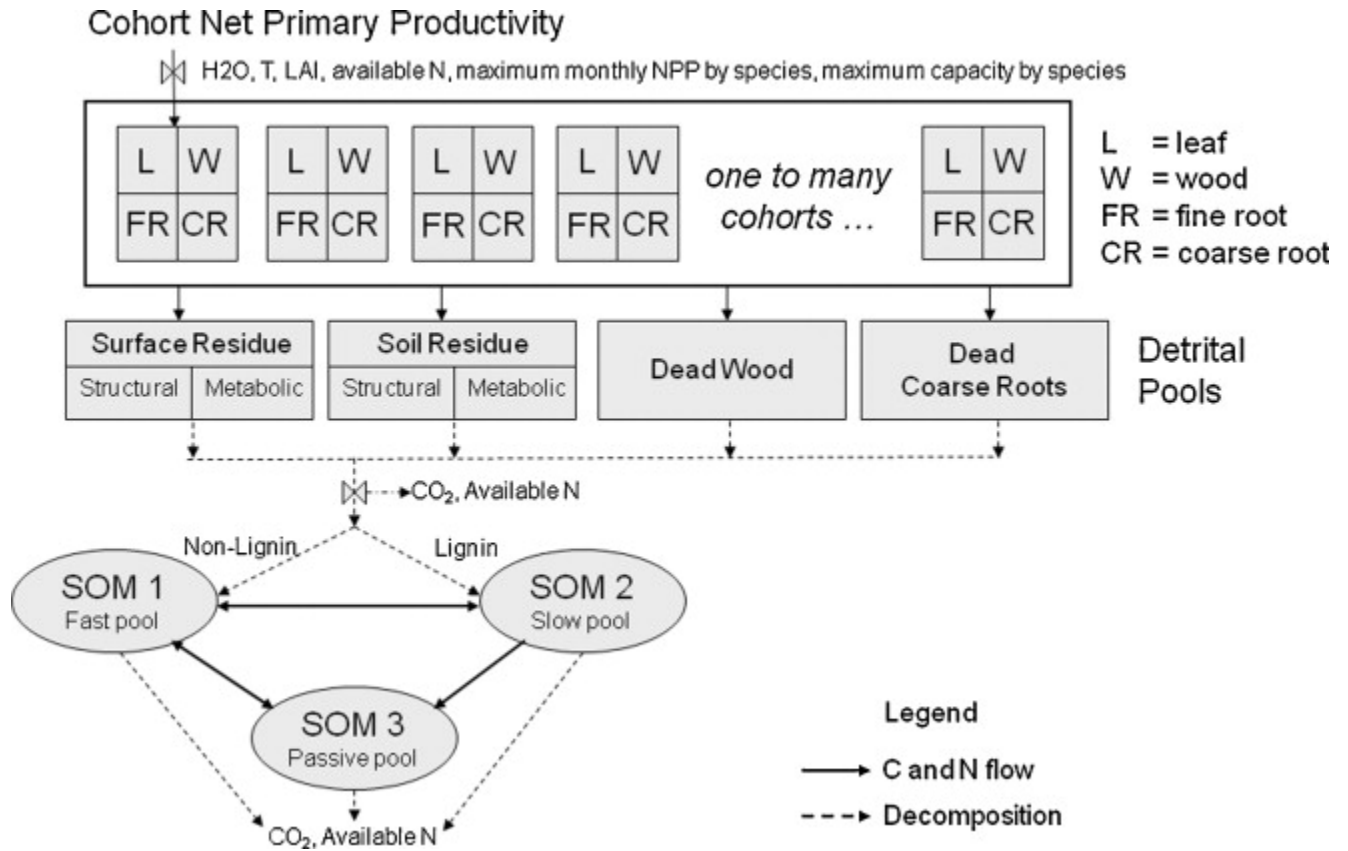
The remainder of this final report focuses on *project objective 2* as the modeling effort, including parameterization, calibration, and performance evaluation was the most extensive portion of the project. The inter-model comparison used the Ichauway data *only* (Appendix B, D).

For regional level management questions either a landscape class or global class model is often used and should be selected based on the model's ability to simulate the desired environmental change and predict the necessary ecosystem attributes one wishes to examine. As each class has relative strengths and weaknesses, a model comparison was conducted between a landscape class, the Landscape Disturbance and Succession II (LANDIS-II) model, and a global class, the Ecosystem Demography (ED) model, to explore some of these differences.

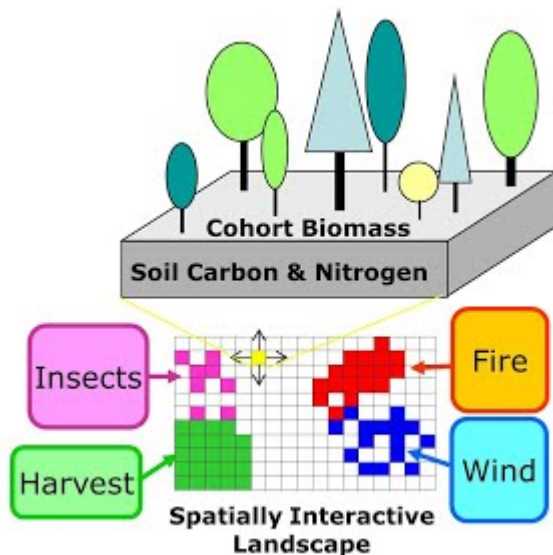
### 2.2 TECHNOLOGY/METHODOLOGY DEVELOPMENT

LANDIS-II (v6.2.1) (Scheller et al. 2007) integrates various ecosystem processes and disturbances that interact at the landscape scale and over longer time periods. LANDIS-II uses a gridded landscape where each cell contains species-age-cohorts of woody species whose growth and succession is governed by a species competitive ability, dispersal, and reproduction. It has been successfully implemented for understanding ecosystem dynamics, succession, insects, fire, wind, dispersal, harvesting, fuel treatment effectiveness, and climate change research (Sturtevant et al. 2004, 2009, Scheller et al. 2011b, Syphard et al. 2011, Xu et al. 2012, Loudermilk et al. 2013, 2014, 2017). Within LANDIS-II, we used the Net Ecosystem Carbon and Nitrogen (NECN) Succession extension (v4.2) (Scheller et al. 2011a) and the Biomass Harvest extension (v3.1.6) (Gustafson et al. 2000). The NECN extension implements succession with above and below ground carbon and nitrogen and simulates the regeneration and growth of vegetation based on age, competition for resources (water, nitrogen, light), and disturbance. Vegetation growth and response to disturbance is determined by unique species attributes (e.g., shade tolerance). Dead biomass (woody and leaf litter) and soil organic carbon (SOC) are also tracked

over time (Figure 1). Biomass Harvest simulates the removal of aboveground live leaf and woody biomass of designated species and ages within selected areas (Figure 2).

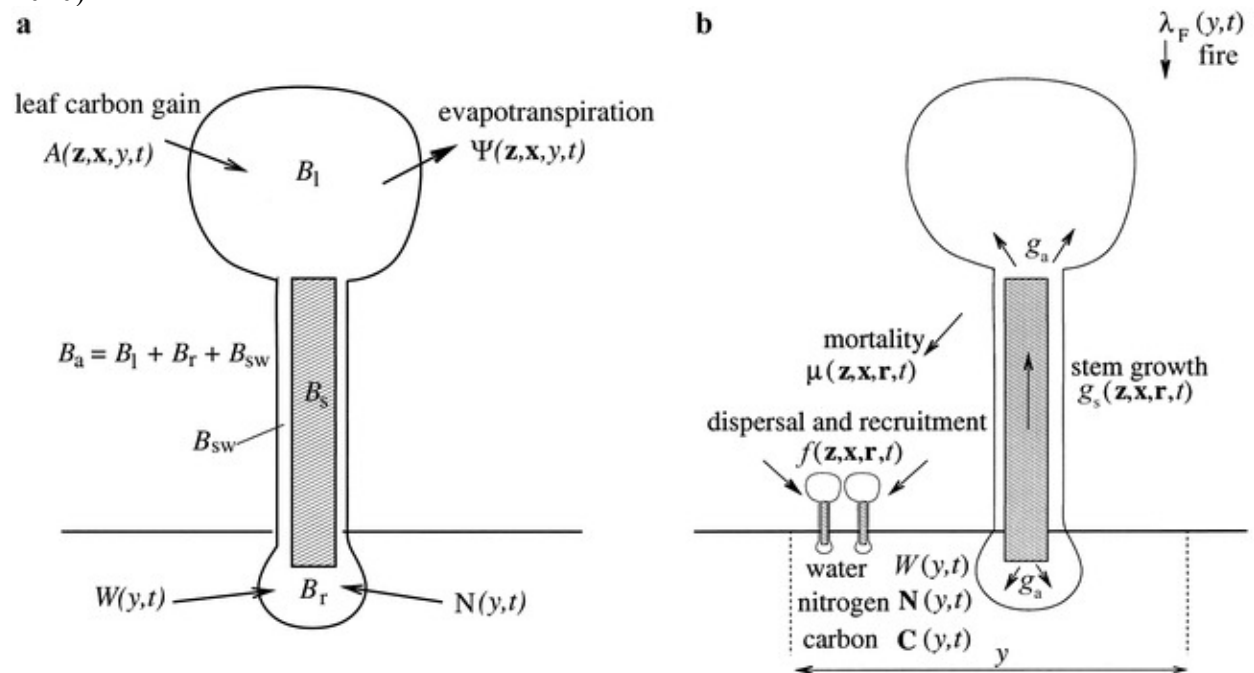


**Figure 1.** Schematic diagram of the Net Ecosystem Carbon Nitrogen Succession ('LANDISII/NECN') model structure. From Scheller et al. (2011a).



