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Advances in Application of a Process-Based Crop Model to Wetland Plants and Ecosystems

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Abstract

For decades crop models have been proven to help agronomists simulate plant growth interactions in the environment, for instance with soil, water, and nutrients. Now scientists are turning their attention to agronomic interactions with ecosystems, specifically wetlands. Wetlands are an integral part of the landscape both as a habitat, and as a buffer between agricultural areas and large watersheds. Process-based simulation models such as APEX, and ALMANAC are used for crops, but have now been applied to wetlands. These models simulate vegetation growth, plant competition, nutrient cycling, erosion, and hydrology. Recent research has allowed wetland plant growth to be simulated, and more complex modeling of the landscape has begun. Here we summarize advances in wetland plant simulation using crop modeling and application of these process-based crop models to wetland plants and ecosystems.

Keywords Wetland plants · ALMANAC · APEX · Ecosystem modeling

Introduction

Wetlands are a key ecological component within the landscape; they are an ecosystem unto themselves and play a vital role between uplands and major water resources. Scientists are trying to assess the impacts agriculture is having on wetlands, specifically contamination of water leading to streams and aquifers(USDA NRCS 2018). The conservation effects assessment project (CEAP) aims to determine the most effective agricultural conservation practices to use. The project has four impacts it will deliver: research gaps in conservation and agroecology, inform the conservation programs, disseminate knowledge to policymakers and citizens, and improve decision support tools(Smith et al. 2015). CEAP measures field data and executes modeling simulations to assess agricultural conservation practice effects on the landscape(Johnson et al. 2015). The wetlands component of CEAP began with field research in several US regions including: Prairie Potholes, High Plains, Mid-Atlantic Rolling Plain, and California's Central Valley (Smith et al. 2015). This data was crucial in forming parameters that were then used in model simulations.

Researchers in Temple, Texas have been developing process-based simulation models since 1965, resulting in four models that are still supported today: EPIC, ALMANAC, APEX, and SWAT(Williams et al. 2008). EPIC was created as a daily time-step model with readily available inputs to simulate weather, hydrology, erosion, plant growth, nutrient cycling, and management operations and has since expanded to include pesticide fate, carbon cycling, and numerous refinements(Williams et al. 2008). ALMANAC, APEX, and SWAT all have components of EPIC at their core but have diverged to have different focuses and spatial scales ranging from field, small watershed, to river basin respectively(Williams et al. 2008).

Crop models have been widely developed, tested, and modified to improve their simulation of ecological processes. Improvements in the Temple models for wetland simulation have involved wetland nutrient processes and hydrology(Krysanova and Arnold 2009; Sharifi et al. 2019). Wetlands have been simulated in the past using a multi-model approach that involved EPIC, APEX, and/or SWAT combined with each other or other models, such as SWIM or IMWEB, but those studies focused on water dynamics and nutrient flow and had generic 'wetland' for plants simulated(Bouraoui and Grizzetti 2008; Hattermann et al. 2006; Liu et al. 2018). One EPIC multi-model study did create

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more intense plant growth models with success but the wetland plants were simulated in WetSim 2.0, not EPIC, which is only applicable to the Prairie Pothole region(Poiani et al. 1996). Likewise one APEX multi-model study used REMM for wetland plant simulation instead of APEX and focused on water quality and quantity(Williams et al. 2013).

All good modeling is based on real world data. Our multi-model approach with CEAP has been successful. We begin with ALMANAC to simulate plant growth at a smaller scale comparing field data to simulated data, and developing new plant parameters when needed. Once validated, the parameters are transferred into APEX to simulate field interactions and hydrologic flow. Once validated, SWAT is employed to simulate entire watersheds. These models have been used internationally on every continent excluding Antarctica to study crops, management practices, nutrient cycling, and hydrology. Our approach is significant because these models stem from the same developers with codes and outputs readily transferable from one model to the other. Each model has been thoroughly tested and applied in numerous ecosystems. Using our model combinations, we can focus on different scales or different ecological processes to get a better understanding and more complete answers to our modeling questions. Three papers have collected wetland plant growth data from the CEAP regions mentioned above and from central Texas. This multi-year effort resulted in three simulation publications using ALMANAC and APEX. This paper aims to summarize the improvements in simulating wetland plant growth advancing the modeling of wetlands. These decision support tool improvements help inform CEAP by allowing for more complex modeling of wetland ecosystem interactions with croplands.

