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SWAT-3PG: Improving forest growth simulation with a process-based forest model in SWAT

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ABSTRACT

This study developed a new process-based forest module for the Soil and Water Assessment Tool (SWAT), based on the Physiological Process in Predicting Growth (3-PG) model (SWAT-3PG). The new model allows for improved biomass assimilation, partitioning (stem, foliage, root), and losses (root turnover, foliage loss, mortality). Evaluation at field-scale showed that SWAT-3PG can replicate the different forest biomass components for evergreen forests well. Testing for deciduous and mixed forests sites using remote-sensed data showed that the model can simulate leaf area index (LAI), net primary productivity (NPP) and actual evapotranspiration (AET) reasonably well and can be used to constrain SWAT-3PG when lack of field data. Sensitivity analysis of SWAT-3PG showed its potential in evaluating the impacts of management and climate on forested ecosystems. SWAT-3PG can also be of importance to forest managers as it can estimate variables such as plant height, diameter at breast height (DBH), and basal area.

Software Availability

Name of the software: SWAT-3PG
Developer: Ritesh Karki and Junyu Qi
Contact information: junyuqi@umd.edu
Year first available: 2023
Program language: Fortran 90
Cost: Free
Software availability: https://github.com/riteshkarki/SWAT664-3PG
Program size: 4.05 mb

1. Introduction

Forests play an integral role in hydrologic, nutrient, and carbon cycling at global, regional, as well as basin/watershed scale. Forests dominate terrestrial water dynamics as it has significant influence on transpiration, rainfall interception, percolation, and soil moisture dynamics (Adams et al., 1991; Dunkerley, 2015; Lathuillière et al., 2012; Teuling et al., 2019). As a result, forests also play a critical role in runoff generation, groundwater recharge, and the delivery of water from land to riverine and lake systems. Studies have shown that loss of forest cover can lead to an increase in watershed water yield due to reduction in actual evapotranspiration (AET) and, as a result, also increase streamflow (Jones and Post, 2004; Perry and Jones, 2017). Forests are an integral part of the global carbon cycle as it dominates carbon exchange between the atmosphere and terrestrial biosphere and accounts for about 80% of the global aboveground biomass (AGB) (Dixon et al., 1994). With the increase in atmospheric CO_2 concentrations and resulting climate change a key global issue, forests are an important component of global carbon cycle investigations (Curtis and Gough, 2018; Detwiler and Hall, 1988) as it can contribute to carbon sequestration and storage in standing biomass as well as stored wood products. The Global Climate Observing System (GCOS) identified AGB as one of the 54 essential climate variables because of its role in the global carbon cycle (Santoro et al., 2021). Quantifying forest biomass and sequestration potential are also critical from a policy perspective as information on national/regional forest biomass is critical to decision making for climate mitigation policies (Hurtt et al., 2019).

Forests also impart major influence in aquatic ecosystems through the delivery of water, sediments, nutrients, and carbon (Butman et al.,

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2016; Kreutzweiser et al., 2008; Lee et al., 2018; Martin et al., 2000; Prepas et al., 2001). As such, changes to forest ecosystem including deforestation, wildfire, pests etc. can have significant impact on aquatic carbon fluxes (Kreutzweiser et al., 2008; Prepas et al., 2001). As forests account for up to 28% and 38% of ecosystem N and P (Hart et al., 2003), respectively, it also plays an important role in terrestrial and riverine nutrient balances through uptake and subsequent return to soil through litter and riverine nutrient export. Accurate representation of soil organic carbon (SOC) and transport from terrestrial to aquatic system to quantify aquatic carbon also necessitates accurate simulation of biomass sequestration, storage as well as losses from forested systems (Butman et al., 2016).

Hydrologic models help us understand the complex relationships between atmospheric, terrestrial, and aquatic systems for water, sediment, nutrient, and carbon fluxes under different land management, land use change, climate change etc. As a result, models are important tools that can aid in policy decision making for water resource management (Molina-Navarro et al., 2016; D. Zhang et al., 2018), nutrient reduction (Douglas-Mankin et al., 2010; Endale et al., 2014; Karki et al., 2018), as well as understanding and reducing climate impacts (Diaz and Rosenberg, 2008; J. Lee et al., 2019). It is, however, critical to capture the important processes of the different ecosystems in the model (Wang et al., 2020a, 2020b). The Soil and Water Assessment Tool (SWAT) is a watershed-scale, semi-distributed, process-based model (Neitsch et al., 2011) that has been widely applied across the world in varying climate and topographic regions for evaluating the impacts of land management, land use change, as well as climate (Haro-Monteagudo et al., 2020; Samimi et al., 2020; Tan et al., 2019, 2020; Upadhyay et al., 2022). Model improvement effort in recent years has helped further expand the use of SWAT in additional fields such as soil organic carbon simulation (Zhang, 2018), natural salinity (Tirabadi et al., 2021), as well as soil N_2O emissions (Gao et al., 2019). The model is a key component of the U.S. Environmental Protection Agency (USEPA) – Hydrologic and Water Quality Systems (HAWQS) (HAWQS, 2020) and U.S. Department of Agriculture (USDA) Conservation Effect Assessment Project (CEAP) projects and has also been incorporated into the USEPA Better Assessment Science Integrating point and Nonpoint Sources (BASINS) multipurpose environmental analysis tool (US EPA, 2019).

Although SWAT has been widely used with more than 5000 scientific publications and evaluated in over 90 countries (https://www.card.iastate.edu/swat_articles/), the model has had limited applications in forest dominated watersheds due to its limitations in simulating forest biomass and water and nutrient fluxes (Haas et al., 2022; Yang and Zhang, 2016). As the SWAT model was initially developed with focus on agriculture dominated watersheds, the plant growth module in SWAT is based on a simplified version of the Environmental Policy Integrated Climate (EPIC) model that was developed for simulating physio-chemical processes under agricultural crops and was adjusted minimally for forest growth in the SWAT model (Neitsch et al., 2011; Williams et al., 1989). As a result, current forest growth module in the SWAT model has key issues that needs to be addressed for improving forest simulation. This can be vital to increasing applicability of the model in forest dominated watersheds along with reducing uncertainty of hydrologic, nutrient, and carbon simulation from forested regions even in agriculture dominated watersheds as forests make a significant portion of the land use in most watersheds (Jin et al., 2013).

There have been studies in recent years that aimed to improve forest simulation in SWAT but have been often limited to improving forest simulation by improving forest parameterization (Haas et al., 2022; Yang and Zhang, 2016). And, any attempts to modify the underlying forest growth algorithms in SWAT have been mostly focused on modifying how leaf area index (LAI) is simulated (Alemayehu et al., 2017; Lai et al., 2020; Ma et al., 2019; Strauch and Volk, 2013), which fails to address key issues in the current module that includes the lack of daily partitioning of assimilated biomass into root, stems, and leaves; LAI is solely a function of heat units with no relation to foliage biomass; same litterfall routine for evergreen and deciduous forest types; lack of accurate forest initialization; and, no tree mortality.

There is a wide range of models currently available for forest simulation that are based on empirical/regression relationships, process-based, or a combination of both (Fontes et al., 2010). Although it is ideally desirable to use comprehensive process-based carbon balance models such as Biome-BGC (Thornton and Running, 2000; White et al., 2000) or PnET (Aber and Federer, 1992) for simulating forest growth, the models are very data intensive which makes its usability and compatibility difficult. The Physiological Process in Predicting Growth (3-PG) is a forest growth model that is process-based but also uses empirical relationships that greatly simplifies calculations (Landsberg and Waring, 1997). The model has been successfully used to simulate forest stand growth for multiple tree species and in a range of climatic conditions (Amichev et al., 2010, 2016; Gonzalez-Benecke et al., 2014, 2016; HN Palma et al., 2021). The simplicity of 3-PG in model development yet its robustness in simulating forest growth makes it an ideal model to be incorporated into the SWAT model for improving forest simulation.

In this study, we present an enhanced version of SWAT model with a new forest module that is developed based on 3-PG (herein from referred to as SWAT-3PG) with the goal of better representing forest ecosystems and improving simulation of biomass assimilation, partitioning, and losses from forests. The main objectives are 1) to incorporate the process-based 3-PG forest growth model into SWAT, and 2) to test model performance of SWAT-3PG on simulation of forest biomass and fluxes for different forest types using in-situ measurements and remoted sensed data. We also discuss the advantages as well as limitations of the new forest module for new model applications. We expect the new SWAT-3PG model to also help reduce uncertainty associated with the estimation of hydrologic, nutrient, and carbon fluxes from forest systems along with improved estimation of net primary productivity (NPP), net ecosystem productivity (NEP), and soil carbon.

2. Materials and methods

2.1. Model development

2.1.1. Forest growth in the default SWAT model

Forest growth module in SWAT is based on a simplified version of the EPIC model (Neitsch et al., 2011). The model calculates daily intercepted radiation by the leaf area (Eq. S1) which is then used to calculate the potential maximum biomass that can be assimilated each day under optimal conditions using radiation use efficiency (RUE) (Eq. S2). The potential maximum biomass is then constrained to actual growth using constraints based on water, temperature, and nutrient stresses (Eqs. S3-S7).

Biomass assimilation in SWAT within a single year is limited to a fixed amount based on the current age as well as user-defined number of years for the tree to reach maturity and tree maximum biomass (Eq. S8). Tree growth in a given year is stopped until the next year once the biomass accumulation for the year reaches the maximum limit calculated. Similarly, LAI calculation in forest is a function of the potential heat unit accumulated each day along with the current age of tree and age to maturity (Eq. S9) but has no relation to foliage biomass accumulation. Calculation of canopy height for forests is also based on a user-defined maximum tree height along with the current age and age to maturity (Eq. S10).

The assimilated biomass for each day is allocated to AGB and root. The fraction of biomass allocated to root is based on the user-defined root to shoot ratio at seeding and maturity along with the potential heat units accumulated to that day for each year (Eq. S11). A fraction of assimilated AGB is lost as litterfall each year at the onset of dormancy based on a user-defined fraction (Bio_leaf; plant.dat) irrespective of the forest type (Eq. S12).

2.1.2. Forest growth in 3-PG model

3-PG is a process-based, stand-alone model for forest growth that calculates gross primary productivity (GPP) based on intercepted utilizable photosynthetically active radiation and a canopy quantum coefficient (α_{cx}). Intercepted photosynthetically active radiation is reduced to utilizable amount using environmental modifiers, such as vapor pressure deficit, soil water, temperature, nutrition and, atmospheric CO_2 concentration, as well as a decline in growth efficiency due to age. The model then uses a constant NPP/GPP ratio to calculate NPP (Eqs. S13, S14). The assimilated biomass is allocated to roots based on growing conditions as well as age and the allocated fraction increases if the site nutrition or the available water is low. The remaining assimilated biomass is then partitioned to stem + branches (herein from referred together as stem) and foliage that varies with growing conditions, tree age and size and is based on allometric relationships. The model uses a sub-model derived from the −3/2 power law to calculate density-dependent tree mortality (self-thinning). A density-independent tree mortality sub-routine is also included (mortality due to age). 3-PG has separate litterfall for deciduous and evergreen forests in that deciduous forests lose all leaves at the onset of dormancy. Evergreen forests, on the other hand, have litterfall throughout the year but do not lose all foliage at the onset of dormancy. LAI calculation is based on assimilated foliage biomass and specific leaf area. The model also estimates variables that are important to forest managers including tree height, basal area, and diameter at breast height (DBH). Initial biomass, number of trees per hectare and age are required for the 3-PG model. The readers are referred to Landsberg and Waring (1997) and Sands (2010) for the details regarding 3-PG forest growth module calculation of the different growth modifiers, biomass partitioning, stem mortality, litterfall, and LAI.