**Figure 2.** Gridded diagram of how various extensions of LANDIS-II can be applied. From the Dynamic Ecosystem & Landscapes Lab website (LANDIS-II.org, 2020)

The ED model was selected as the global class model. ED is a mechanistic model that approximates the first moment of the spatial stochastic (“gap”) ecosystem model. The approximation relates size, age, and structure in a pseudo-spatial framework to minimize computational time when compared to spatially explicit simulations. PFTs are grouped into classes dependent on physiognomy, leaf form, photosynthetic pathway, and other characteristics, and compete for water, nutrients, and light governed by submodels of growth, soil water availability, phenology, disturbance, and biogeochemistry (Figure 3). The original ED model (Hurtt et al. 1998, Moorcroft et al. 2001) now has numerous variations that have been published (Hurtt et al. 2002, 2010, Medvigy et al. 2010, Dietze et al. 2011, Medvigy and Moorcroft 2012, Flanagan et al. 2016, 2019). The version chosen here follows the adjustments made by Hurtt et al. (2002) for North American tree species, with the modifications made by Flanagan et al. (2016) and (2019). Previous research successfully implemented this version in North America (Hurtt et al. 2004, 2016, Fisk et al. 2013, Flanagan et al. 2016, 2019, Dolan et al. 2017) and had a harvest function similar to that of LANDIS-II added for charcoal extraction studies in Mozambique (Silva et al. 2019). A version running the same core code but with downscaled inputs is currently being used in NASA’s Carbon Monitoring System (CMS) (Hurtt et al. 2014, 2019), and the NASA Global Dynamics Investigation (GEDI) mission (Dubayah et al. 2014, 2020).



**Figure 3.** Ecosystem Demography model carbon flux framework. (a) Individual-level fluxes of carbon, water, and nitrogen and the partitioning of carbon between active and structural tissues ( $B_a$  and  $B_s$ , respectively). (b) Summary of the processes occurring within each gap  $y$ . Each plant's structural and living tissues grow at rates  $g_s$  and  $g_a$ , respectively. Individuals die stochastically at rate  $\mu$  and give birth to offspring at rate  $f$ , which are then dispersed randomly across gaps. These vital rates vary as a function of the type ( $x$ ), size ( $z$ ) and resource environment ( $r$ ) of the plant. Fires occur stochastically at rate  $\lambda_F$  calculated by the fire sub-model. Hydrologic and decomposition sub-models track the dynamics of water ( $W$ ), carbon ( $C$ ), and nitrogen ( $N$ ) within each gap. (Figure and caption are adopted from Moorcroft et al., 2001.)

## 2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/METHODOLOGY

There are limited alternative technologies or methods to meet the applicable regulatory or stewardship needs of this project. Landscape simulation models can address some management questions in regards to how a change in the environment may impact ecosystem attributes. However, as they are not explicitly process models, they often neglect many underlying processes. There are other landscape and global class process models that could be used in a similar analysis. We stress that model selection should always depend on the ability of the model to simulate the desired change in the environment and the outputs the model is able to produce. For this project, multiple classes of ecosystem models could be used that meet these criteria and they do have relative advantages and limitations.

As transportability is likely desired for informing management plans it should be noted that once a model is built it is highly transportable for the domain/landscape it was built for. ED was set up to run globally so it can be applied anywhere but at half degree spatial resolution (~60 km x 60 km). LANDIS-II had not previously been built at this site, so it needed to be heavily parameterized, but was simulated at a much finer resolution than ED: 1 ha for a total of 1,267 simulation sites, or 1,267 ha. Ultimately there is a tradeoff between input requirements (transportability) and time needed for model parameterization in how it affects desired model realism and research or management questions. ED has high transportability because the inputs are pre-computed, but at the cost of lowering realism at the site level since it runs at a higher resolution (0.5 degrees) and only has two PFTs for this region (pine and deciduous). LANDIS-II may be more time consuming to parameterize, but results in significantly higher realism at the site level, and provides the user with more flexibility in ‘scenario’ design (climate change, fire regimes, insects outbreaks, harvesting regimes, etc.) and species level responses (12 individual species). In our study, we found that ED was quick but inflexible and requires knowledge of manipulation of the core code. LANDIS-II offered deeper research into species dynamics and how that impacted total carbon in the system but required significantly longer time to build even without needing to modify the core code. We also suggest that one could start with an already constructed DGVM, such as ED, and then determine whether or not the higher resolution examination of the research question is needed and whether the time to build the complex landscape class model is worth the effort. In the end, it comes down to why the model is needed in the first place – what is the research or management question? How will the model be used?

Furthermore, we are aware that the domain sizes of these models are gradually moving in both directions. ED was recently downscaled for a 90 m resolution study of three northeastern states (Hurt et al. 2019) and is in the works for the contiguous U.S. at a yet to be determined resolution (greater than 90m but less than half degree) as it is being used in the NASA CMS and GEDI missions. LANDIS-II is being parameterized for the southern Appalachians (3.5M ha) at 4 ha resolution and is in the process of being parameterized for the entire USDA Forest Service area of the Southern Research Station (all 13 southern states) at a yet to be determined resolution. Continued research once these updates are complete could be beneficial in informing DoD decision making.

### 3.0 PERFORMANCE OBJECTIVES

The six performance objectives are best separated into two parts, where four objectives are in Test Design (section 5.0) and two are in Performance Assessment (section 6.0).

To compare and examine the benefits of the landscape and global class models, the Test Design (section 5.0) was based on parameterizing, and calibrating LANDIS-II and ED to simulate southeastern U.S. pine forests. As such, empirical data from the Jones Center at Ichauway and literature values were used to parameterize and calibrate both models for four performance objectives to assess: 1) initial vegetation distributions, 2) maximum carbon sequestration potential under prescribed fire, 3) fire exclusion, and 4) three wildfire disturbance regimes. This included:

- **Initial Communities** - Datasets from the Jones Center at Ichauway on ecosystem properties that were primarily used to establish species abundance and distribution (Appendices B, D). This became an input file for LANDIS-II and the species percentages were used to determine the starting distribution for ED.
- **Maximum Carbon Sequestration Potential** – Literature values were used to verify that model predictions of maximum AGB under a prescribed fire regime and fire exclusion approached empirical values and that species proportions of pines versus hardwoods were properly represented.
- **Fire Disturbance Regimes** – The return intervals for fire were based on literature values and determined percentage tree mortality.

The Performance Assessment (section 6.0) involved two additional objectives, i.e.: 5) validation of model predicted carbon flux and 6) performing an inter-model comparison. Our inter-model comparison focused on aboveground biomass (AGB), net ecosystem productivity (NEP), net ecosystem carbon balance (NECB) and species composition. This included:

- **Carbon Flux** – Model predictions of net ecosystem exchange (NEE) were compared to eddy- covariance flux tower data from the Jones Center at Ichauway for calibration and validation.
- **Model Inter-comparison** – Compare the models predictions of above ground biomass (AGB), net ecosystem productivity (NEP), net ecosystem carbon balance (NECB), and species distribution under all scenarios.

All performance objectives from Test Design (section 5.0) and Performance Assessment (section 6.0) are summarized in Table 1.