Temple Models Wetland Framework

The Temple models, each with their different focus, all have similarities when it comes to nutrient modeling. Wetland simulations here do not focus on benthic organisms, or entirely submerged aquatic vegetation, nor tidal effects and ocean modeling. Temple models began with plant growth and edge of field effects on watersheds. With these goals in mind, when simulating wetland plants, models need to quantify plant growth, nutrient uptake, and environmental nutrient cycles. As such, the Temple models contain plant growth regulated by light interception and environmental stresses (temperature, water availability, nutrient stresses, and aeration stress), plant nutrient uptake, N and P cycling along with water quality (sediment, organic N, NO3, NH4 and PO4), water table and water cycle dynamics.

Wetlands and wetland plants have many similarities with crop systems and crop models, however there are a few additional processes that should be addressed, such as standing water and hydrological flux, and plant adaptation to flooding. The water table is simulated separately from other root zone soil water processes to account for offsite effects changing the water table level between maximum and minimum depths. For details on this and other equations for processes mentioned here, see the EPIC and APEX model and theoretical documentation website https://epicapex.tamu.edu/manuals-and-publications/. Percolation, subsurface flow, and surface runoff are calculated, but flood routing depends on which model is used, APEX and SWAT have connecting fields, while ALMANAC and EPIC are single field models. Choices of available evapotranspiration equations are: Hargreaves and Samani(Hargreaves and Samani 1985), Penman(Penman 1948), Priestley-Taylor(Priestley and Taylor 1972), Penman-Monteith(Monteith 1965), and Baier-Robertson(Baier and Robertson 1965). Plant tolerance to flooding is described by a critical aeration stress factor. Aeration stress is modeled with the water content in the top meter of soil and has a factor for each species. Saturation (SAT) is calculated as:

$$\mathrm{SAT} = 100*((\mathrm{Soil\ water\ content{-}FC})/(\mathrm{Soil\ porosity{-}FC}) - \mathrm{CAF})/(1.0 - \mathrm{CAF}) \quad (1)$$

Where FC is the field capacity, and CAF is the zero to 1.0 critical aeration factor. The critical aeration factor is a plant parameter variable unique to each species. Aeration stress (AS) is calculated as:

$$\mathrm{AS} = 1.0 \quad \text{if SAT} \le 0.0 \quad (2a)$$

$$\mathrm{AS} = 1.0 - \mathrm{SAT}/\left(\mathrm{SAT} + e^{(2.901-0.0387*\mathrm{SAT})}\right) \quad \text{if SAT} > 0.0 \quad (2b)$$

The daily increase in plant biomass (root depth, height, leaf area, and mass) is limited by five possible stresses, water, temperature, nutrients (nitrogen and phosphorus), and aeration. The ALMANAC model includes a plant competition of resources component and is useful for detailed look at plant interactions at the field scale. The Temple models also calculate soil erosion from wind and water, manure runoff, and pesticide fate, all critical environmental elements CEAP wants to quantify and help mitigate.

Plant nutrient uptake is calculated by several equations. Soil supply of nitrogen is the amount of NO3-N in the top soil layer multiplied by the water use rate divided by the soil water content. The plant nitrogen uptake is calculated by the rate of nitrogen from the top soil layer multiplied by the plant nitrogen demand divided by the total soil profile supply of nitrogen. If demand is greater than supply the equation is rate of nitrogen from the top soil layer plus plant nitrogen demand minus total soil profile supply of nitrogen. This is calculated layer by layer until total soil nitrogen has been removed from the root zone. The daily nitrogen crop demand is determined by optimal nitrogen content in the crop minus actual crop nitrogen content. Optimal nitrogen content is determined as biomass multiplied by the three crop parameters of optimal nitrogen content throughout the season which is a function of