2.1.3. Development of the SWAT-3PG model

The new forest module in SWAT based on 3-PG consists of three separate sub-routines for the simulation of evergreen, deciduous, and mixed forest systems separately. The sub-routine for deciduous forest is different from evergreen in that all foliage biomass is lost at the onset of dormancy and biomass assimilation at the beginning of growing season (end of dormancy) is allocated all to foliage biomass until the total foliage biomass lost at the onset of dormancy the previous year is recovered. A limitation of SWAT using Hydrologic Response Units (HRUs) as the basis of all calculations is that it allows for only one plant type to be growing at any time in an HRU. This prohibits a realistic simulation of mixed forest systems that requires multiple tree-species to be growing simultaneously. As a result, mixed forest system is simulated by making a slight modification to the deciduous forest module in which only a portion of the total foliage biomass is lost at the onset of dormancy which could be a proxy to the foliage loss only from deciduous trees in a mixed forest ecosystem. Although only a single tree species is simulated, the proposed module for mixed forest system can replicate the average biomass, foliage, and losses of a mixed forest system.

Biomass assimilation in the new forest module is calculated using equations based on the 3-PG model rather than the SWAT default module so that already calibrated optimal canopy quantum efficiency (α_{cx}) (Eqs. S13, S14) for different tree species with 3-PG can be directly incorporated into SWAT-3PG. Potential maximum biomass assimilation under optimal conditions in SWAT-3PG is, therefore, calculated using α_{cx} rather than RUE. The growth modifiers/constraints were slightly modified in that nutrient stresses (nitrogen and phosphorus stresses) were used instead of the user-defined site-fertility rating index used in the 3-PG model. Frost modifier was removed as SWAT already prevents biomass accumulation when the average daily temperature is below the user-defined minimum temperature below which biomass assimilation does not occur. The new equation for calculating assimilated biomass each day is presented in Eqs. (1)–(3).

$$Bio_{opt} = 0.47 * \alpha_{cx} * H_{phosyn} * 10 \quad \text{(Eq. 1)}$$

where, Bio_{opt} is the biomass assimilation under optimal conditions, H_{phosyn} is the amount of intercepted photosynthetically active radiation, and α_{cx} is the optimal canopy quantum efficiency.

$$f\_phys = min\{f_{VPD} f_{SW}\} f_{age} \quad \text{(Eq. 2)}$$

where, f_phys is the total modifier, f_{VPD} is the vapor pressure deficit modifier, f_{SW} is soil water modifier, and f_{age} is age-related modifier. Equations for calculating f_{VPD}, f_{SW}, and f_{age} are provided in Eqs. S15 – S17.

$$Bio_{act} = Bio_{opt} * \ tstrs * \min(wstrs, nstrs, pstrs) * f\_phys \quad \text{(Eq. 3)}$$

Where, Bio_{act} is the actual biomass assimilation, *tstrs* is the temperature stress for the given day (Eq. S5), *wstrs* is the water stress for the given day (Eq. S4), *nstrs* is the nitrogen stress for the given day (Eq. S6), *pstrs* is the phosphorus stress for the given day (Eq. S7), and f_phys is the total modifier.

Assimilated biomass for each day is first partitioned to root fraction based on environmental conditions as well as user-defined minimum and maximum NPP fraction to roots (Eqs. (4) and (5)). The remaining biomass is then partitioned to stem and foliage (Eqs. (6)–(8)).

$$n_R = \frac{pRx * \ pRn}{pRn + (pRx - pRn) * f_{phys} * m_{root}} \quad \text{(Eq. 4)}$$

where, n_R is the root fraction for the day; *pRx* and *pRn* are the maximum and minimum fraction of assimilated biomass to roots; f_{phys} is the total modifier, and m_{root} is calculated using Eq. 5

$$m_{root} = m0 + (1 - m0) * \ \min(wstrs, nstrs, pstrs) \quad \text{(Eq. 5)}$$

where, *m*0 is the root fraction under poor growing conditions.

$$n_S = \frac{1 - n_R}{1 + P_{FS}} \quad \text{(Eq. 6)}$$

where, n_S is the stem fraction for the day, n_R is the root fraction for the day and P_{FS} is calculated using Eq. 7

$$P_{FS} = a * dbh\_tree^b \quad \text{(Eq. 7)}$$

where, *a* and *b* are coefficients calculated based on user-defined foliage: stem partitioning ratio at plant diameter at breast height of 2 cm and 20 cm respectively, and *dbh_tree* is the current diameter at breast height calculated using allometric relationships.

$$n_F = 1 - n_R - n_S \quad \text{(Eq. 8)}$$

where, n_f, n_R, and n_S are the foliage, root, and stem fraction of assimilated biomass for each day.

The exception for assimilated biomass partitioning for deciduous and mixed forest systems is at the beginning of growing season when all assimilated biomass is assigned to foliage until the total foliage biomass lost at the onset of dormancy is recovered. Calculations for root turnover, foliage loss, mortality due to self-thinning and age along with the associated biomass losses were incorporated directly from 3-PG.

Modifications were also made to the source code such that forest biomass and age could be initialized for each forest HRU using the. mgt file which is a requirement with 3-PG. The initialized total biomass is partitioned to the three biomass pools for stem, roots, and leaves based on Poorter et al. (2012). The dormancy module was modified such that evergreen forests would lose a certain amount of foliage biomass as litterfall during each day of the simulation period based on age while deciduous forests, in addition to daily losses, lost all foliage at the onset of dormancy. A new input file SWAT3PG.3PG was created to read all 3-PG related input parameters. Activation key was incorporated in the SWAT3PG.3PG input file that allowed the user to activate or deactivate tree loss due to mortality as well as self-thinning. It is important to note that 3-PG runs at a monthly time scale and hence it was necessary to convert all of the parameters with monthly time units to daily when incorporating into the SWAT3PG.3PG parameter input file. The source code was also modified to generate a new output file that lists all the forest outputs.

2.2. Study sites and data

Five field-sites were selected in the U.S to test the new forest module for simulation of evergreen, deciduous, and mixed forest systems (Fig. 1). Evergreen-FL-1, Evergreen-FL-2, and Evergreen-GA are long-term forest productivity evaluation sites and had annual measurements of total, stem, coarse root, and foliage biomass, LAI, and litter fall for loblolly pine (*Pinus taeda*; evergreen forest type) (Gonzalez-Benecke et al., 2014, 2016). All evergreen forest sites were in the Appalachian Highlands but still varied in climatic and soil conditions (Table 1). Similar long-term field measurements were not available for deciduous and mixed forest systems. As a result, a site in Wisconsin (WI) (Deciduous-WI) was identified that was dominated by Aspen forests using the U.S. Forest Service (USFS) national forest type dataset and was used to evaluate the deciduous forest module. As field-measured data were not available, the forest module for simulating deciduous forest systems was calibrated and validated for remote-sensed NPP-Carbon (NPP–C), AET, and LAI data products and evaluated for simulating forest biomass and its components. Similarly, a mixed-forest site (Mixed-VA) was identified and selected for evaluation in Virginia (VA).

Remote sensed data products (LAI, AET, and NPP-C) for the deciduous and mixed-forest sites were acquired from Moderate Resolution Imaging Spectroradiometer (MODIS) datasets (Justice et al., 2002; Running et al., 2017). Table 1 provides the important information for each site.

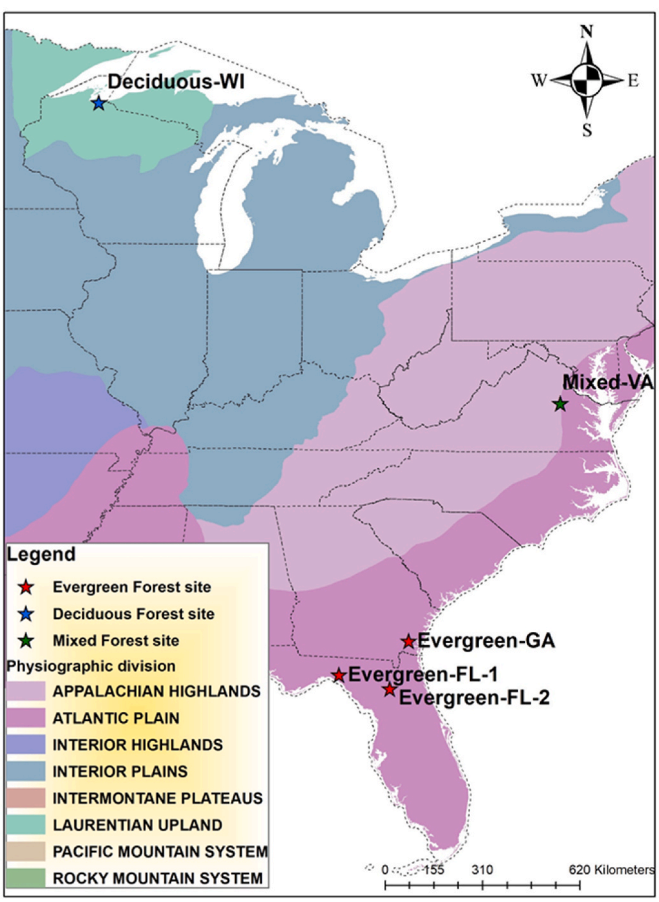

Fig. 1. Selected field sites for SWAT-3PG testing and physiographic division based on the region's geomorphology in the United States (U.S.).

2.3. Model setup and evaluation

Field-scale SWAT models (Karki et al., 2020) were set up for each of the forest sites. Datasets utilized for setting up the field-scale SWAT models are provided in Table 2. Field-scale SWAT models for the evergreen sites were developed from the year of initial year of planting to 2020 (Table 1) even though the observed datasets did not extend to the year 2020. This allowed for comparison of model simulated forest biomass against observed values along with the evaluation of long-term forest simulation with the new forest module. The forest module for evergreen forest simulation was calibrated at Evergreen-FL-1 site and validated at the remaining two evergreen sites (Evergreen-FL-2 and Evergreen-GA; Fig. 2). Model validation was performed by transferring only the calibrated forest parameters to the two validation sites and no additional adjustments were made for model simulation. Field-scale models for the deciduous (Deciduous-WI) and mixed-forest (Mixed-VA) sites were developed from 2000 to 2020 with the model calibrated using remote-sensed data from 2001 to 2010 and validated from 2011 to 2020 at the same sites (Fig. 2). As the Deciduous-WI and Mixed-VA had existing forests, the initial forest age and biomass required for model initialization was acquired from Williams et al. (2020). Model performance evaluation for the simulation of different field-measured data in the evergreen sites were limited to graphical comparison between simulated and observed data due to temporal data limitations of one data point for each year (Fig. 2). The deciduous and mixed sites were evaluated using graphical as well as statistical methods as monthly remote-sensed data was available from 2001 to 2020. Statistical evaluation was performed by calculating the coefficient of determination (R^2), Nash Sutcliffe Efficiency (NSE), and percent bias (PBIAS), which are commonly used measures for evaluating model performance in hydrologic and water quality modeling (Moriasi et al., 2015). Fig. 2 details the model calibration and validation approach for the simulation of the three forest types using SWAT-3PG.