**Table 1. Performance Objectives for Performance Assessment**

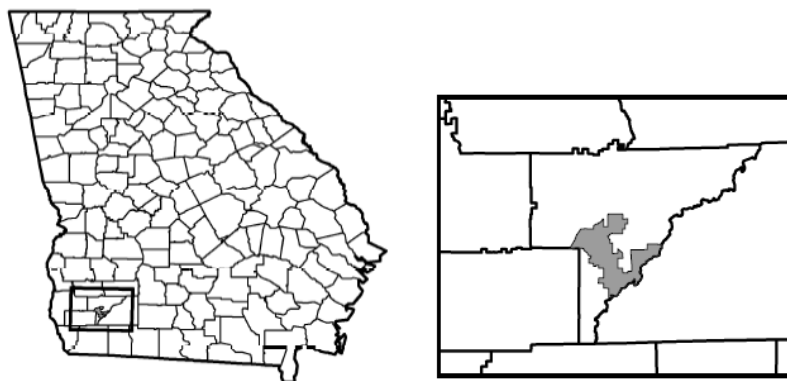
<b>Performance Objective</b>	<b>Metric</b>	<b>Data Requirements</b>	<b>Success Criteria</b>	<b>Section Presented</b>
<b>Performance Objectives</b>				
1. Construction of current species abundance and distribution on the landscape	<ul style="list-style-type: none"> <li>Biomass</li> </ul>	Empirical data from the Jones Center at Ichauway	Quantitative comparison to empirical estimates, plus qualitative assessment	Model calibration – Test Design. 5.2.1
2. Carbon sequestration potential under a prescribed fire regime	<ul style="list-style-type: none"> <li>Maximum AGB</li> <li>Species percentages</li> </ul>	Empirical data from literature and management maps	Models must be >10% from literature values of maximum AGB and the percentage of AGB that belongs to longleaf pine versus all other species, with adjustments made for burn frequency	Model calibration – Test Design. 5.2.2
3. Carbon sequestration potential under a fire exclusion regime	<ul style="list-style-type: none"> <li>Maximum AGB</li> <li>Species percentages</li> </ul>	Empirical data from literature	Models must be >10% from literature values of maximum AGB and must predict the transition to a hardwood forest	Model calibration – Test Design. 5.2.2
4. Fire disturbance regimes	<ul style="list-style-type: none"> <li>AGB mortality</li> </ul>	Empirical data from literature	Comparison to empirical estimates	Model calibration – Test Design. 5.2.2
5. Carbon Flux	<ul style="list-style-type: none"> <li>NEE</li> </ul>	Eddy-covariance data from the Jones center at Ichauway	NEE must be qualitatively reasonable between each model and data	Model validation – Performance Assessment. 6.0.1.
6. Model inter-comparison (LANDIS-II vs. ED model)	<ul style="list-style-type: none"> <li>AGB, max AGB</li> <li>NECB, NEP</li> <li>Species distribution</li> </ul>	Model outputs	Qualitative assessment to empirical and literature values, and an assessment between models.	Model comparison – Performance Assessment. 6.0.2-6.0.5.

## 4.0 SITE DESCRIPTION

Ichauway, Newton, GA, has been extensively studied and is a representation of a southeastern U.S. pine forest dominated by second growth longleaf pine as it has been under a prescribed fire regime for ~80-100 years. The data itself comes from the “Jones Center at Ichauway”, although the site itself is referred to simply as “Ichauway”. The research center previously went by the Joseph W. Jones Ecological Research Center.

### 4.1 SITE LOCATION AND HISTORY

Ichauway (Figure 4) was chosen because the Jones Center at Ichauway have a robust assortment of long-term forest inventory and biogeochemistry data and whom we have a strong working relationship. These data were used to initialize, calibrate, and validate the models in this project, and models in other projects. These data include three eddy covariance flux towers that have collected carbon flux for over a decade. The longleaf pine forest that dominates this landscape combined with these long-term and robust datasets were meant to develop and test various ecosystem process models with the potential of transferring these models to similar locations such as Ft. Bragg, NC and Eglin Air Force Base, FL.



**Figure 4.** Study site location illustrating a map of Georgia, USA (left) and its counties with the location of the Jones Center at Ichauway, Baker county, highlighted in gray and expanded on the right.

### 4.2 SITE CHARACTERISTICS

Ichauway is a 115 km<sup>2</sup> (11,736 ha) research and conservation site located in the Coastal Plain of southwestern Georgia, USA (31°13'N, 84°29'W) (Mitchell et al. 1999, Goebel et al. 2001). It is situated within the Dougherty Plain physiographic region (Holder and Schretter 1986) in the Gulf Coastal Plain Province described by Walker and Coleman (1987) of the Lower Coastal Plain and Flatwoods (LCPF) section (Plains and Wiregrass Plains subsections) described by McNab et al. (2007). The area is a karst landscape with flat, weakly dissected alluvial deposits over Ocala Limestone is characteristic of the LCPF section and elevation ranges from 23 m to 91 m above sea level (Holder and Schretter 1986). The soils are fine to moderately fine textured loamy or clayey subsoils and drainage classes range from excessively to poorly drained (Goebel et al. 2001). The climate is characterized as humid subtropical (Christensen 2013) and consists of

long, hot summers with mean daily temperatures ranging from 21° C to 34° C and short, cool winters with mean daily temperatures ranging from 5° C to 17° C (Lynch et al. 1986; Goebel et al. 1998). The average annual precipitation of 131 cm is evenly distributed throughout the year (Goebel et al. 1998).

Ichauway is comprised of a diverse range of ecological communities: prominent longleaf pine forests, slash pine forests, old field loblolly pine stands, mixed pine hardwood forests, riparian hardwood forests, isolated depressional wetlands, agricultural fields, shrub-scrub uplands, human cultural zones, rivers and creeks (Goebel et al. 2001). Species commonly found in the forests include longleaf pine, loblolly pine (*P. taeda*), shortleaf pine (*P. echinata*), slash pine (*P. elliotti*), live oak (*Quercus virginiana*), laurel oak (*Q. laurifolia*), water oak (*Q. nigra*), southern red oak (*Q. falcata*), and post oak (*Q. stellata*) (Mitchell et al. 1999, Kirkman et al. 2001). Open longleaf pine forest covers 6,000 ha, with wiregrass (*Aristida beyrichiana* or *A. stricta*) an understory component on approximately 4,000 ha (Goebel et al. 2001, Kirkman et al. 2001). Longleaf pine ecosystems at Ichauway, including longleaf – wiregrass ecosystems, span the range of soil moisture conditions found in the LCPF Province (Mitchell et al. 1999, Wilson et al. 1999).

We focused our study area to 1,267 ha within Ichauway where longleaf pine ecosystems are the dominant forest community under a range of environmental conditions and long-term monitoring plots were available. The study area was an extensive site of 2<sup>nd</sup> growth longleaf pine, with predominantly 80-100 y old trees in the overstory. Dormant season prescribed burns have been applied at a frequency of one to three years for at least 80 years. Previously, the area was predominantly used for agriculture. The understory was primarily composed of wiregrass, many forb and prairie grass species, as well as inter-dispersed hardwood shrubs (e.g., *Diospyros* spp., *Prunus* spp, *Quercus* spp., *Sassafras albidum*). Hardwoods are generally maintained at shrub size with frequent fire, but mature hardwoods make up a minor component of the overstory as well.

## 5.0 TEST DESIGN

Ecosystem process models are essential tools for predicting how ecosystem attributes change relative to disturbance(s). There are many models, in multiple classes (stand, landscape, and global), that all have different data requirements and relative strengths and weaknesses. Our test design was created to compare models in two of the different classes, the landscape and global class, as these are representative of the optimal scale of forest landscape managers and therefore the benefits of each class could be explored.

### 5.1 CONCEPTUAL TEST DESIGN

Our test design was based on parameterizing (performance objective 1) and calibrating (performance objectives 2-4) LANDIS-II and ED to simulate southeastern U.S. pine forests. Ichauway, GA, was chosen as the Jones Center at Ichauway has expansive empirical data on forest composition and structure, along with well described flux tower sites that could be used for validation. Additional empirical data including climate, soils, and fire disturbance were used to generate parameters for each model. As detailed biogeochemistry and belowground data was not available, we focused on AGB, NEP, and NECB to characterize the carbon sequestration

potential of the forest under various disturbance (fire) regimes. All input parameters and output processing scripts can be found in the LANDIS-II permanent and public GitHub repository, <https://github.com/LANDIS-II-Foundation>, under Project-JonesEcologicalResearchCenter-2019.

## 5.2 BASELINE CHARACTERIZATION AND PREPARATION

### 5.2.1 INITIAL VEGETATION COMMUNITIES –PERFORMANCE OBJECTIVE 1

Baseline characterization and preparation primarily focused on development of the models. As we are starting with a defined landscape with species type and distribution, the first thing was to construct initial vegetation communities at Ichauway. This was done with the data provided by the Jones Center at Ichauway. The land base at Ichauway is comprised of a longleaf pine woodland with extensive long-term monitoring (LTM) plots. For longleaf pine plantations, time series satellite images determined the establishment year. For non-plantation areas, 120 0.1 ha LTM plots provided species composition and DBH measurements of trees greater than 10 cm were used to estimate ages from diameter-age equations or regressions for the twelve most prominent species. These species were: longleaf pine, slash pine, pond cypress (*Taxodium ascendens*), swamp tupelo (*Nyssa biflora*), and eight oak species - live, southern red, laurel, water, post, bluejack (*Q. incana*), turkey (*Q. laevis*), and sand post (*Q. margaretta*). Their percentage across the landscape by AGB is shown in Table 2.