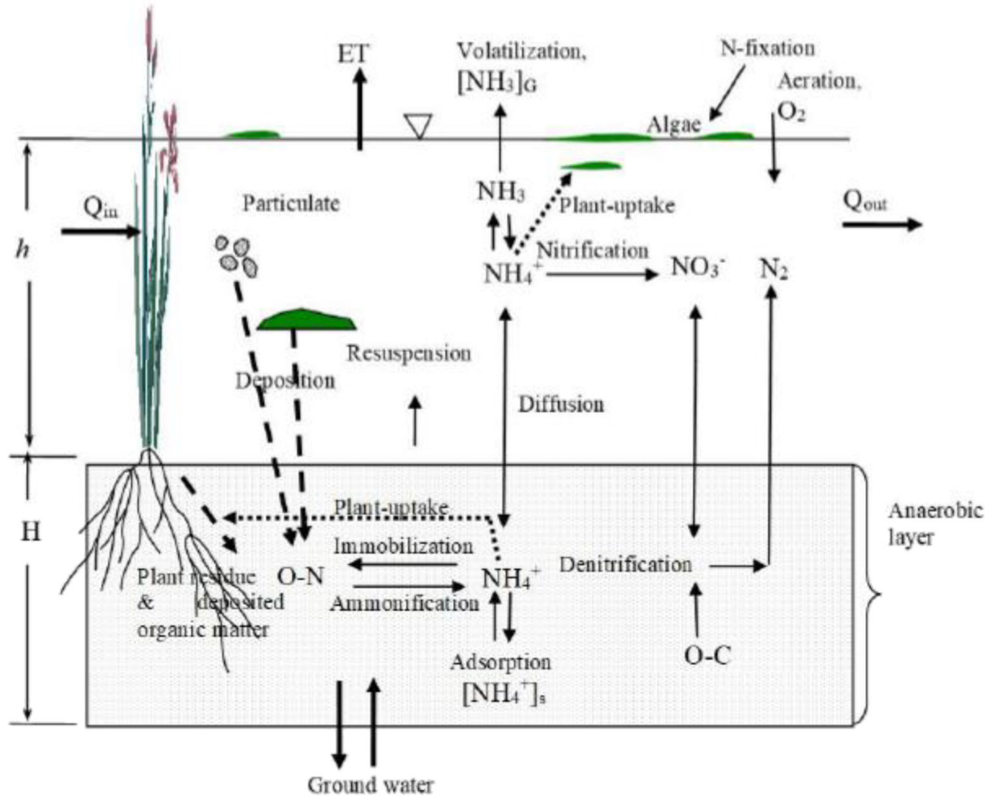

Fig. 1 Schematic diagram of nitrogen processes in wetlands: water column and soil layer. Adapted from Sharifi et al. (2019)

crop development and declines over time. The three crop parameters are optimal plant nitrogen content at early, mid, and late season intervals for the specific plant. For plants not already included in the model database these parameters are measured or gleaned from literature. Plant uptake of phosphorus is done in the same manner as that listed for nitrogen. To address wetland plant nutrient uptake these nutrient parameters were adjusted for each species based on field data.

Nitrogen and phosphorus cycling is originally based on the CENTURY model, putting organic N into three modules that have different turnover times size and function, but Temple models have different leaching, transformation rates, surface litter biogeochemistry, and lignin than in Century. New wetland biogeochemistry functions were added to APEX to address flooded wetland soils nutrient cycling in reservoirs. Concepts from WetQual were added to APEX, but APEX keeps the soil column anaerobic while WetQual puts a thin aerobic soil layer on top which had minimal impact on overall model results in APEX(Sharifi et al. 2019). The updated nitrogen transport mechanisms and loss pathways in sediment and free-water are described in Fig. 1 (Sharifi et al. 2019). The new APEX component for reservoirs just has two modules, the water column and the wetland soil layer(Sharifi et al. 2019). With these approaches of plant growth restrained by stresses, water balance, and biogeochemistry, wetland modeling can be performed at the field or landscape scale depending on research goals. For detailed field scale looking at wetland volume, sediment yields to the outflow, and nutrient content APEX can be used (Kim et al. 2020; Sharifi et al. 2019), for detailed look at plant growth and interactions ALMANAC can be used (Kim et al. 2018; Williams et al. 2020).