2.4. SWAT-3PG model sensitivity analysis

Multiple scenario runs were performed to evaluate how the new SWAT-3PG forest module responded for forest simulation under different growing conditions as well as forest initialization. The different scenarios simulated and evaluated to test SWAT-3PG sensitivity are listed in Table 3. All the scenario runs were performed at the Evergreen-FL-1 site and the calibrated model run was used as the baseline against which all scenarios were evaluated (Fig. 2). The scenario runs are important to understand if the new module can provide a response in forest growth under varying growth stresses and initial forest growth conditions, which will be critical in using the SWAT-3PG model for forest management, climate, and land use change scenario evaluations.

3. Results

3.1. SWAT-3PG simulation of evergreen forests

Initial model parameters for SWAT-3PG simulation of the evergreen forest site with loblolly pine (Evergreen-FL-1) were acquired from literature (Bryars et al., 2013; Gonzalez-Benecke et al., 2016; Subedi et al., 2015) after which a sensitivity analysis for parameters was performed using R-SWAT (Nguyen et al., 2022) and model calibration was performed using automated (R-SWAT) as well as manual approaches. Calibrated model parameters for SWAT-3PG for the simulation of evergreen forest at Evergreen-FL-1 site is presented in Table S1.

Graphical comparison between SWAT-3PG simulated forest biomass components for the Evergreen-FL-1 site after calibration and observed data is presented in Fig. 3. It can be seen from the figure that the new forest module successfully replicates the observed trend as well as

Table 1
Selected forest sites used to test the SWAT-3PG model and dataset information.

Site name	Evergreen-FL-1	Evergreen-FL-2	Evergreen-GA	Deciduous-WI	Mixed- VA
Latitude	29.8	30.2	31.1	46.6	37.9
Longitude	−82.3	−83.7	−81.8	−90.6	−77.4
Elevation	51 m	9 m	5 m	234 m	60 m
Hydrologic soil group	B	B	D	C	B
Field observation period	1987–2008	2001–2013	2001–2013	*NA*	*NA*
Remote sensed data period	*NA*	*NA*	*NA*	2001–2020	2001–2020
Annual average precipitation (mm)	1262	1310	1278	889	1183
Mean daily Temp max (°C)	27	25.9	26.0	9.9	20.2
Mean daily Temp min (°C)	17	16.5	16.4	4.4	9.9
Mean daily Solar radiation (MJ/m^2)	18.2	18.3	18.9	13.9	16.2
Model simulation period	1984–2020	2000–2020	2000–2020	2000–2020	2000–2020

Table 2
Datasets for SWAT model setup at each site.

S. no	Data type	Dataset	Source
1.	Topography	10m × 10m Digital Elevation Model (DEM)	USGS (Gesch et al., 2002)
2.	Soil	Gridded Soil Survery Geographic (gSSURGO)	USDA/NRCS (USDA-NRCS, 2019)
3.	Meteorological forcing	Precipitation; Temperature; Relative Humidity; Solar radiation	NLDAS-2 (Xia et al., 2012)
4.	Atmospheric deposition	Nitrate/Ammonia deposition	NADP dataset (Gay, 2020)

magnitude in the simulation of total, stem, and foliage biomass along with foliage loss and LAI (Fig. 3). The new forest module was able to capture very well the observed trend of biomass assimilation in total and stem biomass from planting to the juvenile years (Fig. 3a and b). SWAT-3PG was also able to capture the trend of reduction/stabilization in total biomass assimilation after the year 2004 with the activation of mortality due to self-thinning that can be simulated by the new forest module (Fig. 3a).

The forest module also replicated well the quick accumulation of foliage biomass in the first few years after planning and the stabilization as well as slight reduction in foliage biomass afterwards (Fig. 3c). Annual foliage loss was also captured well by the new forest module (Fig. 3e). Foliage loss in evergreen forests with the new forest module happens throughout the year from the foliage biomass pool unlike the default forest module in SWAT which makes a proxy foliage biomass loss by removing a certain user-defined fraction of biomass from the AGB pool at the onset of dormancy. The new forest module was also able to show temporal variability in the accumulation of foliage biomass, the effect of which can be observed in the slight variability in the assimilation of annual biomass. With accurate simulation of foliage biomass and losses, the new forest module also matched the observed LAI well (Fig. 3f).

Root biomass was the only forest biomass component that the new module was not able to replicate closely (Fig. 3d). Comparison against observed data shows that the model was able to capture the trend of observed root biomass well in that the accumulation of coarse root biomass was linear in the early years which stabilized later (Fig. 3d). The

Table 3
Model scenario runs for SWAT-3PG sensitivity evaluation.

Scenario No.	Scenario Variable	Scenario Description
Scenario 1	Rainfall	Scale rainfall by 30% (Increase)
Scenario 2	Rainfall	Scale rainfall by 30% (Decrease)
Scenario 3	Nutrient	Double atmospheric deposition load
Scenario 4	Nutrient	Nitrate fertilizer application of 200 kg/ha
Scenario 5	Forest initialization	Initialize with already growing forest (Age: 10 years; Initial total biomass: 130 tons/ha)
Scenario 6	Self-thinning	Forest mortality due to self-thinning as well as age was turned off.

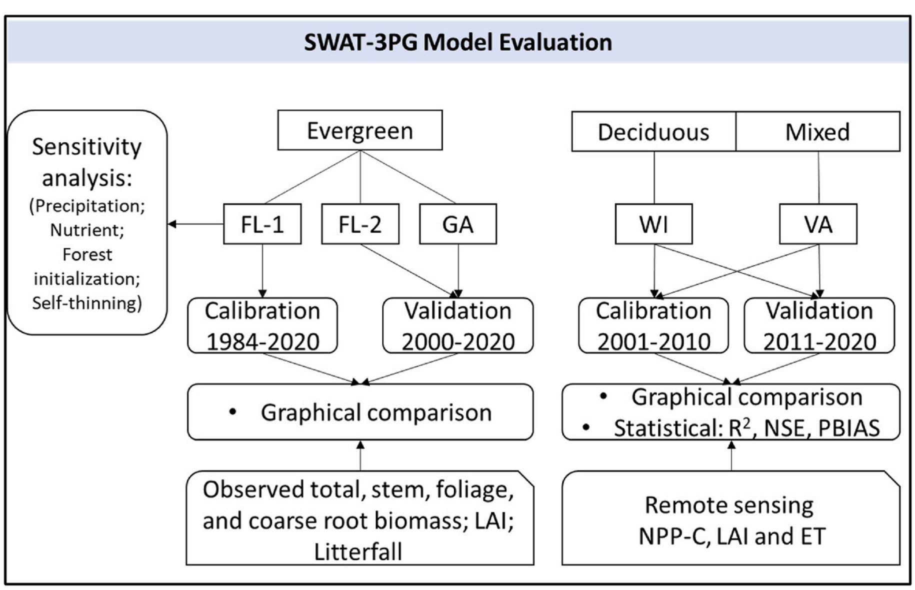

Fig. 2. A SWAT-3PG model evaluation flowchart using three sites of evergreen forest with observed total, stem, foliage, and coarse root biomass, LAI and litterfall and a deciduous and mixed forest site with MODIS remote sensing NPP, LAI and AET data.

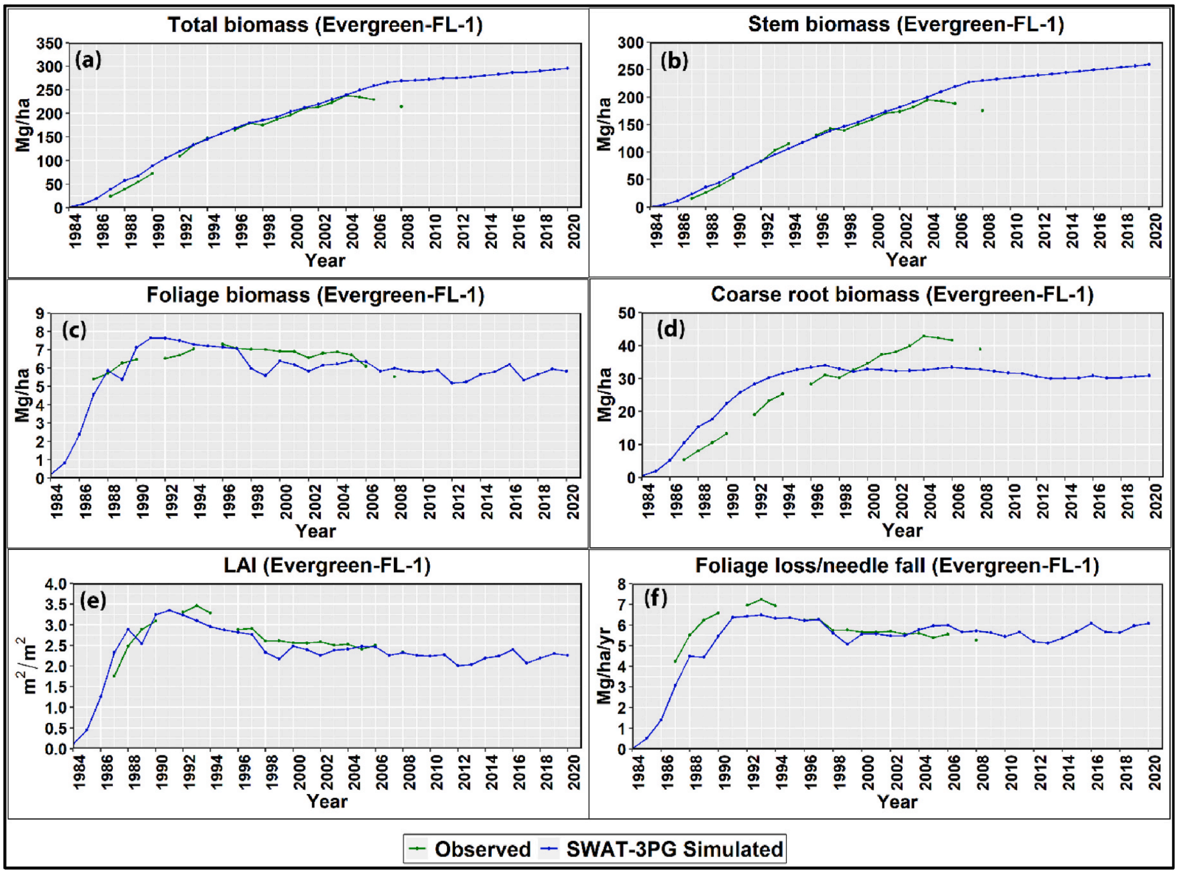

Fig. 3. SWAT-3PG simulation of evergreen forest at Evergreen-FL-1 site after calibration.

model, however, over-simulated the magnitude of coarse root biomass assimilated in the early years and the assimilation of coarse root biomass also stabilized earlier than observed. It is important to note that the observed root biomass only included coarse root biomass and fine root biomass was not accounted for. This could have resulted in the under-reporting of observed total root biomass and potentially explains the over-simulation of root biomass by the new forest module in the early years.

Comparison of model simulated biomass components at the two validation sites (Evergreen-GA and Evergreen-FL-2) against field-measured observed dataset shows that the model performed reasonably well at both sites (Fig. 4 & Fig. 5). Although the model tended to overestimate the forest biomass components at the Evergreen-GA site (Fig. 4) and underestimate at the Evergreen-FL-2 site (Fig. 5), the model simulated forest biomass closely matched the field-measured values and also followed the observed trend well at both validation sites. It is worth noting that the calibration and validation sites had different climatic and soil conditions (Table 1) and the validation run was performed by incorporating only the calibrated SWAT-3PG forest parameters from the calibration site. This can help increase confidence in the new forest module to simulate forest biomass over a large spatial domain with varying climate and soil conditions as the new forest module performed well by only incorporating the calibrated forest parameters from the calibration site.