**Table 2.** The percentage of total AGB for each species.

Species	Percentage of total AGB
Longleaf pine	57
Live Oak	16
Laurel Oak	7
Slash Pine	5
Southern Red Oak	4
Water Oak	3
Turkey Oak	2
Post Oak	2
Swamp Tupelo	1
Pond Cypress	1
Sand Post Oak	<1
Bluejack Oak	<1

These 12 species and their age (representative of biomass) and location on the landscape served as an input to LANDIS-II and to inform the starting conditions of ED. LANDIS-II was the chosen landscape class model not only for its wide range of capabilities, but because it had previously been parameterized and validated at nearby Fort Benning in Southwest GA (Martin et al. 2014, Swanteson-Franz et al. 2018). Each new application of the model requires the user to generate this initial vegetation input so working off of a similar location can reduce the time it takes to build the model. The initial vegetation communities at Ichauway differed slightly from Fort Benning so values from the literature and available databases, including the Net Ecosystem Carbon and Nitrogen (NECN) succession guide that is an extension for LANDIS-II, were used to complete the parameterization (Botkin et al. 1972, Pastor and Post 1986, Burns and Honkala

1990, Sutherland et al. 2000, Wimberly 2004, Hendricks et al. 2006, Scheller et al. 2011a, 2011b, 2012 Samuelson et al. 2014). ED is a potential vegetation simulator, meaning it typically starts from bare ground, so it did not explicitly use the initial vegetation community as an input. Instead, as the current vegetation distribution would not exist if it had not undergone frequent prescribed fire application for approximately the last 80 years, a spin-up run was performed where the mortality factor for the deciduous PFT was increased so that the percentage of pine versus deciduous species on the landscape approximated the values in Table 2. As a global class model ED uses PFTs instead of explicit species and in this location there are two: deciduous and pine.

## **5.2.2 FIRE SCENARIOS – PERFORMANCE OBJECTIVES 2-4**

Five fire scenarios were run for both models. A frequent prescribed fire regime, fire exclusion, and three infrequent wildfire scenarios with return intervals at 20, 50, and 100 yrs. The return intervals were informed by literature or empirical data. The prescribed fire scenario had fires occurring every two years, the mean return interval at Ichauway. For the fire exclusion scenario, both models were run from the initial conditions without additional disturbance events. As controls, maximum AGB for the prescribed fire and fire exclusion scenarios were compared to literature values. For each model in the prescribed fire scenario (performance objective 2) a species dependent percentage of vegetation was removed such that total AGB was similar to Gonzalez-Benecke et al. (2015) for an unthinned longleaf pine stand burned every 3 years and the percentage of longleaf to hardwoods on the landscape was set to be similar to Loudermilk et al. (2011). With consistent prescribed fire, hardwoods occupied ~5% of the total landscape versus ~8% in Loudermilk et al. (2011), who simulated a slightly longer fire return interval (~2.85 yrs) and demonstrated a decline in percentage of hardwoods as the return interval was lowered. The AGB of the mature longleaf pine stand of ~190 Mg/ha is similar to Gonzales-Benecke et al. (2015) who reported ~230 Mg/ha in an unthinned, burned longleaf pine stand with a 3 yr fire return interval. For the fire exclusion scenario (performance objective 3) each model transitioned from a pine to a hardwood forest with a maximum AGB of ~250 Mg/ha which is similar to Brown et al. (1997).

For the wildfire scenarios (performance objective 4), Outcalt and Wade (2004) found that in the absence of fire, fuel accumulated rapidly enough that stand replacing fires could occur in some longleaf pine ecosystems in as little as a decade. Varner et al. (2007) found 91% mortality of the overstory following fire at a site that had not experienced fire for 45 years. Although environmental conditions influence mortality rates, this ecosystem is prone to stand replacing fires if fire is excluded for only a few years, with mortality resulting mainly from consumption of organic matter accumulated above the mineral soils and the fine roots contained therein (Morgan Varner et al. 2009, O'Brien et al. 2010). As such, all wildfires were simulated as a stand replacing fire. Also, we set a conservative lower boundary for wildfire frequency at a 20 y interval. We chose 50 and 100 y intervals to represent other forest successional stages at the time of wildfire. In reality, a small percentage of overstory conifer and hardwood trees could survive such a wildfire depending on fuel moisture conditions; younger cone-bearing pines might survive to provide a seed source, and smaller hardwoods (understory and midstory trees) could re-sprout after a fire (Rebertus et al. 1989). Both models have dedicated fire extensions but they are stochastic. As we wanted these events to be deterministic, we instead used the models harvest

functions so the time and amount of species removed was deterministic. Therefore, we created a surrogate approach by simulating survival of the youngest cohorts (ages 1-3) so that it was not necessary to re-seed or resprout the domain after a wildfire. All other age classes were removed during a wildfire which was simulated in a single time step for the entire domain. With this approach the soil carbon pools were also appropriately adjusted after fire events to match literature values. For the prescribed fire scenario, values for consumption rates in a longleaf ecosystem of 30% of woody AGB and 77% of leaf litter were used (Ottmar et al. 2016). For the wildfire scenarios, 81% and 100% of the respective pools were adjusted (Regelbrugge and Smith 1994).. All simulations were run for 300 years. ED is deterministic so each scenario was run once. LANDIS-II has stochastic components but our methodology meant deterministic fire events dominated stochastic physiological processes. Therefore, each scenario was run for a relatively low number of five simulations. We compared each model's outputs of AGB, NEE, NECB, and species dynamics.

### **5.3 DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS**

As this is a modeling exercise there is no layout for equipment. The technology and methodology applied in this work is described above.

### **5.4 FIELD TESTING**

No fieldwork was required for this research.

### **5.5 SAMPLING PROTOCOL**

No field sampling was conducted as this project relied on previously collected data and available literature.

### **5.6 SAMPLING RESULTS**

No field sampling was performed in this demonstration.

## 6.0 PERFORMANCE ASSESSMENT

To address the performance assessment, we begin by providing a description of the inherent differences between the two classes of models. Each model has slightly different climatologies and soil properties. LANDIS-II used 16 years of climate data (2000-2016) from the Georgia Automated Environmental Monitoring Network (GAEMN), ED used 21 years of data (1989-2010) from the Multi-Scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) conducted by the North American Carbon Program (NACP) that is a combination of the National Centers for Environmental Prediction (NCEP) and Climate Research Unit (CRU) climatologies at global half-degree resolution. A representative year of monthly climate was constructed for each model to smooth any potential yearly anomalies and this representative yearly climatology was used for ever year of the simulation. Both models used soil data from the National Resources Conservation Service Soil Survey Geographic database (NRCS SSURGO). The differences in model parameters and other general information is shown in Table 3. As LANDIS-II is a landscape class model the climate and soil attributes were used to create 9 different ecoregions across the 1,267 ha area at a 1ha resolution. ED being a global class model, has only one climate and soil combination that ran for its half-degree resolution.

**Table 3.** Model parameters and general information.

<b>Model</b>	<b>LANDIS-II</b>	<b>ED</b>
Resolution	1ha, for 1267 total sites	Half degree (~60km by 60km), for 1 total site
Time scale (300 yrs of simulations)	Monthly predictions outputted yearly.	Monthly predictions outputted yearly.
Species	12 species of age-cohorts	2 Plant Functional Types (PFTs)
Climate inputs	Minimum temperature, maximum temperature, total precipitation	Temperature, precipitation, specific humidity or dewpoint, photosynthetically active radiation (PAR)
Soil inputs	Depth, drainage, field capacity, wilting point, percent sand, percent clay	Depth, conductivity, degree of saturation, maximum moisture content, texture
Ecoregions (soil and climate combinations)	9 combinations	1 combination
Simulation type	Stochastic	Deterministic
Growth	Age & species based	Age & PFT & height based

The unique nature of this study meant that the first four of our six performance objectives were best explained in the test design section (5.0), as they pertained to examining model performance during the model calibration phase and development of the fire scenarios. These objectives were focused on calibrating species abundance and distributions, calibrating species percentages and maximum AGB for the prescribed fire and fire exclusion scenarios and determining scenarios of wildfire return frequencies. As the last two performance objectives pertained directly to model