Materials and Methods

Wetland Plant Growth Measurements

Between the 4 supported models from Temple, Texas, ALMANAC is the more thorough choice for modeling plant growth due to its more complex plant growth algorithms. ALMANAC is used to determine new plant parameters that have not yet been included in the models. Once parameterized, these plant parameters are shared between models. A standardized protocol has been written to gather the appropriate measured field data (shown online at https://www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-waterresearch-laboratory/docs/193226#Information). This can be modified as needed for each experiment, but the general steps are consistent as summarized in Kiniry and Kim (2020). Measurements are taken on a clear sky day between 10 am and 2 pm to allow maximum solar angle. Photosynthetically active radiation (PAR) is measured using Accupar LP-80 Ceptometer

Table 1 Wetland plant species measured from 2013 to 2017 including wetland indicator status, functional group and location sampled. OBL is obligate wetland, FACW is facultative wetland, FAC is facultative, and FACU is facultative upland. All species were used to create functional groups indicated. [1]Indicates species was simulated. [2]Indicates multi-site species. Underlined were simulated at the site shown

Plant Species	Common Name	Wetland Indicator	Functional Group[a]	Location	Years Sampled
Ambrosia grayi	Bur ragweed	FAC	Forbs	Playas	2013–2014
Chenopodium leptophyllum	Narrowleaf goosefoot	FACU	Forbs	Playas	2013
[2]*Eleocharis macrostachya*	Spikerush	OBL	Rushes and Sedges	Playas	2013–2014
Malvella leprosa	Cheeseweed	FAC	Forbs	Playas	2013–2014
[1,2]*Polygonum* spp.	Smartweed	FACW/OBL	Forbs	Playas	2013–2014
Sagittaria longiloba	Arrowhead/Duck potato	OBL	Forbs	Central TX	2014–2015
Salix nigra	Black willow	FACW	–	Central TX	2014
[1,2]*Schoenoplectus acutus*	Hardstem bulrush	OBL	Rushes and Sedges	Central TX	2014
[1]*Phalaris arundinacea*	Reed canarygrass	FACW	Grasses	Potholes	2014–2017
[1,2]*Polygonum amphibium*	Water smartweed	OBL	Forbs	Potholes	2014
[1,2]*Schoenoplectus acutus*	Hardstem bulrush	OBL	Rushes and Sedges	Potholes	2014–2017
[1,2]*Typha angustifolia*	Narrowleaf cattail	OBL	Forbs	Potholes	2014–2017
Carex atherodes	Slough sedge	OBL	Rushes and Sedges	Potholes	2014–2017
[1]*Scolochloa festucacea*	Sprangletop	OBL	Grasses	Potholes	2014–2017
[1]*Cyperus pseudovegetus*	Marsh flatsedge	FACW	Rushes and Sedges	Delmarva	2014–2017
[1]*Juncus tenuis*	Poverty rush	FAC	Rushes and Sedges	Delmarva	2014–2017
[1,2]*Polygonum pensylvanicum*	Pink smartweed	FACW	Forbs	Delmarva	2014–2017
[1,2]*Typha latifolia*	Broadleaf cattail	OBL	Forbs	Delmarva	2014–2017
[1]*Crypsis schoenoides*	Swamp timothy	OBL	Grasses	California	2016–2017
[1]*Echinochloa crus-galli*	Watergrass	FAC	Grasses	California	2016–2017
[2]*Eleocharis* spp.	Spikerush	FACW/OBL	Rushes and Sedges	California	2017
[1]*Paspalum distichum*	Joint grass	FACW	Grasses	California	2016–2017
[1,2]*Persicaria lapathifolium*	Annual smartweed	FACW	Forbs	California	2016–2017
Polypogon monspeliensis	Rabbitsfoot	FACW	Grasses	California	2017
[1,2]*Scirpus maritimus*	Alkaline bulrush	OBL	Rushes and Sedges	California	2016–2017
[1,2]*Typha* spp.	Cattail	OBL	Forbs	California	2016–2017

[a] Adapted from Williams et al. (2020)

(Decagon Devices Inc., Pullman, WA, USA). It measures available PAR, and PAR beneath the plant canopy. Fraction intercepted photosynthetically active radiation (FIPAR) is then calculated as:

$$\text{FIPAR} = 1\text{–}(\text{Below plant canopy PAR})/(\text{Available PAR}). \quad (3)$$