Comparison of the observed dataset (especially foliage biomass, LAI, and foliage loss) at the two validation sites showed that the observed datasets at Evergreen-FL-2 site (Fig. 5) had more variability when compared to Evergreen-GA site (Fig. 4) which was captured well by the new forest module. Simulated foliage biomass, LAI, and foliage loss at the Evergreen-FL-2 site (Fig. 5c, e, and 5f) had high temporal variability while the Evergreen-GA (Fig. 4c, e, and 4f) showed minimal variability consistent with the observed datasets. The variability in the simulation of different forest biomass components in the calibration and validation sites also helps reinforce that the model can respond to varying forest growing conditions which will be critical when using the SWAT-3PG at larger spatial domain with varying climatic and soil conditions.

3.2. SWAT-3PG simulation of deciduous and mixed forest

As the Deciduous-WI site was dominated by Aspen (*Populus tremuloides*), initial parameters for SWAT-3PG were derived from Amichev et al. (2010) which estimated 3-PG parameters for hybrid poplar tree species. Calibrated SWAT-3PG parameters for the simulation of Deciduous-WI site is presented in Table S1. Comparison of SWAT-3PG simulated LAI, AET, and NPP-C against MODIS estimated data for the deciduous forest site (Deciduous-WI) during calibration and validation is presented in Fig. 6. It can be seen from the figure that SWAT-3PG does a good job of capturing the observed variability for all three variables during the calibration (2011–2010) and validation period (2011–2020). R^2 and NSE of greater than 0.5 for the simulation of all three variables (LAI, AET, and NPP-C) during both calibration and validation (Table 4) indicates that SWAT-3PG can simulate the three variables well for deciduous forest systems. PBIAS for LAI and AET was less than 20% for both calibration and validation indicating a good model fit. PBIAS for NPP-C was, however, −26.9% during model validation period (Table 4) indicating to the model having slight difficulty in replicating the remote-sensed estimated NPP-C.

An additional model run performed for the Deciduous-WI site using calibrated SWAT-3PG parameters, but forest initialized at planting (rather than already growing – as initialized during calibration) to evaluate how the calibrated model parameters would simulate forest from planting. Model results evaluation showed that SWAT-3PG was

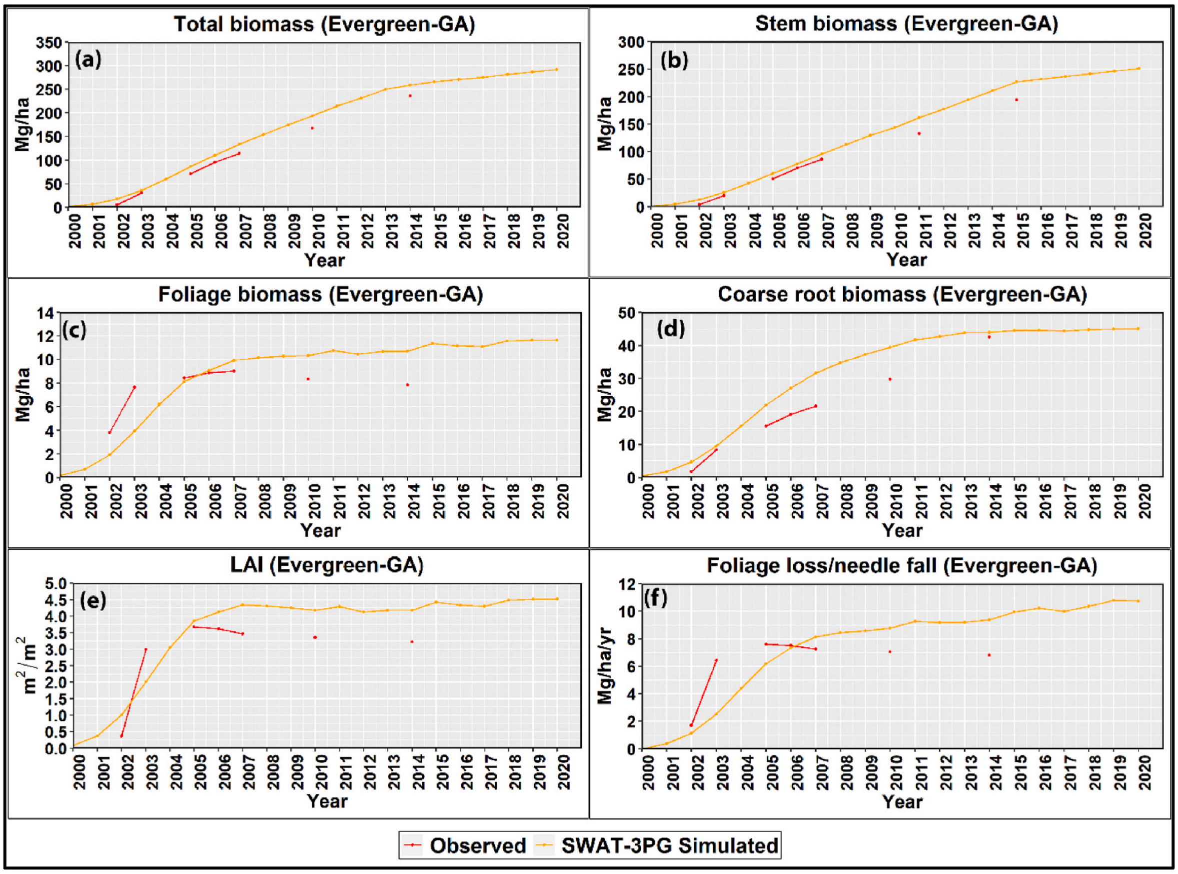

Fig. 4. SWAT-3PG simulation of evergreen forest at Evergreen-GA site for validation.

able to simulate realistic forest biomass components including total, stem, and foliage biomass as well as LAI (Fig. 7) with the calibrated parameters. This shows that the use of remote-sensed data products (LAI, AET, NPP-C) can be important and helpful datasets for constraining SWAT-3PG parameters for forest simulation, especially when performing model simulations at regional/watershed-scale and there is a lack of field-observed data for different forest types.

As the mixed-forest site had multiple forest species, initial parameters used for the Deciduous-WI site were also used as the initial parameters for this site. Comparison of model simulated monthly LAI, AET, and NPP-C against MODIS estimated for the mixed-forest site is shown in Fig. 8. The new module simulated LAI and AET well with a close match between simulated and remote sensed variables (Fig. 8). R^2 and NSE was greater than 0.5, and PBIAS was less than 10% during both calibration and validation periods (Table 5). A close match between simulated and observed LAI and AET shows that the module for simulation of mixed forests, which represents mixed forest systems using a single plant type due to the limitation in SWAT model, can still replicate the spatial as well as temporal variability in LAI and AET of the mixed forest system as a whole. Evaluation of NPP-C, however, showed that the mixed-forest module had difficulty in replicating the remote-sensed estimated NPP-C. SWAT-3PG was able to capture the observed trend in the assimilation of NPP-C well (Fig. 8) but the model was not able to capture the observed magnitude in NPP-C assimilation with the model under simulating NPP-C during both calibration and validation periods (NSE <0.1 and PBIAS $< -40\%$). It should be noted that SWAT-3PG simulates mixed forest system similar to a deciduous forest with a single forest type but loses only a portion of foliage biomass as litterfall to replicate the loss of foliage from deciduous trees. This limit in SWAT-3PG does not allow for biomass assimilation of different tree species in a mixed forest system to be simulated separately but is estimated by calibrating for biomass assimilation that is representative of the mixed forest system, which can lead to difficulty in the model replicating the observed NPP-C. A better starting parameters by identifying the major forest types in the mixed forest site could also have potentially helped in better NPP-C simulation. Evaluation of MODIS estimated NPP-C for the mixed site also showed NPP-C assimilation in the winter months, possibly from forest understory, which was not captured by the model with no NPP-C simulation in the winter months. This also contributed to the poor performances measure for NPP-C simulation for the mixed-VA site. It is also equally important to acknowledge the inconsistencies and uncertainties associated with NPP-C datasets when evaluating against model simulated values (Xie et al., 2020; Zhao et al., 2006).

An additional model run using the calibrated parameters was also performed for the Mixed-VA site but with forest initialized as planting to evaluate the impact of the calibrated parameters on forest simulation. The new forest module for mixed forest simulation in SWAT-3PG was also able to simulate the important components of a mixed forest system including temporal variability in LAI, foliage biomass loss, and total, stem, and root biomass assimilation (Fig. 9). This shows that remote-sensed data products can be successfully used to constrain parameters for the simulation of mixed forest systems in SWAT-3PG.

3.3. SWAT-3PG model sensitivity for forest simulation

Sensitivity of the SWAT-3PG model to forest biomass simulation due to changes in rainfall, nitrate, forest initialization, and self-thinning/age mortality is presented in Fig. 10. Model scenario runs with rainfall showed that SWAT-3PG is sensitive to changes in rainfall. A reduction in daily rainfall by 30% led to a reduction in total biomass assimilation by an average of 8% when compared to baseline. The reduction in biomass assimilation at the end of the simulation period was close to 12 Mg/ha

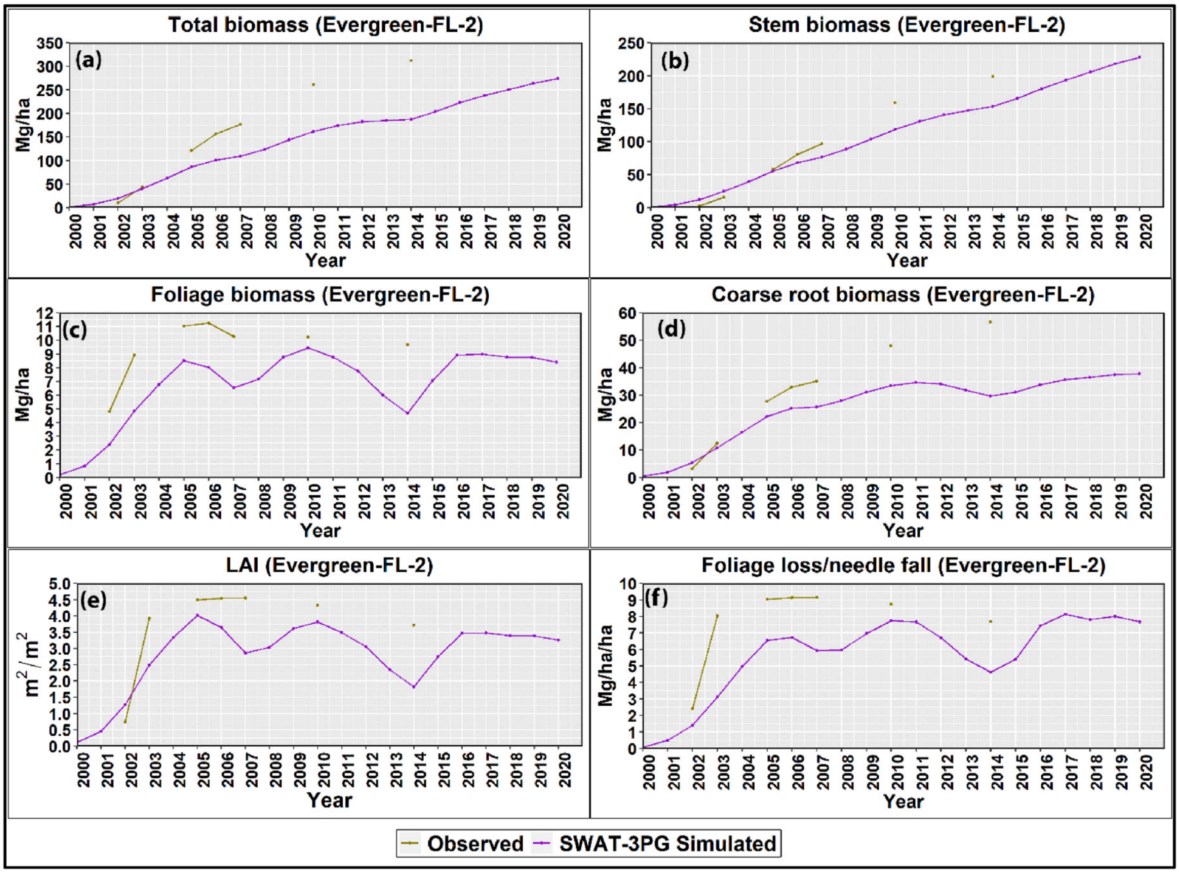

Fig. 5. SWAT-3PG simulation of evergreen forest at Evergreen-FL-2 site for validation.