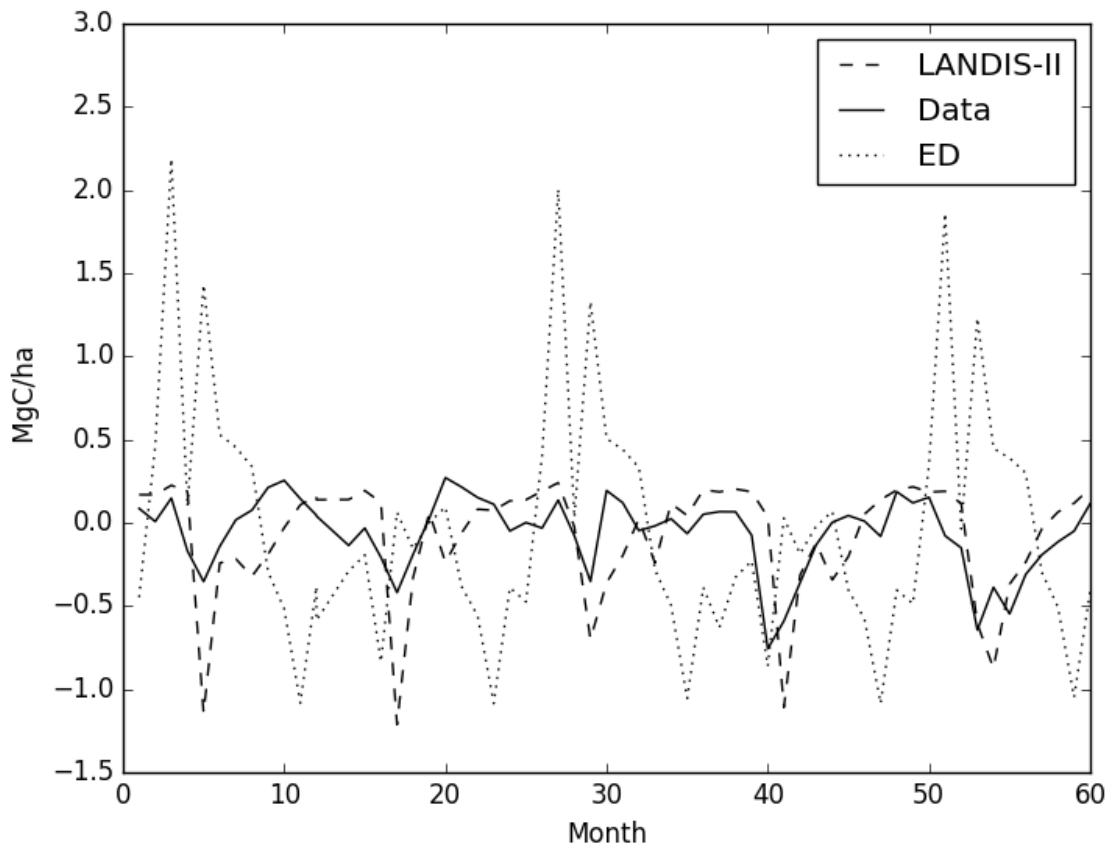
performance *after* model calibration and scenario development, the carbon flux and model inter-comparison results are presented here.

**Table 4.** Summary of performance assessment associated with each of the six performance objectives, described in Table 1. The results for the first four objectives are in the Test Design section – 5.2.

Performance Objective	Metric	Results
1. Calibration/Initialization - Construction of current species abundance and distribution on the landscape	<ul style="list-style-type: none"> <li>Biomass</li> </ul>	Constructed from empirical data that each model started with. Each model starts with species or PFTs that match empirical data provided by the Jones Center at Ichauway (See 5.2.1).
2. Calibration - Carbon sequestration potential under a prescribed fire regime	<ul style="list-style-type: none"> <li>Maximum AGB</li> <li>Species percentages</li> </ul>	Models were within range of both maximum AGB (~200 Mg/ha) and percentage of longleaf vs other species (5%) when compared to literature values adjusted for prescribed fire frequency (See 5.2.2)
3. Calibration - Carbon sequestration potential under a fire exclusion regime	<ul style="list-style-type: none"> <li>Maximum AGB</li> <li>Species percentages</li> </ul>	Models were within range of maximum AGB (~230 Mg/ha) and transitioned to hardwoods in the absence of fire (See 5.2.2)
4. Calibration - Fire disturbance regimes	<ul style="list-style-type: none"> <li>AGB mortality</li> </ul>	Informed by literature values. A stand replacing fire can occur in as little as a decade in this ecosystem. Therefore to be conservative bounds of 20, 50, and 100 yrs were used (See 5.2.2)
5. Validation - Carbon Flux	<ul style="list-style-type: none"> <li>NEE</li> </ul>	NEE was only $\pm 0.3$ Mg/ha/yr difference across 5 years of data and respective model simulations: Empirical: -0.73 MgC/ha/yr LANDIS-II: -0.94 MgC/ha/yr ED: -0.40 MgC/ha/yr
6. Model inter-comparison (LANDIS-II vs. ED model)	<ul style="list-style-type: none"> <li>AGB, max AGB</li> <li>NECB, NEP</li> <li>Species distribution</li> </ul>	Qualitative assessment of metrics, and description of overall model performance and usefulness

### 6.0.1 CARBON FLUX VALIDATION –PERFORMANCE OBJECTIVE 5

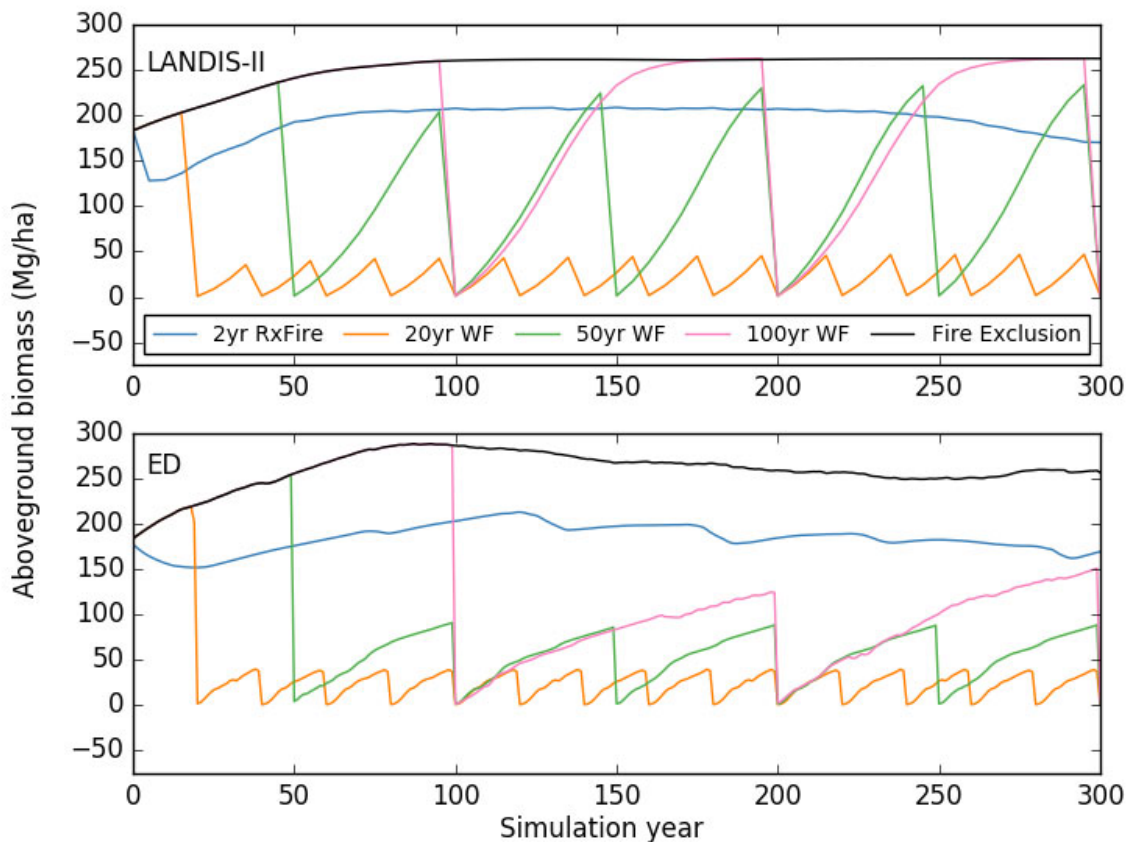
Model validation involved comparison to flux tower measurements taken from the Jones Center at Ichauway. Three flux towers, which experienced biannual burning from January 2009-December 2013, were compared to each model's outputs. LANDIS-II requires the user to input climate variables so climate from these explicit times were used. ED's climate is precomputed so it could not be made to fluctuate yearly. Each model's predicted NEE for the prescribed fire scenario, which is the research site's standard management practice, was compared to the eddy covariance values for NEE (Figure 5). The average net ecosystem exchange (NEE) over this five-year period was  $-0.73$  MgC/ha/yr for the data,  $-0.94$  MgC/ha/yr for LANDIS-II, and  $-0.40$  MgC/ha/yr for ED. This illustrates a  $\sim\pm 0.3$  MgC/ha/yr difference in mean NEE between models and data, which is quite small, especially given the flux tower data was not used to calibrate either model