The plant is then harvested at the height the ceptometer was used to record PAR, and taken to the lab where plant structures are separated and weighed fresh. Leaf area of separate plant structures are measured using a leaf area meter such as LI-3100 Leaf Area Meter (LI-COR Biosciences, Lincoln NE, USA). Leaf area index (LAI) is calculated using leaf area, and sampling area as:

$$\text{LAI} = (\text{Leaf area})/(\text{Area sampled}). \quad (4)$$

The light extinctions coefficient (k) can then be calculated using FIPAR and LAI:

$$\text{k} = (\text{Ln}\ (1\text{–FIPAR}))/(\text{LAI}). \quad (5)$$

Fig. 2 Wetland plant sampling sites. Filled stars were also simulated locations

Plant samples are then dried at 66 °C until dry weights of each sample are stable, and the final dry weight is recorded. After several harvests have been collected with an increase in dry weight, and daily FIPAR between harvests are calculated by interpolation, the radiation use efficiency (RUE) can then be calculated. RUE is the slope of the linear regression of daily cumulative FIPAR and dry weight. Ground dry plant matter is analyzed for nutrients, specifically nitrogen (N), phosphorus (P), and potassium (K).

ALMANAC has 53 plant parameters with species specific values. FIPAR, LAI, k, and RUE are the major plant parameters needed for ALMANAC. Along with these measurements, values like height, maximum and minimum growing temperatures, potential rooting depth, sensitivity to frost and all the remaining parameters are derived by either direct field measurements, from literature reviews, or by using informed inferences. All plant parameters can be adjusted to the specific species or variety.

All study sites listed below were in naturally occurring wetlands which were not fertilized, planted, or hydrologically managed excluding the California site. California was heavily managed and seasonally flooded due to the site's proximity to the historic flood plains of the Central Valley, and purpose as a refuge stopover in the Pacific Flyway for migratory birds. Plant species in the studies were identified in the field by site experts before sampling. See the original papers for a list of cooperating authors, entities, and permissions granted for plant collections and sampling.

Wetland plant growth was measured from 2013 to 2015 at 4 locations for 18 species(Williams et al. 2017). Additional data was collected from 2016 to 2017 at 3 locations for 17 species(Williams et al. 2020). This combined effort spans 5 years, 26 species (Table 1), and 5 locations (Fig. 2) (Playas in the Southern Great Plains, Central Texas wetlands, North Dakota Prairie Potholes, Delmarva peninsula on the eastern US coastal plain, and California Central Valley). Closely related plant species were lumped together as multi-site species. For example, *Typha latifolia* and *Typha angustifolia* were listed as cattail. Thus 17 species were measured and parameterized. Species-specific parameters were also organized into "functional groups". Means of these functional group parameters are useful for simulating the multitude of plant species not measured directly. Wetland plant functional groups were created here based on plant growth habit: rushes and sedges, forbs, or grasses. Harvests followed the sampling protocol described above. Sampling ground area varied between 0.25mX0.3 m to 0.8mX0.8 m depending on species and location. Sampling area size was consistent for a species at a site. For example, cattail (*Typha* spp.) in Delmarva had the same ground area sampled for every replicate. These locations were all naturally occurring depressional wetlands excluding California. California was a created wetland in an historic floodplain with inflows and outflows managed by the United States Fish and Wildlife Service (USFWS).

Additionally, an intensive study on tree species was conducted to derive wetland tree parameters. Wetland tree