(4%) (Fig. 10a). Evaluation of the whole simulation period showed that the reduction in biomass assimilation in the middle years from 1999 to 2006, when the forest is juvenile and actively assimilating biomass, was much higher (~13%). Increasing daily rainfall by 30% showed only a slight increase in annual biomass assimilation with an average of 2%. The maximum increase in biomass assimilation was, again, observed in the middle years (~5%) but the difference at the end of the simulation period was only 2% (4.84 Mg/ha) (Fig. 10a).

Scenario runs involving changes to nitrogen availability demonstrated the model's sensitivity to change in nutrient levels. A slight increase in assimilated forest biomass was observed when doubling the atmospheric deposition of nitrate (Fig. 10b). Application of nitrate as fertilizer each year (200 kg/ha), however, led to substantial increase in forest biomass assimilation. The increase in biomass at the end of the simulation period was close to 12% (35 Mg/ha) but the increase was much higher in the middle years at close to 18%. (40 Mg/ha).

A scenario run with already growing forest of 10 years and initial biomass of 130 Mg/ha showed that the model stabilizes the forest biomass assimilation much faster than when initializing the model at planting due to earlier self-thinning (Fig. 10c). This shows that the SWAT-3PG model can vary forest biomass assimilation based on the initialized age and biomass. The importance of incorporating mortality due to age as well as self-thinning for realistic assimilation of biomass, especially when the forest reaches towards maturity, can be visualized with the model scenario run that turned-off mortality due to age as well as self-thinning (Fig. 10d). Turning off mortality due to age alone had minimal change in forest biomass assimilation, which could be potentially attributed to the model run of only 34 years. Turning off mortality due to self-thinning, however, led to a somewhat linear increase in biomass till the end of the simulation period which can be considered unrealistic (Fig. 10d). The reduction/stabilization in biomass assimilation after 2006 is due to self-thinning sub-routine in the SWAT-3PG model which reduces the number of trees/ha based on a −3/2 power rule when the average stem biomass becomes higher than a user-defined threshold. This also shows the importance of making sure to activate the self-thinning sub-routine when simulating forest biomass with SWAT-3PG.

4. Discussion

4.1. SWAT-3PG for forest simulation

SWAT-3PG improves on the default SWAT forest module by incorporating important processes for forest simulation that were missing in the default module. SWAT-3PG partitions assimilated biomass into stem, root, and foliage based on growth conditions and age, which with the default model was partitioned only into above ground and root biomass. LAI, as a result in SWAT-3PG, is a function of assimilated foliage biomass which was calculated only based on accumulated heat units with the default model. Evaluation of SWAT simulated biomass and LAI with the default forestry module and default parameters in the Evergreen-FL-1 site (Fig. S1) shows that the model simulated the LAI well but poorly simulated total biomass which could potentially be attributed to the lack of check and balance between biomass assimilation and LAI simulation with the default model. Calibration of the default SWAT model parameters for forest simulation could better match the observed total biomass in the Evergreen-FL-1 site, but model would not be well constrained as it does not simulate and provide output for variables such as foliage biomass, stem biomass, tree mortality.

Evaluation of SWAT-3PG at the evergreen, deciduous, and mixed forest sites shows that the new forestry module can accurately simulate the different forest biomass components by incorporating important

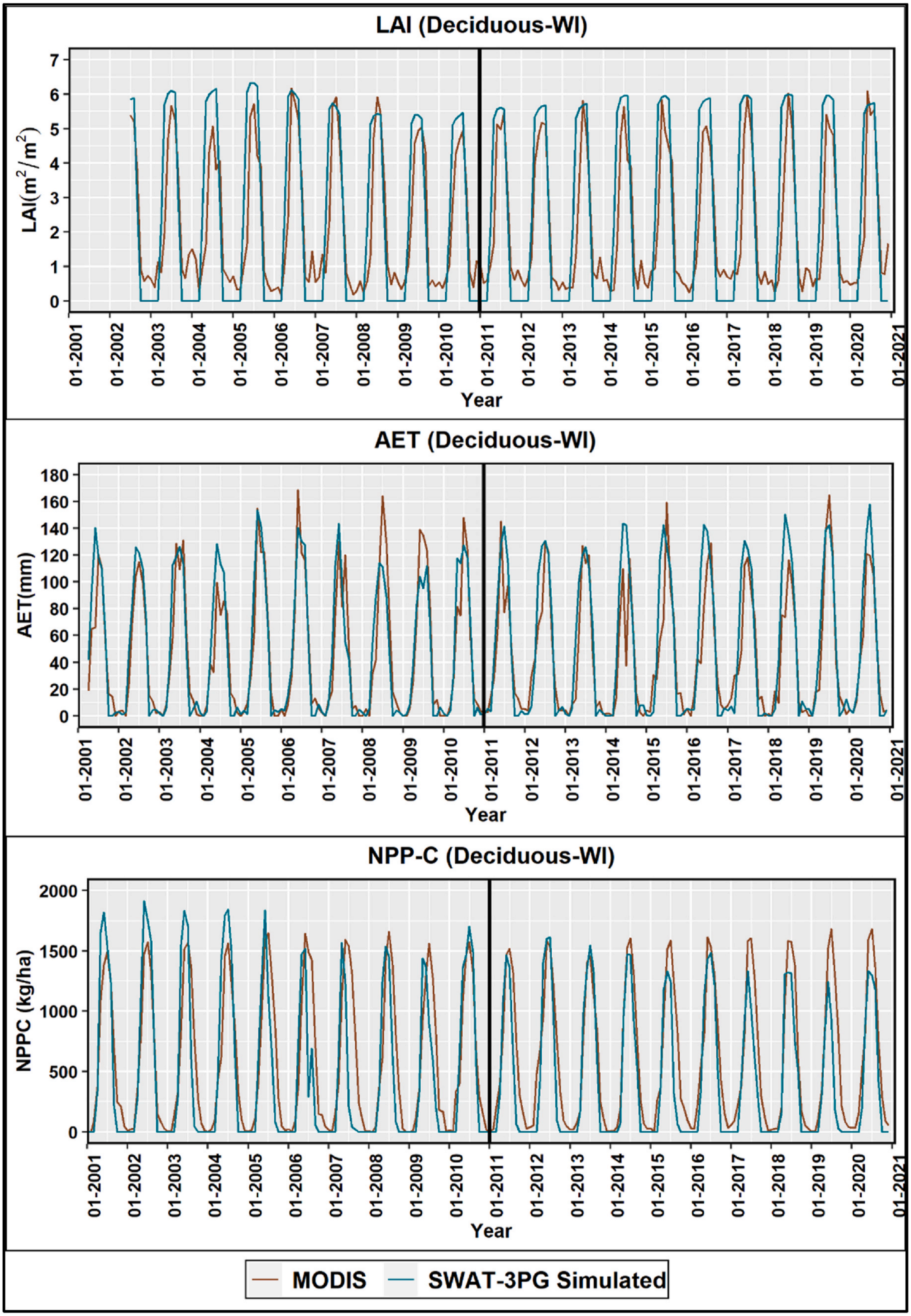

Fig. 6. Evaluation of SWAT-3PG simulation of Deciduous forests (NPP, LAI, and AET). The black vertical line divides the plot between the calibration (2001–2010) and validation (2011–2020) periods.

Table 4
Model performance evaluation for simulation of AET, LAI, and NPP-C for deciduous forest at Deciduous-WI site.

Variable	Calibration (2001–2010)			Validation (2011–2020)		
	R^2	NSE	PBIAS	R^2	NSE	PBIAS
AET	0.85	0.83	4.1	0.82	0.70	16.3
LAI	0.76	0.56	7.0	0.76	0.53	10.2
NPP-C	0.70	0.60	−14.6	0.82	0.75	−26.9

processes that were missing in the default SWAT. It is important to note that the default SWAT module only tracks AGB and does not partition AGB to stem and foliage biomass. Similarly, the default SWAT model also does not report root biomass. SWAT-3PG also improves litterfall simulation with realistic representation of litterfall from evergreen forests when compared to the default module (Fig. S1b) and also shows temporal variability in LAI simulation which was not captured by the default module (Fig. S1b). SWAT-3PG also simulates tree mortality due to age (density independent) and self-thinning (density dependent) for all forest types which is a more realistic way of constraining biomass than the default SWAT forestry module which uses a user-defined maximum biomass along with the current age of tree and tree age to maturity to limit maximum biomass growth for each year of the simulation period. This will contribute to a more realistic approach of biomass stabilization in mature tree forests as well as help in improving the simulation of SOC along with lateral carbon and nutrient fluxes to the inland aquatic environment from forest ecosystems. As SWAT-3PG was able to show good variability in the temporal simulation of LAI, the model should also benefit with improved simulation of hydrology due to improvement in AET simulation. Comparison against field observations as well as MODIS NPP-C shows that the forest module can replicate observed biomass assimilation from forest systems. And, as the forest module was able to simulate realistic stabilization in biomass assimilation at maturity, even with different forest initialization, SWAT-3PG can be an important tool for answering carbon sequestration and storage questions from forest systems. The sensitivity of SWAT-3PG forest growth to climate, nutrient, and forest initialization also demonstrates its value in evaluating the impacts of climate and management scenarios in forest systems. As SWAT-3PG provides additional outputs such as stock density, DBH, height, basal area, stem biomass etc. which were not available with the default model, SWAT-3PG can be a tool for forest management evaluation even for commercial purposes. With improved simulation of forest ecosystems, SWAT-3PG can be helpful in reducing hydrologic and water quality simulation uncertainties from forested regions which can be important in accurately understanding the physical and chemical processes along with the impacts of multiple scenarios in agriculture dominated watersheds.