**Figure 5.** Monthly predicted NEE of the models and the empirical flux tower data.

## 6.0.2 MODEL INTER-COMPARISON: ABOVEGROUND BIOMASS –PERFORMANCE OBJECTIVE 6

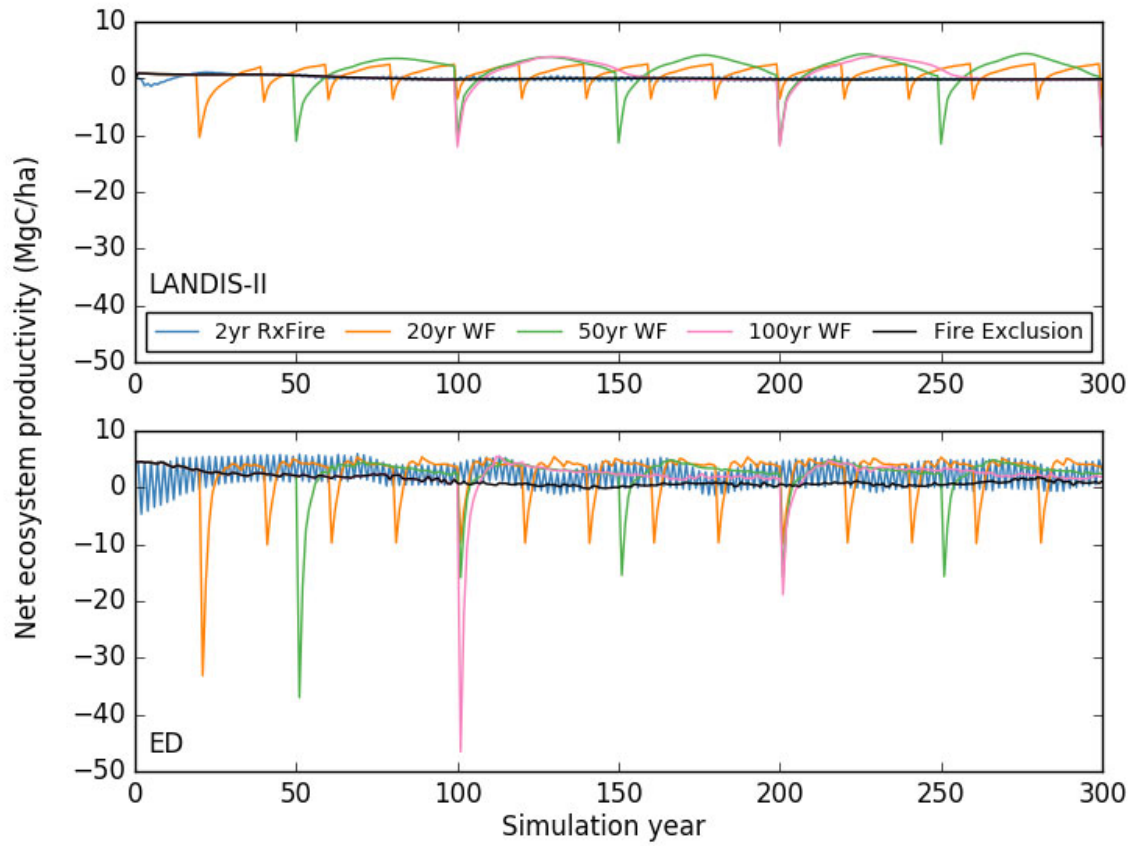
Both models predicted maximum AGB of ~250 Mg/ha in the fire exclusion scenario (Figure 6). Also, both LANDIS-II and ED showed a decrease in AGB towards the end of the prescribed fire scenario as the landscape was essentially dominated by one species--either longleaf pine or the pine PFT, respectively. As this is a second growth forest of relatively the same age, age related mortality caused both models to predict a decline in AGB near the end of the prescribed fire scenario. By extending the scenarios past this time frame, total AGB overcame this age related perturbation and returned to the established maximum AGB, due to recruitment of new individuals into the stand. The wildfire scenarios showed that LANDIS-II's representation of multiple similar species on the landscape quickly achieved maximum predicted total biomass and made for a smoother curve. In LANDIS-II this was ~80 years after a fire event, while ED was still not at maximum predicted AGB 100 years after a fire event.



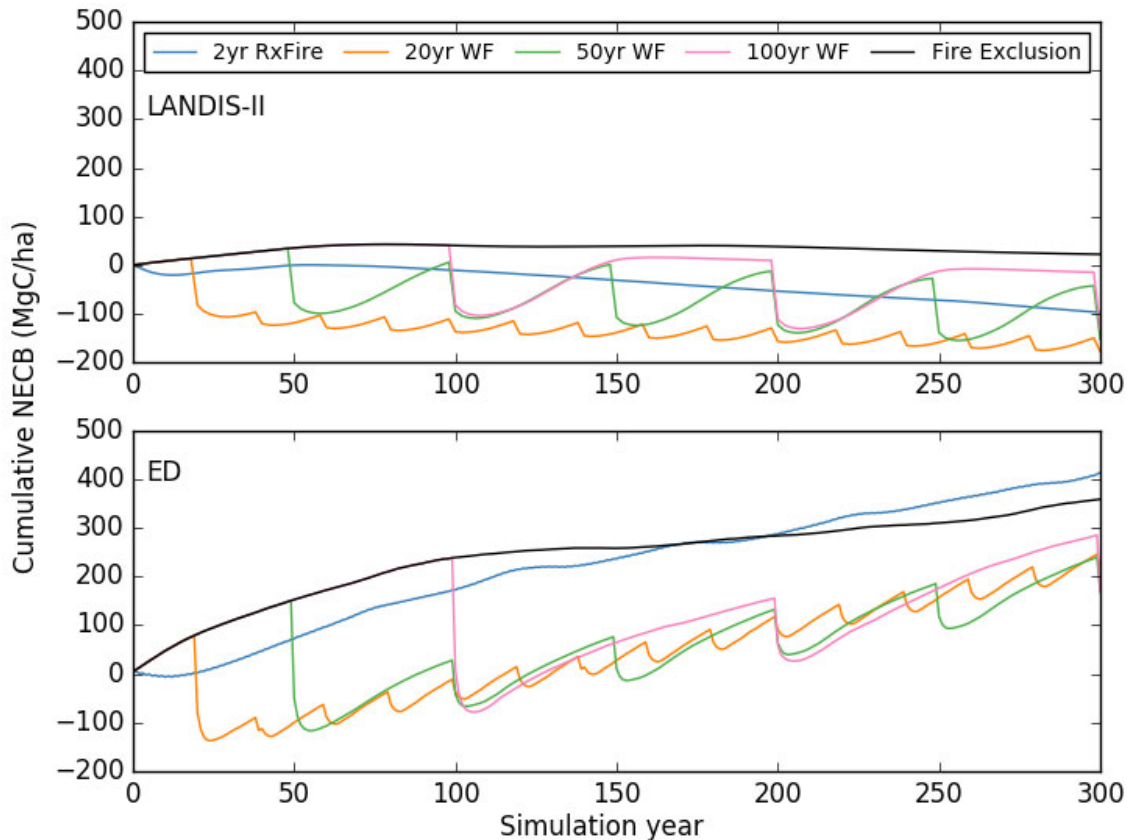
**Figure 6.** Yearly model predicted AGB for all scenarios.

### **6.0.3 MODEL INTER-COMPARISON: NET ECOSYSTEM CARBON BALANCE – PERFORMANCE OBJECTIVE 6**

Net ecosystem productivity (NEP), which does not account for biomass removed by fire, also showed the impact of ED not reaching maximum biomass. Both models predicted emissions after a fire event (negative values) and then sequestration (positive values) a few years later. However, as LANDIS-II had reached maximum potential AGB by the end of the 100 y wildfire return scenario, and reached near-maximum values (~80-90% of maximum) in the 50 y wildfire scenario (Figure 6), predicted NEP was zero or near zero (Figure 7) for these scenarios. As ED did not reach maximum potential AGB in any of the wildfire scenarios (Figure 6), it continued to predict positive NEP until the next fire event (Figure 7). As with the flux validation, ED had greater peaks and valleys in its predicted response. To calculate NECB, NEP was combined with the loss of biomass from fire. This was tracked through time cumulatively, with ED predicting slight net carbon gains (sequestration) for all scenarios, whereas LANDIS-II predicted slight net losses of C (emissions) (Figure 8). ED predicted prescribed fire to be the ideal scenario in terms of NECB while LANDIS-II predicted it as the ideal scenario except for the fire exclusion scenario.