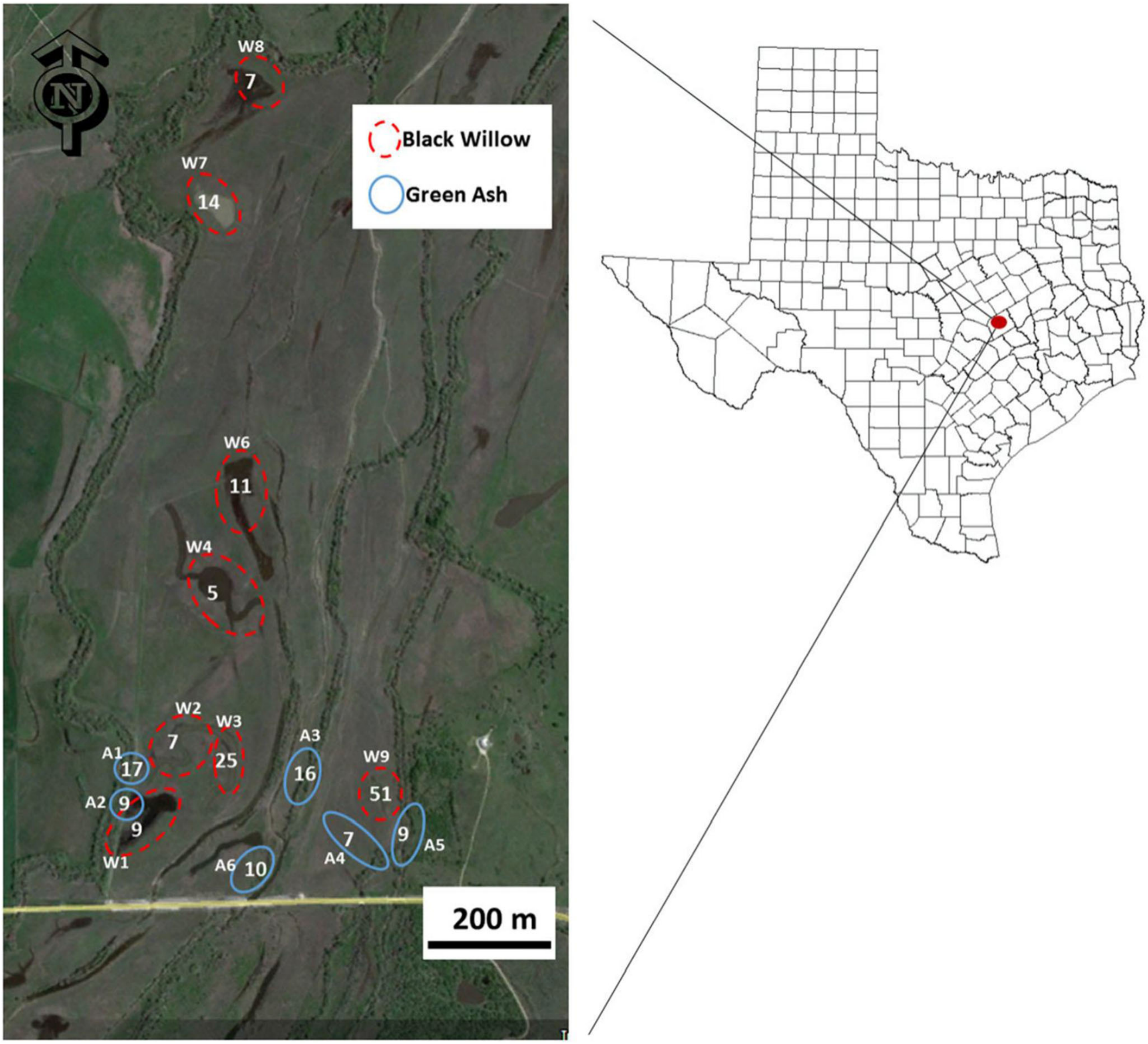

Fig. 3 Satellite imaginary of study area. The image is from 26 March 2015 and was obtained from Web Soil Survey (available in http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). Red dotted circles indicate areas where black willow trees were sampled, while solid blue circles indicate the area where green ash trees were sampled. The numbers inside the circles indicate tree density (number of trees per 100 m^2 area). Adapted from Kim et al. (2018)

Table 2 Experimental locations, nearest weather stations' latitude and longitude, and the wetland soil type. Due to privacy agreements, specific site latitude and longitude cannot be divulged, but the coordinates listed are the weather stations used in the simulations. Soil types shown occur at field site locations and were used for simulations. Adapted from Williams et al. (2020)