Evaluation of different forest age and biomass initialization shows that biomass assimilation is sensitive to forest initialization. Hence, it is important to utilize available resources such as Williams et al. (2020) and make sure that forest age and biomass is initialized accurately when using SWAT-3PG. An advantage of SWAT-3PG is that forest parameterization already performed in many 3-PG studies can be leveraged as initial parameters into SWAT-3PG by evaluating for the dominant forest species in the watershed of interest. With accurate forest initialization of age, biomass, and tree species along with the use of existing 3-PG studies

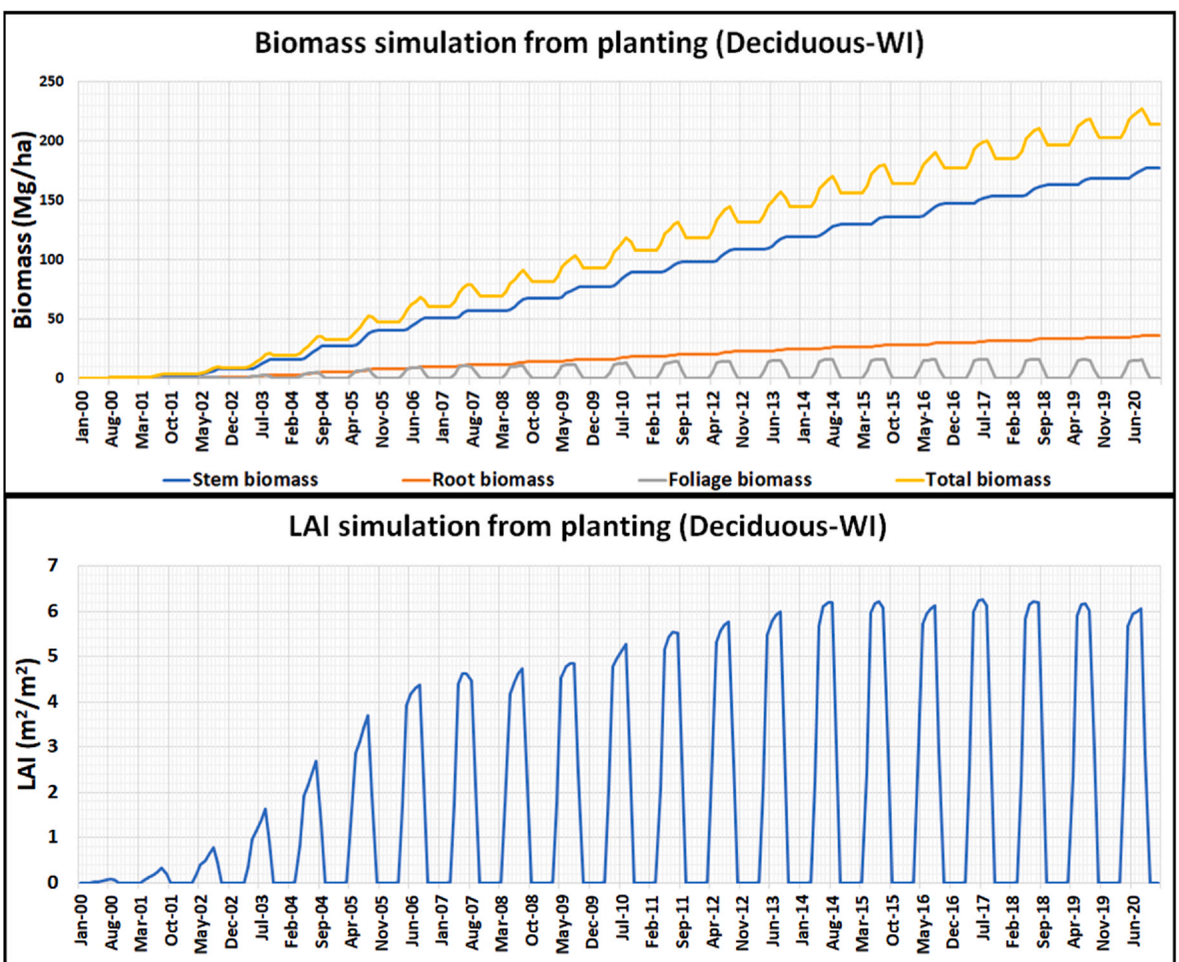

Fig. 7. SWAT-3PG simulation of Deciduous forests from planting with calibrated parameters.

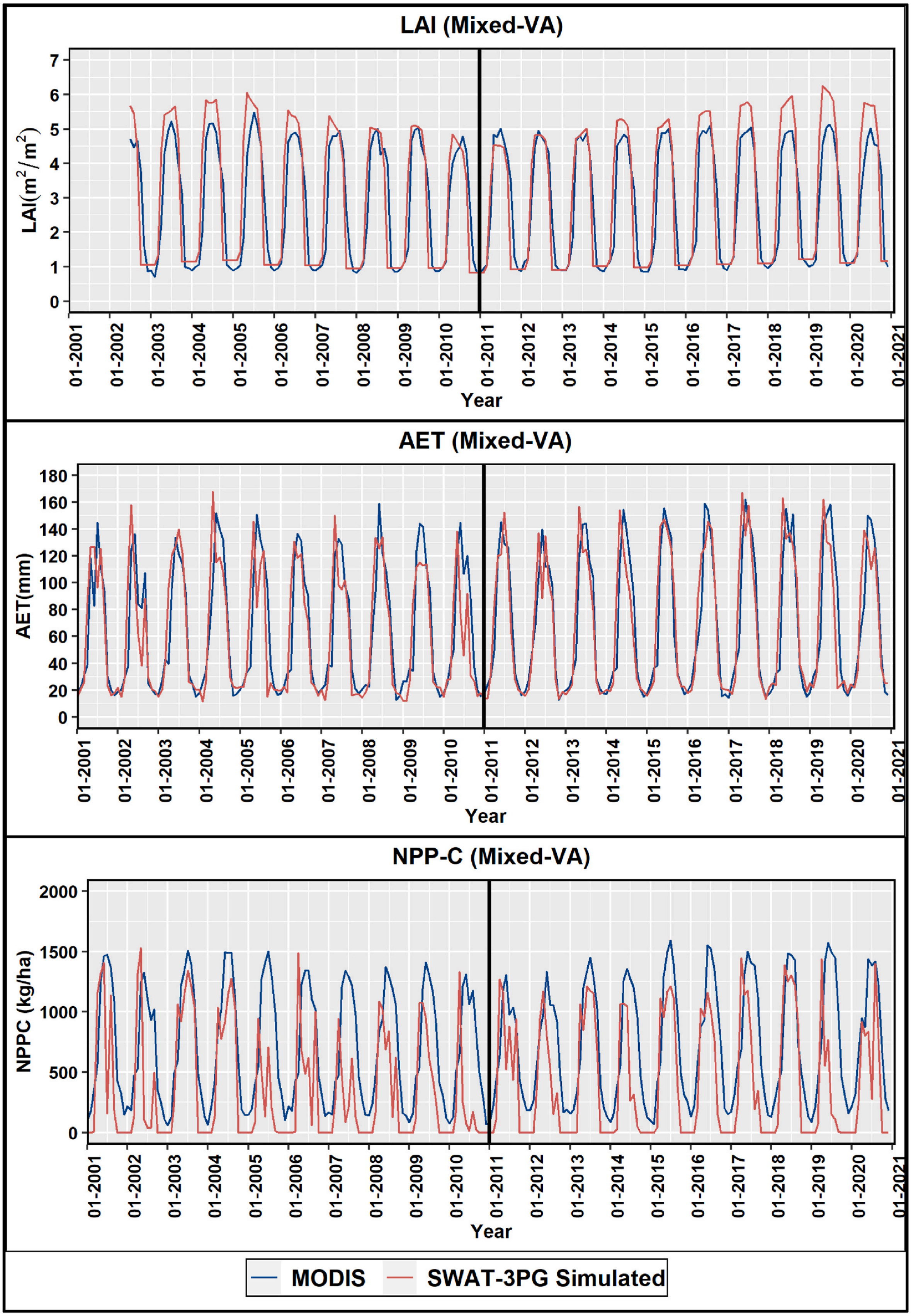

Fig. 8. Evaluation of SWAT-3PG simulation of Mixed forests (NPP, LAI, and AET). The black vertical line divides the plot between the calibration (2001–2010) and validation (2011–2020) periods.

Table 5
Model performance evaluation for simulation of AET, LAI, and NPP-C for a mixed forest at Mixed-VA site.

Variable	Calibration (2001–2010)			Validation (2011–2020)		
	R^2	NSE	PBIAS	R^2	NSE	PBIAS
AET	0.70	0.68	−4.1	0.81	0.80	0.4
LAI	0.74	0.64	6.4	0.80	0.70	6.4
NPP-C	0.35	−0.27	−48.4	0.53	0.08	−41.0

for initial parameterization and leveraging remote sensed data products such as MODIS for calibration, SWAT-3PG can be an important tool for estimating current and near-future carbon stock in forested systems at a regional/watershed-scale which can be valuable information to planners and policymakers for climate mitigation.

4.2. SWAT-3PG limitations and future development

Although SWAT-3PG improved on the simulation of forest ecosystems and provided important additional model outputs when compared to the default forest module in SWAT, there are important limitations that should be considered when using the enhanced model. As evident from the simulation results of mixed forest sites, it needs to be understood that SWAT-3PG simulates mixed forest systems using a single plant type due to the limitations in the SWAT HRU approach for model simulation. In addition, it is important to note that SWAT-3PG cannot simulate forest succession. As such, care should be taken when using the SWAT-3PG for multi-century model runs as NPP-C assimilation in SWAT-3PG decreases when forest reaches maturity when in reality a forest succession due to natural/anthropogenic events is more likely. Although SWAT-3PG improves on the litterfall simulation of the default model, foliage loss at the onset of dormancy for deciduous and mixed forest systems is simulated on a single day while it happens gradually and could last for multiple weeks in reality. It was also observed that SWAT-3PG simulation of root biomass can be improved as it was not able to accurately represent the observed temporal variability in root biomass. An important consideration when using SWAT-3PG is the initialization of forest age and biomass. As SWAT-3PG requires initialization of forest age and biomass, care should be taken when initializing forests, especially in watersheds with mature forests. As evident from the SWAT-3PG sensitivity runs, biomass assimilation is sensitive to forest age and biomass and it is important to get accurate forest age estimates when initializing the model without which it could be difficult to replicate the estimated biomass and NPP-C using remote-sensed data products.

Incorporating forest succession into the SWAT-3PG model would be beneficial for using the model for multi-century model runs and evaluating long-term climate impacts. Similarly, improving the litterfall routine for deciduous forests could be helpful in evaluating the model in a finer-temporal scale. A new mixed-forest subroutine that allows for multiple forest species to grow with competition between the species can be important to improve SWAT-3PG simulation in mixed forest systems. As SWAT-3PG provides model outputs that are also beneficial for forest managers, incorporating forest management practices into the model that are used by forest managers can be beneficial in expanding the model usability to other sectors. An important advantage of SWAT-3PG