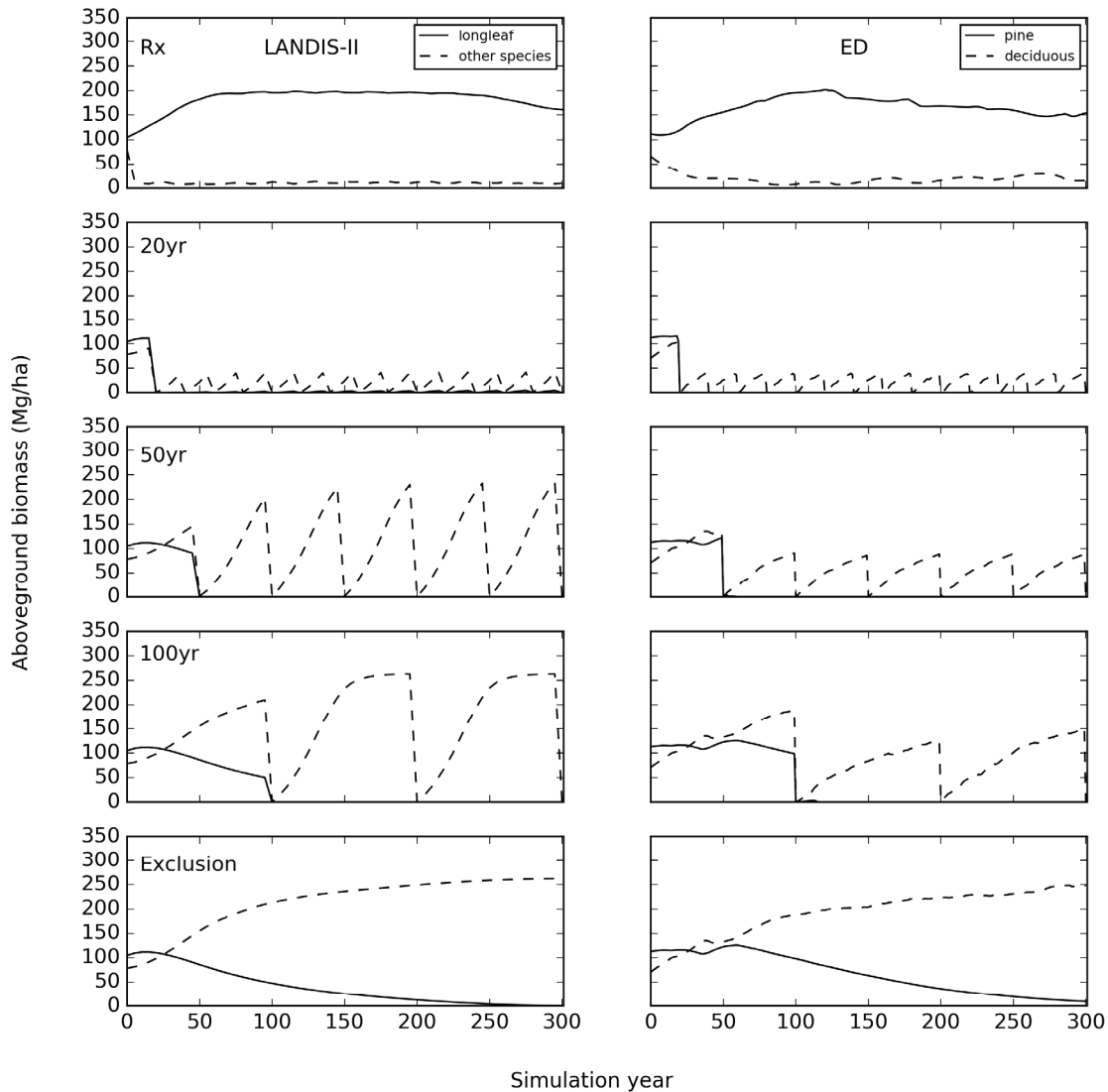
**Figure 7.** Yearly model predicted NEP for all scenarios.



**Figure 8.** The cumulative predicted NECB for all scenarios.

#### 6.0.4 MODEL INTER-COMPARISON: SPECIES DISTRIBUTION –PERFORMANCE OBJECTIVE 6

Under a frequent prescribed fire regime, both models approached max AGB of a longleaf pine stand similar to Gonzales-Benecke et al. (2015), with proportions of biomass from longleaf versus all other species (Figure 9 Rx), similar to that of Loudermilk et al. (2011). In the absence of fire, both models predicted a switch to a hardwood dominated forest (Figure 9 Exclusion) with a higher maximum total biomass found in Brown et al. (1997). The 20 yr scenarios showed similar results for both models as well. The major difference was between the 50- and 100 year scenarios. For example, in the 100 year scenario, hardwoods are predicted to dominate in both models, but these hardwood forests are predicted to reach maximum biomass between fire events only in the LANDIS-II simulations. However, it is important to note that this result does not imply forest stability. When LANDIS-II was separated by species, the 8 oaks had outcompeted the other species on the landscape, but were still on various and divergent trajectories as the forest matured (results not shown). The addition of similar species that did not outcompete one another predicted a shorter time to maximum total biomass but not a stable ecosystem state regarding species dynamics.



**Figure 9.** Yearly model predicted AGB for longleaf vs. other species (LANDIS-II) and pine vs. deciduous (ED).

### 6.0.5 OVERALL MODEL PERFORMANCE

In this model comparison, two classes of models, a landscape scale and DGVM, both illustrated the benefits of a prescribed fire regime to promote carbon sequestration and stable AGB in a southeastern U.S. pineland (Figure 8). Given the large discrepancies between resolution, independent core model development, inherent processes, and species dynamics, the model outputs were remarkably similar, particularly when fires occurred either very frequently or were excluded for the entire timeframe (Figure 9: Rx, 20yr, Exclusion). Model similarities were also supported by their validation against an independent dataset of NEE (Figure 5), where only

minor temporal differences were found, and time series of both models tracked well with the validation dataset. This supports the use of either model for illustrating the changes in carbon flux due to fire regime changes within this ecosystem type. Consideration should be given at longer time-scale fire intervals (here, 50, 100 yr intervals, Figures 6 and 9), where inherent species representations (individual species versus PFTs) and dynamics within each given model illustrated more significant discrepancies.

Although general simulations of NEP and NECB were similar between models, there were also distinct differences. For instance, cumulatively (Figure 8) ED predicted slight net carbon sequestration while LANDIS-II predicted slight net carbon emissions. As such, conclusions on determining which fire regime showed *maximum* carbon sequestration potential were different; ED predicted maximum carbon sequestration potential under a prescribed fire regime, while LANDIS-II predicted maximize sequestration potential to occur under a no fire scenario; i.e. no fire on the order of centuries, which is unrealistic given this fire-prone landscape (Balch et al. 2017). The next best scenario for LANDIS-II to *minimize* carbon emissions was the prescribed fire regime. Interestingly, though the slopes were in opposite directions, the yearly difference between the models NECB was plus or minus  $\sim 1\text{Mg/ha/yr}$ , a relatively small amount. These values, but not the slope or the ranking order of the simulations, are influenced by the amount of AGB converted to detrital carbon after a fire (results not shown). With the inherent differences in these models, the relative similarity of their outputs vis-à-vis frequent prescribed fire argues in favor of the carbon sequestration benefits provided by this regime in southeast U.S. pinelands.

The two models generally agreed with AGB, NEP, and species distribution results for prescribed fire, fire exclusion, and the 20 yr wildfire return (Figures 6, 7, and 9). Differences primarily occurred in the predictions for the 50 and 100 y wildfire scenarios because of the underlying species dynamics (Figure 9). In these scenarios, where LANDIS-II had 8 similar species growing on the landscape versus one for ED, LANDIS-II was able to reach maximum potential AGB at  $\sim 80\text{y}$  while ED did not reach maximum AGB until after 100y. Both models showed the dominance of hardwoods in the absence of fire, but the underlying species dynamics impacted their time to reach maximum potential AGB. Even though in ED the deciduous PFT had less competition for resources, growth was still limited by the number of new individuals the PFT could produce in a year. With only one dominant PFT per scenario, and one soil and climate type for the entire domain, ED's response to disturbance events was not as smooth (Figures 6 and 9) as LANDIS-II's response after fire where more species reproduced in multiple ecoregions. Ultimately, the inherent discrepancies between models were only notable when the heterogeneity or lack thereof was simulated for enough time (here, more than 20 y) to see their respective differences in growth responses after a disturbance. Here, at short fire return intervals, the growth potential of multiple species is not different enough between models to see notable discrepancies, and at extremely long intervals or no disturbance at all, the growth patterns converged.

When choosing a model, there is a tradeoff between input requirements and time needed for model parameterization and the effect on desired model realism to address research questions. ED has high transportability because many inputs are pre-computed but is limited in how it can be modified and lacks individual species. LANDIS-II contains this information but requires a longer parameterization, which also provides greater flexibility in 'scenario' design (climate

change, fire regimes, insects outbreaks, harvesting regimes, etc. If uncertain about what level of detail is needed, one approach is to start with an already constructed DGVM, such as ED, which has high transportability, then examine the initial outputs. If the results recommend a more in-depth analysis, take the time to build the more complex landscape class. These decisions should always be informed by what the model was needed for in the first place – what is the specific management question(s) of interest. Also see section 2.3 for further details on advantages and limitations of these models. Based on our expertise, if and where LANDIS-II has been implemented on DoD lands (e.g., Ft. Benning, Ft. Bragg), they should continue to use this model because it is ‘ready to use’, has higher site realism, and is more flexible (as described above) than ED or another similar coarse-scale model. For sites that have not been parameterized by a stand or landscape scale process-based ecosystem model, ED could be considered as an initial model, based on ease of use for initial assessment (again, described above).