Location	Weather station's latitude, longitude	Soil type for vegetation
North Dakota	46.9258, −98.6691	Parnell silty clay loam, 0–1% slopes
Delmarva	39.1733, −76.683	Corsica mucky loam, 0–1% slopes
California	39.1875, −122.0269	Willows silty clay, 0–1% slopes, frequently flooded

measurements were taken in 2016 at 15 sites at 1 floodplain location in central Texas (Fig. 3) for 2 species, black willow (*Salix nigra*) and green ash (*Fraxinus pennsylvanica*)(Kim et al. 2018). Tree sizes varied within each site, and each site was a different cluster of trees. At each site 15 trees were selected for measurements of trunk diameter, number of trunks, height, and canopy diameter. These were used to determine tree volume assuming the tree was conical:

$$\text{Tree Volume} = ((\text{canopy area})* (\text{tree height}))/3. \quad (6)$$

Five of those trees were selected for harvest operations as listed above with some modifications. A total of 75 trees were sampled, 45 black willow and 30 green ash. FIPAR was measured on the entire tree canopy, and whole tree fresh weight was measured, then a subsample was taken to the lab to determine LAI, k, and dry weight. Tree age was determined by counting rings of the largest undamaged trunk from each sample. Growth rate was determined by:

$$\text{Growth rate} = (\text{tree ring radius})/(\text{number of growth rings}). \quad (7)$$

Wetland Plant Simulation

The values collected from Williams et al. (2017) and Williams et al. (2020) provided parameters and measured data allowing for ALMANAC simulations and comparisons to be made in Williams et al. (2020). 3 locations (Fig. 2), 10 species, and 3 functional groups were simulated (Table 1). These species had the more robust dataset than those that were excluded and included some multi-site species. The functional groups were based on multiple species and included plant species that were not simulated individually. Specific coordinates of some locations were unable to be shared due to privacy agreements, so soil type and nearest weather stations used for simulation were disclosed (Table 2). Simulation management was kept consistent for all 3 sites with first year planting on April 2nd and then harvesting aboveground biomass every year on August 1st. These dates were used as an average from green up and harvest across sites and species. Automatic irrigation and fertilizer were used to simulate the ideal growing conditions. When water or nitrogen stress on the plant occurred, the model automatically applied irrigation or N fertilizer. Furrows were used to irrigate in the simulation so ponding would occur on the surface. A yearly maximum limit of nitrogen applied was set in the model for each location. California had irrigation water applied by managers at the field site, unlike the other two locations which were rainfed. Therefore, it was assumed that the California site received higher application of nutrients via this river irrigation water. California's yearly maximum auto fertilizer was set to 300 kg/ha, compared to 100 kg/ha in Delmarva and 200 kg/ha at North Dakota. Simulations were run based on the number of sample years at the site. Example, cattail in California was run from 2016 to 2017 while in Delmarva cattail was run from 2014 to 2017. Single species were run first, followed by runs with functional groups.

The values collected from Kim et al. (2018) provided parameters and measured data for 2 tree species. In this paper both ALMANAC and APEX runs were performed. Only 1 year of data collection was needed because trees are long lived perennial plants, and Kim et al. (2018) took a range of samples that covered trees aged 3–10 years. ALMANAC simulations were done to ensure the developed parameters were within range of measured values. Two sets of parameters were created for black willow in ALMANAC, the distinctions were based on tree age, ≤ 5 and ≥ 6 years. Green ash had a single set of parameters created instead of 2 because the measured black willows grew more trucks as they aged while the measured green ash did not. The study location had Tinn clay, 0 to 1% slope, occasionally flooded soil and was near Cameron, Texas. Model management was set to harvest the trees on August 1, 2016 with base temperature 10 °C and 3000 annual potential heat units (PHU) which is the degrees days from planting to maturity.

Table 3 The Summer and winter irrigation operation schedule of the T6 wetland at Colusa National Wildlife Refuge in California, U.S. Adapted from Kim et al. (2020)

Year	Date	Operation	Amount
2017	9 May	Discharge water from weirs	0–50 mm depth
2017	9 June	Summer irrigation	300–350 mm ponding
2017	10 June	Store water	300–400 mm depth
2017	15 June	Discharge water from weirs	0–50 mm depth
2017	15 July	Mowing wetland plants	
2017	18 Sep.	Fall irrigation	300–490 mm ponding
2017	19 Sep.	Store water	300–400 mm depth
2018	9 May	Discharge water from weirs	0–50 mm depth
2018	16 June	Summer irrigation	300–350 mm ponding
2018	17 June	Store water	300–400 mm depth
2018	28 June	Discharge water from weirs	0–50 mm depth
2018	6 July	Summer irrigation	300–350 mm ponding
2018	10 July	Summer irrigation	300–350 mm ponding
2018	11 July	Summer irrigation	300–350 mm ponding
2018	15 July	Mowing wetland plants	
2018	18 Sep.	Fall irrigation	300–490 mm ponding
2018	19 Sep.	Store water	300–400 mm depth

Wetland Simulation

APEX simulated black willow and green ash for the small watershed in Kim et al. (2018). The small watershed was divided into 3 subareas each set up using the same model parameters and management practices as in ALMANAC.