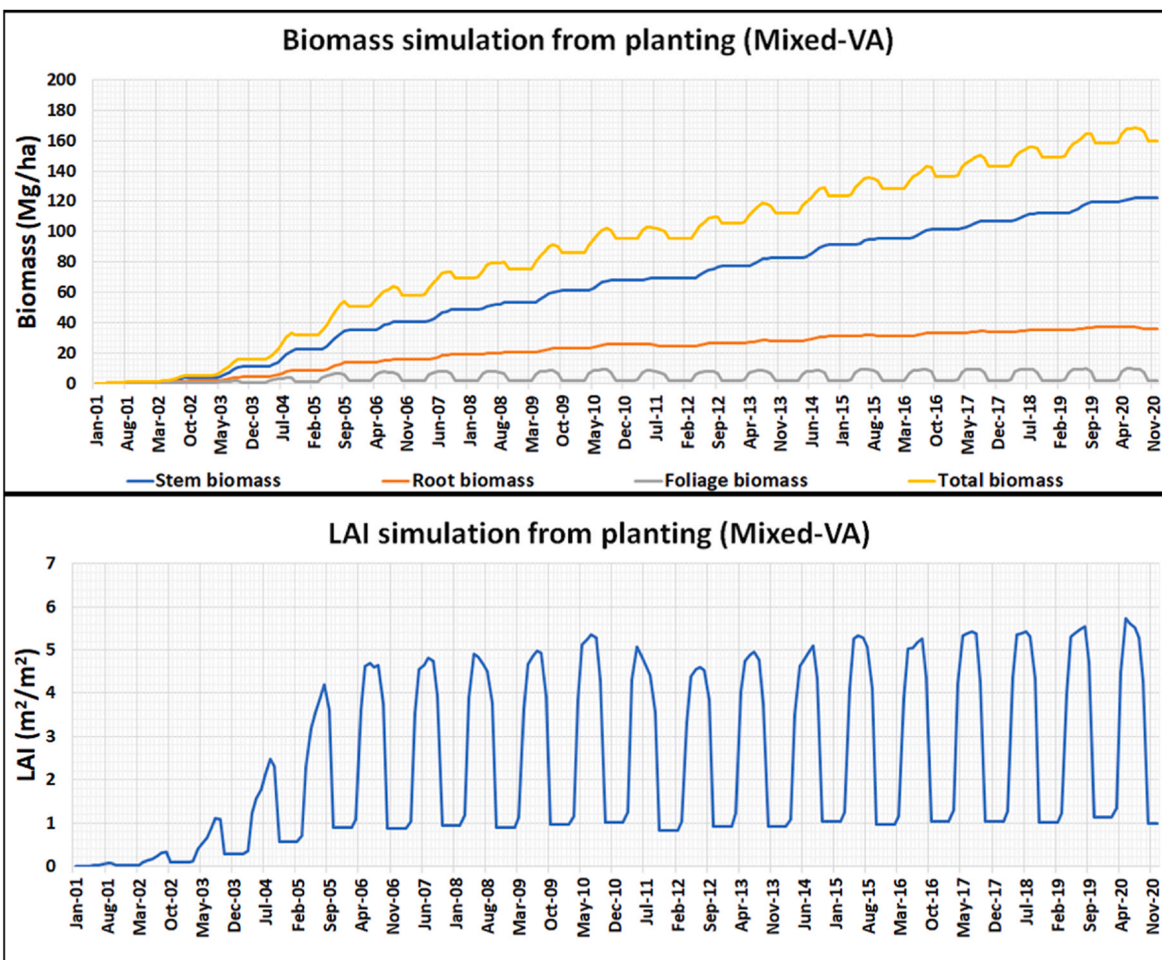

Fig. 9. SWAT-3PG simulation of Mixed forests from planting with calibrated parameters.

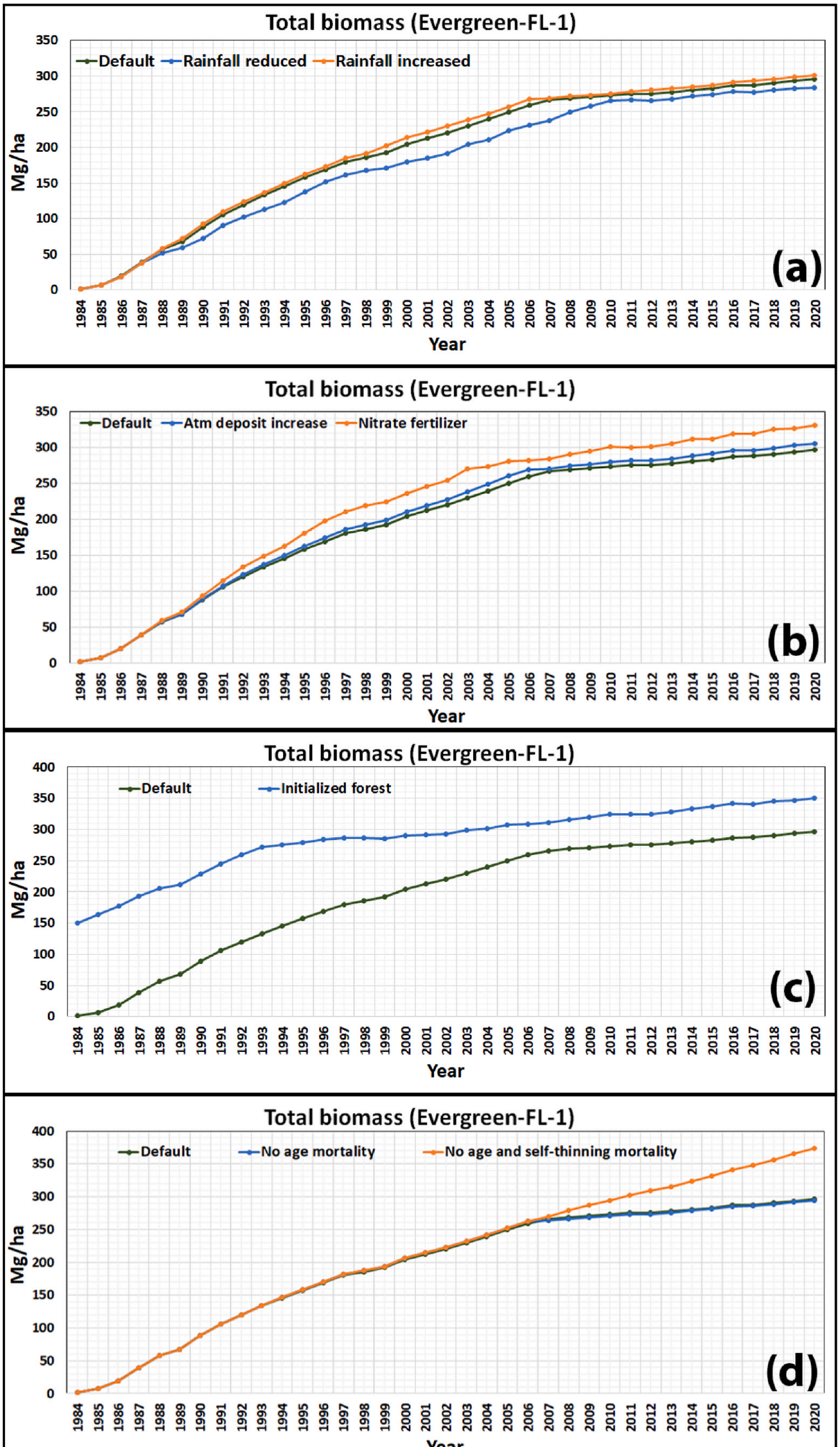

Fig. 10. SWAT-3PG simulation of biomass under (a) different rainfall (b) nitrogen application (c) forest initialization, and (d) activation and de-activation of age and self-thinning mortality at Evergreen-FL-1.

is that the new innovations in the 3-PG model can be easily incorporated into the model. As a result, any advancement in 3-PG will also be beneficial in improving SWAT-3PG. It will be important to evaluate the SWAT-3PG's performance for forest simulation over a large spatial domain with multiple forest species, climate, and soil to improve confidence in the new forest module which will be critical for using the tool in policy decision-making. The impact of improved SWAT-3PG forest simulation on hydrology and water quality including carbon over a large spatial domain also needs to be evaluated. With the advancement in the data types and spatial resolution of remote sensed datasets, modification to SWAT-3PG to incorporate remote sensed datasets directly into the model for leveraging these datasets can be an important next step in improving model simulation.

5. Conclusions

This study developed and tested a new forest module for the SWAT model that is based on 3-PG (SWAT-3PG) and improves on the default forest module with improved biomass assimilation, partitioning, and losses for evergreen, deciduous, and mixed forest systems. The new forest module partitions assimilated biomass into stem, foliage, and root biomass and also simulates tree mortality due to age as well as self-thinning which was not possible with the default module. LAI in the new forest module is related to foliage biomass rather than heat units as simulated in the default module, which allows for improved temporal variability in biomass assimilation. Modification to the litterfall routine with separate litterfall for evergreen, deciduous, and mixed forest systems allows for improved litterfall simulation from forest ecosystems.

Evaluation at site-scale for evergreen forest using field-measured data showed that the new forest module can adequately simulate stem, foliage, and coarse root biomass along with LAI, and foliage loss. Deciduous and mixed-forest sites were calibrated against remote-sensed LAI, NPP-C, and AET datasets due to the lack of field data for the two forest types. Evaluation of the new forest module for deciduous and mixed forest sites shows that the new forest module could adequately replicate LAI, NPP-C, and AET at deciduous forest site but the new module had slight difficulty in replicating NPP-C at mixed forest site. The difficulty in accurately simulating NPP-C at mixed forest site could potentially be attributed to SWAT's inability to simulate multiple plant types in a single HRU but improvement in NPP-C simulation should be achieved with improved initial parameterization for simulation of mixed forest sites. Assessment of model simulated stem, foliage, and root biomass as well as LAI with calibrated SWAT-3PG parameters constrained using remote-sensed products shows that the remote-sensed products could be a valuable asset for constraining parameters for forest simulation with SWAT-3PG over a large spatial domain when field measured datasets are not available. This, along with the ability to initialize already existing forests in SWAT-3PG, should allow the new model for improved estimation of carbon stock in forested ecosystems over regional domain. As SWAT-3PG also estimates variables such as DBH, height and stand basal area, the new model can also be of importance to forest managers and growers. Model sensitivity analysis of SWAT-3PG showed that the model can also be a useful tool for evaluating climate and management impacts in forested ecosystems as well as at a watershed-scale with reduced uncertainty when compared to the default model.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2023.105705.

References

Aber, J.D., Federer, C.A., 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. Oecologia 92 (4), 463–474.

Adams, P.W., Flint, A.L., Fredriksen, R.L., 1991. Long-term patterns in soil moisture and revegetation after a clearcut of a Douglas-fir forest in Oregon. For. Ecol. Manag. 41 (3–4), 249–263.

Alemayehu, T., Van Griensven, A., Woldegiorgis, B.T., Bauwens, W., 2017. An improved SWAT vegetation growth module and its evaluation for four tropical ecosystems. Hydrol. Earth Syst. Sci. 21 (9), 4449–4467.

Amichev, B.Y., Bentham, M.J., Kurz, W.A., Laroque, C.P., Kulshreshtha, S., Piwowar, J. M., Van Rees, K.C.J., 2016. Carbon sequestration by white spruce shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 model simulations. Ecol. Model. 325, 35–46.

Amichev, B.Y., Johnston, M., Van Rees, K.C.J., 2010. Hybrid poplar growth in bioenergy production systems: biomass prediction with a simple process-based model (3PG). Biomass Bioenergy 34 (5), 687–702.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., Teskey, R., 2013. Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. For. Ecol. Manag. 289, 501–514.

Butman, D., Stackpoole, S., Stets, E., McDonald, C.P., Clow, D.W., Striegl, R.G., 2016. Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting. Proc. Natl. Acad. Sci. USA 113 (1), 58–63.

Curtis, P.S., Gough, C.M., 2018. Forest aging, disturbance and the carbon cycle. New Phytol. 219 (4), 1188–1193.

Detwiler, R.P., Hall, C.A.S., 1988. Tropical forests and the global carbon cycle. Science 239 (4835), 42–47.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321 (5891), 926–929. https://doi.org/10.1126/science.1156401.

Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexier, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science 263 (5144), 185–190.

Douglas-Mankin, K.R., Maski, D., Janssen, K.A., Tuppad, P., Pierzynski, G.M., 2010. Modeling nutrient runoff yields from combined in-field crop management practices using SWAT. Transactions of the ASABE 53 (5), 1557–1568.

Dunkerley, D., 2015. Percolation through leaf litter: what happens during rainfall events of varying intensity? J. Hydrol. 525, 737–746.

Endale, D.M., Bosch, D.D., Potter, T.L., Strickland, T.C., 2014. Sediment loss and runoff from cropland in a southeast Atlantic coastal plain landscape. Transactions of the ASABE 57 (6), 1611–1626.