## 7.0 COST ASSESSMENT

**Table 5:** Cost model for a monitoring technology.

<b>Cost Element</b>	<b>Data Tracked During the Demonstration</b>
<b>Sensor procurement</b>	N/A
<b>Installation costs</b>	N/A: All software and datasets are open-source and freely available.
<b>Sensor consumable</b>	N/A

<b>Operation costs</b>	<p>Data technician(s), GIS specialist(s), and model expert(s) or some combination thereof, is the primary cost element. Though the models and datasets are freely available they will need to be altered by specialists. This involves processing the data, potentially changing the spatial resolution, and constructing the appropriate input files for the models. Then the models need to be parameterized, calibrated, and validated before simulations are even run.. The primary labor expenses are a GIS technician with some scripting skills and a modeling expert. We found our funding breakdown that was used for this project to be accurate and necessary. We utilized a fulltime GS-12 post-doc and a GS-09 data technician at 0.33 FTE for 2.5 years. This was for the execution of two ecosystem process models with involved research questions, while providing other teams with data and supporting them with questions about data and various modeling needs. Dr. Scheller, one of the research teams we supported and the creator of LANDIS-II, estimated 8 months of a GIS technician and 2 months of a modeling expert for his LANDIS-II project. We similarly estimated 1 year of support to build LANDIS-II over a much larger area. Given this, we could estimate that it takes ~1yr of 1 FTE of a GS-12 to build LANDIS-II at any given site. However, once the model is developed for an area the costs could be considerably less if you were looking to address a specific research question with the developed model. In addition, there are various extensions (e.g. wind damage, harvesting, insect outbreaks, etc.) that can be added, and we estimate 3-6 months of FTE effort needed per extension. The ED model would be similar as it is already built for the U.S., but it does not have many pre-existing extensions. As such, the modeling expert would have to write code to add an extension, taking 3-6 months of FTE per extension. In the end, the main cost would be the initial construction of the model for a given site.</p>
<b>Maintenance</b>	<ul style="list-style-type: none"> <li>• N/A</li> </ul>
<b>Sensor lifetime</b>	N/A, No unique data tracked

## 8.0 IMPLEMENTATION ISSUES

We encountered no implementation issues.

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## APPENDICES

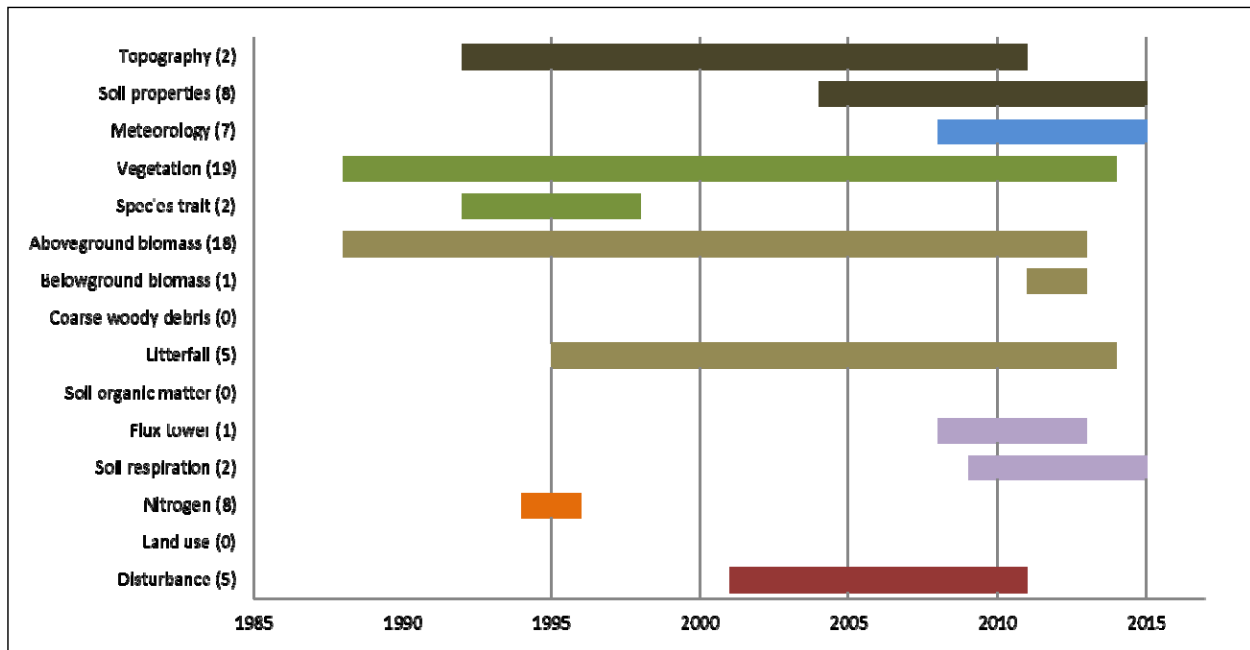
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## Additional Appendices

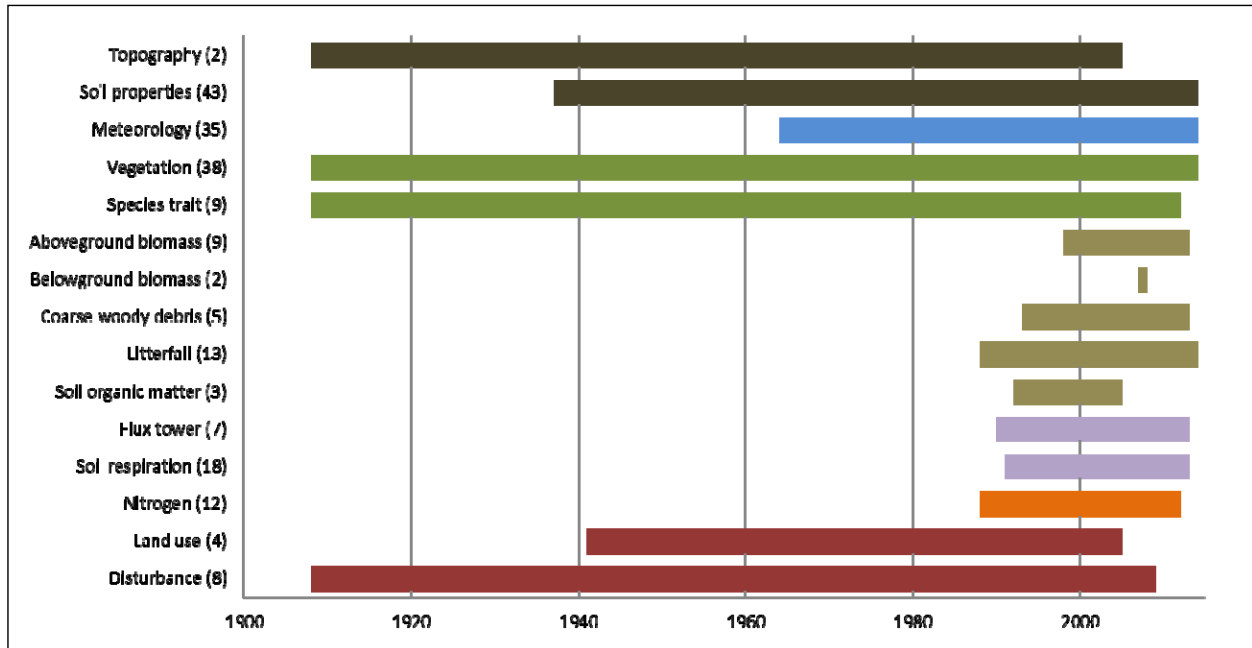
### Appendix B: Ichauway Dataset

Summary of data synthesis for Ichauway, through the Jones Center at Ichauway. This graph represents the time span of data collection; it does not indicate how frequently data was collected during that timeframe. The number of datasets is shown in parentheses. Portions of these data were used for model parameterization, calibration, and validation within this project for inter-model comparison.



## Appendix C: Harvard Forest Dataset

Summary of data synthesis for Harvard Forest, a Long-Term Ecological Research Site. This graph represents the time span of data collection; it does not indicate how frequently data was collected during that timeframe. The number of datasets in shown in parentheses. These data were transferred to the other project performers (RC17-201702, RC17-201703). These data were not used for this project.



## Appendix D: Dataset Comparison and Overview

Overview of data synthesis across study sites. These data were transferred to the other project performers (RC17-201702, RC17-201703). Only the Ichauway data was used for this project for model inter-comparison. \* Dataset = a collection of data organized by measurement type and research project or study. \*\* Temporal resolution varies across datasets (e.g., data collection daily, weekly, monthly, annually). \*\*\* Number of plots varied by research project and the data being collected

	Harvard Forest	Jones Center at Ichauway
Total Datasets (files)*	165	69
Total Metadata Documents	70	16
Date Range**	1908 - 2015	1988 - 2015
Number of Research Compartments	4	6
Number of Plots***	4 plots (30 m x 30 m) to 269 plots (22.5 m x 22.5 m)	6 plots (0.25 m x 0.25 m) to 12 plots (50 m x 50m)
Flux Towers	3	3
Meteorological Stations	1	3
Disturbances	Hurricane (1938), fire (1957), ice, tornado, wind, hemlock woolly adelgid, exotic species, agricultural abandonment	
Management	Silviculture treatments: planting, removal, pruning, thinning, weeding	Prescribed burning