Fontes, L., Bontemps, J.-D., Bugmann, H., Van Oijen, M., Gracia, C., Kramer, K., et al., 2010. Models for supporting forest management in a changing environment. Forest Systems 19, 8–29.

Gao, X., Ouyang, W., Hao, Z., Xie, X., Lian, Z., Hao, X., Wang, X., 2019. SWAT-N2O coupler: an integration tool for soil N2O emission modeling. Environmental Modelling \& Software 115, 86–97.

Gay, D., 2020. National atmospheric deposition program (NADP) datasets - wye (choptank). National atmospheric deposition program. Retrieved from. https://data.nal.usda.gov/dataset/national-atmospheric-deposition-program-nadp-datasets-wye-choptank.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., Tyler, D., 2002. The national elevation dataset. Photogrammetric Engineering and Remote Sensing 68 (1), 5–32.

Gonzalez-Benecke, C.A., Jokela, E.J., Cropper Jr., W.P., Bracho, R., Leduc, D.J., 2014. Parameterization of the 3-PG model for Pinus elliottii stands using alternative methods to estimate fertility rating, biomass partitioning and canopy closure. Forest Ecology and Management 327, 55–75.

Gonzalez-Benecke, C.A., Teskey, R.O., Martin, T.A., Jokela, E.J., Fox, T.R., Kane, M.B., Noormets, A., 2016. Regional validation and improved parameterization of the 3-PG model for Pinus taeda stands. Forest Ecology and Management 361, 237–256.

Haas, H., Reaver, N.G.F., Karki, R., Kalin, L., Srivastava, P., Kaplan, D.A., Gonzalez-Benecke, C., 2022. Improving the representation of forests in hydrological models. Science of The Total Environment 812, 151425.
Haro-Monteagudo, D., Palazón, L., Beguer\'\ia, S., 2020. Long-term sustainability of large water resource systems under climate change: a cascade modeling approach. Journal of Hydrology 582, 124546.
Hart, P.B.S., Clinton, P.W., Allen, R.B., Nordmeyer, A.H., Evans, G., 2003. Biomass and macro-nutrients (above-and below-ground) in a New Zealand beech (Nothofagus) forest ecosystem: implications for carbon storage and sustainable forest management. Forest Ecology and Management 174 (1–3), 281–294.
HAWQS, 2020. HAWQS System and Data to model the lower 48 conterminous U.S using the SWAT model. https://doi.org/10.18738/T8/XN3TE0. Texas Data Repository Dataverse, V1.
HN Palma, J., Hakamada, R., Moreira, G.G., Nobre, S., Rodriguez, L.C.E., 2021. Using 3PG to assess climate change impacts on management plan optimization of Eucalyptus plantations. A case study in Southern Brazil. Scientific Reports 11 (1), 1–8.
Hurtt, G., Zhao, M., Sahajpal, R., Armstrong, A., Birdsey, R., Campbell, E., 2019. Beyond MRV: high-resolution forest carbon modeling for climate mitigation planning over Maryland, USA. others Environmental Research Letters 14 (4), 45013.
Jin, S., Yang, L., Danielson, P., Homer, C., Fry, J., Xian, G., 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. Remote Sensing of Environment 132, 159–175.
Jones, J.A., Post, D.A., 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. Water Resources Research 40 (5).
Justice, C.O., Townshend, J.R.G., Vermote, E.F., Masuoka, E., Wolfe, R.E., Saleous, N., et al., 2002. An overview of MODIS Land data processing and product status. Remote Sensing of Environment 83 (1–2), 3–15.
Karki, R., Srivastava, P., Veith, T.L., 2020. Application of the Soil and Water Assessment Tool (SWAT) at field scale: categorizing methods and review of applications. Transactions of the ASABE 63 (2), 513–522.
Karki, R., Tagert, M.L.M., Paz, J.O., 2018. Evaluating the nutrient reduction and water supply benefits of an on-farm water storage (OFWS) system in East Mississippi. Agriculture, Ecosystems & Environment 265, 476–487.
Kreutzweiser, D.P., Hazlett, P.W., Gunn, J.M., 2008. Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: a review. Environmental Reviews 16 (NA), 157–179.
Lai, G., Luo, J., Li, Q., Qiu, L., Pan, R., Zeng, X., et al., 2020. Modification and validation of the SWAT model based on multi-plant growth mode, a case study of the Meijiang River Basin, China. Journal of Hydrology 585, 124778.
Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95 (3), 209–228.
Lathuillière, M.J., Johnson, M.S., Donner, S.D., 2012. Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil. Environmental Research Letters 7 (2), 24024.
Lee, J., Jung, C., Kim, S., Kim, S., 2019. Assessment of climate change impact on future groundwater-level behavior using SWAT groundwater-consumption function in Geum River Basin of South Korea. Water 11 (5), 949.
Lee, M.-H., Park, J.-H., Matzner, E., 2018. Sustained production of dissolved organic carbon and nitrogen in forest floors during continuous leaching. Geoderma 310, 163–169.
Ma, T., Duan, Z., Li, R., Song, X., 2019. Enhancing SWAT with remotely sensed LAI for improved modelling of ecohydrological process in subtropics. Journal of Hydrology 570, 802–815.
Martin, C.W., Hornbeck, J.W., Likens, G.E., Buso, D.C., 2000. Impacts of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Canadian Journal of Fisheries and Aquatic Sciences 57 (S2), 19–29.
Molina-Navarro, E., Hallack-Alegr\'\ia, M., Mart\'\inez-Pérez, S., Ram\'\irez-Hernández, J., Mungaray-Moctezuma, A., Sastre-Merl\'\in, A., 2016. Hydrological modeling and climate change impacts in an agricultural semiarid region. Case study: Guadalupe River basin, Mexico. Agricultural Water Management 175, 29–42.
Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Transactions of the ASABE 58 (6), 1763–1785.
Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009.
Nguyen, T.V., Dietrich, J., Dang, T.D., Tran, D.A., Van Doan, B., Sarrazin, F.J., et al., 2022. An interactive graphical interface tool for parameter calibration, sensitivity analysis, uncertainty analysis, and visualization for the Soil and Water Assessment Tool. Environmental Modelling \& Software 156, 105497.
Perry, T.D., Jones, J.A., 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. Ecohydrology 10 (2), e1790.
Poorter, H., Niklas, K.J., Reich, P.B., Oleksyn, J., Poot, P., Mommer, L., 2012. Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. New Phytologist 193 (1), 30–50.
Prepas, E.E., Pinel-Alloul, B., Planas, D., Méthot, G., Paquet, S., Reedyk, S., 2001. Forest harvest impacts on water quality and aquatic biota on the Boreal Plain: introduction to the TROLS lake program. Canadian Journal of Fisheries and Aquatic Sciences 58 (2), 421–436.
Running, S.W., Mu, Q., Zhao, M., Moreno, A., 2017. MODIS Global Terrestrial Evapotranspiration (ET) Product (NASA MOD16A2/A3) NASA Earth Observing System MODIS Land Algorithm. NASA, Washington, DC, USA.
Samimi, M., Mirchi, A., Moriasi, D., Ahn, S., Alian, S., Taghvaeian, S., Sheng, Z., 2020. Modeling arid/semi-arid irrigated agricultural watersheds with SWAT: applications, challenges, and solution strategies. Journal of Hydrology 590, 125418.
Sands, P., 2010. 3PG PJS User Manual. Retrieved in April, 16, 2021.
Santoro, M., Cartus, O., Carvalhais, N., Rozendaal, D., Avitabile, V., Araza, A., 2021. The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations. others Earth System Science Data 13 (8), 3927–3950.
Strauch, M., Volk, M., 2013. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. Ecological Modelling 269, 98–112.
Subedi, S., Fox, T.R., Wynne, R.H., 2015. Determination of fertility rating (FR) in the 3-PG model for loblolly pine plantations in the southeastern United States based on site index. Forests 6 (9), 3002–3027.
Tan, M.L., Gassman, P.W., Srinivasan, R., Arnold, J.G., Yang, X., 2019. A review of swat studies in southeast asia: applications, challenges and future directions. Water 11 (5), 914.
Tan, M.L., Gassman, P.W., Yang, X., Haywood, J., 2020. A review of SWAT applications, performance and future needs for simulation of hydro-climatic extremes. Advances in Water Resources 143, 103662.
Teuling, A.J., De Badts, E.A.G., Jansen, F.A., Fuchs, R., Buitink, J., van Dijke, A.J., Sterling, S.M., 2019. Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe. Hydrology and Earth System Sciences 23 (9), 3631–3652.
Thornton, P.E., Running, S.W., 2000. User's Guide for BIOME-BGC, Version 4.1. 1. University of Montana. Numerical Terradynamic Simulation Group, School of Forestry, Missoula, MT.
Tirabadi, M.S.M., Banihabib, M.E., Randhir, T.O., 2021. SWAT-S: a SWAT-salinity module for watershed-scale modeling of natural salinity. Environmental Modelling \& Software 135, 104906.
Upadhyay, P., Linhoss, A., Kelble, C., Ashby, S., Murphy, N., Parajuli, P.B., 2022. Applications of the SWAT model for coastal watersheds: review and recommendations. Journal of the ASABE 65 (2), 453–469.
USDA-NRCS, 2019. Soil Survey Geographic (SSURGO) Database. Retrieved from. https://websoilsurvey.nrcs.usda.gov/.
US EPA, 2019. BASINS 4.5 (Better Assessment Science Integrating point & Non-point Sources) Modeling Framework. National Exposure Research Laboratory, RTP, North Carolina. BASINS Core Manual.
Wang, Q., Qi, J., Li, J., Cole, J., Waldhoff, S.T., Zhang, X., 2020a. Nitrate loading projection is sensitive to freeze-thaw cycle representation. Water research 186, 116355.
Wang, Q., Qi, J., Wu, H., Zeng, Y., Shui, W., Zeng, J., Zhang, X., 2020b. Freeze-Thaw cycle representation alters response of watershed hydrology to future climate change. Catena 195, 104767.
White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and sensitivity analysis of the BIOME–BGC terrestrial ecosystem model: net primary production controls. Earth Interactions 4 (3), 1–85.
Williams, C.A., Hasler, N., Gu, H., Zhou, Y., 2020. Forest Carbon Stocks and Fluxes from the NFCMS, Conterminous USA, 1990-2010. ORNL DAAC, Oak Ridge, Tennessee, USA.
Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Transactions of the ASAE 32 (2), 497–511.
Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., 2012. Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. others Journal of Geophysical Research: Atmospheres 117 (D3).
Xie, X., Li, A., Tan, J., Jin, H., Nan, X., Zhang, Z., et al., 2020. Assessments of gross primary productivity estimations with satellite data-driven models using eddy covariance observation sites over the northern hemisphere. Agricultural and Forest Meteorology 280, 107771.
Yang, Q., Zhang, X., 2016. Improving SWAT for simulating water and carbon fluxes of forest ecosystems. Science of the Total Environment 569, 1478–1488.
Zhang, D., Li, R., Batchelor, W.D., Ju, H., Li, Y., 2018. Evaluation of limited irrigation strategies to improve water use efficiency and wheat yield in the North China Plain. PLOS ONE 13 (1), e0189989. https://doi.org/10.1371/journal.pone.0189989.
Zhang, X., 2018. Simulating eroded soil organic carbon with the SWAT-C model. Environmental Modelling \& Software 102, 39–48.
Zhao, M., Running, S.W., Nemani, R.R., 2006. Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. Journal of Geophysical Research: Biogeosciences 111 (G1).