Table 4 Average values for plant functional group parameters used in models of plant growth collected from wetlands in California, North Dakota, Texas, and the Delaware, Maryland, and Virginia peninsula, 2013–2017. FIPAR is the fraction of intercepted photosynthetically active radiation. Max LAI is the maximum leaf area index. k is the light extinction coefficient. Dry Wt is the total above ground plant dry weight. Seed Wt is the seed weight. HI is the harvest index. RUE is the radiation use efficiency. Seed Wt and RUE were measured only in 2016 and 2017. Adapted from Williams et al. (2020)

Wetland Plant Species	FIPAR	Max LAI	k	Dry Wt (g m^{-2})	Seed Wt (g m^{-2})	HI	RUE (g MJ^{-2})
Rushes and Sedges							
Marsh Flatsedge (*Cyperus pseudovegetus*)	0.28	0.65	−1.27	97	33	0.30	0.67
Spikerush (*Eleocharis* spp.)	0.24	0.88	−0.29	387	123	0.17	–
Bulrush (*Schoenoplectus* spp.)	0.40	1.45	−0.80	406	75	0.13	2.54
Slough Sedge (*Carex atherodes*)	0.67	2.27	−0.94	345	–	–	0.53
Poverty Rush (*Juncus tenuis*)	0.46	4.31	−0.48	688	64	0.16	9.60
Average	*0.41*	*1.91*	*−0.76*	*385*	*74*	*0.19*	–
Standard Deviation	*0.17*	*1.48*	*0.38*	*210*	*38*	*0.07*	–
Forbs							
Bur Ragweed (*Ambrosia grayi*)	0.31	0.55	−0.63	94	–	–	–
Arrowhead/Duck Potato (*Sagittaria longiloba*)	0.32	0.66	−0.60	72	–	–	–
Cheeseweed (*Malvella leprosa*)	0.30	0.80	−0.48	97	–	–	–
Smartweed (*Polygonum* spp.)	0.56	1.76	−1.15	277	7	0.03	1.29
Narrowleaf Goosefoot (*Chenopodium leptophyllum*)	0.70	1.88	−0.66	461	–	–	–
Cattail (*Typha* spp.)	0.52	2.67	−0.70	895	201	0.20	4.1
Average	*0.45*	*1.38*	*−0.70*	*316*	*104*	*0.11*	–
Standard Deviation	*0.17*	*0.85*	*0.23*	*321*	*137*	*0.12*	–
Grasses							
Rabbitsfoot (*Polypogon monspeliensis*)	0.26	1.55	−0.25	342	187	0.55	–
Sprangletop (*Scolochloa festucacea*)	0.62	1.61	−1.26	323	48	0.07	2.14
Watergrass (*Echinochloa crus-galli*)	0.56	2.65	−0.55	774	104	0.11	0.79
Reed Canarygrass (*Phalaris arundinacea*)	0.74	2.84	−0.75	508	64	0.12	1.18
Swamp Timothy (*Crypsis schoenoides*)	0.84	3.44	−1.00	648	149	0.20	1.91
Joint Grass (*Paspalum distichum*)	0.89	5.45	−0.68	447	46	0.07	0.45
Average	*0.65*	*2.92*	*−0.75*	*507*	*99*	*0.19*	–
Standard Deviation	*0.23*	*1.44*	*0.35*	*177*	*58*	*0.18*	–

Flow data was not available for comparison so simulated run off was compared with rainfall data. Simulated yields were compared to ALMANAC and measured values. Tree biomass prediction by tree age for 15, 20, 25, 30, 35 years were made using both ALMANAC and APEX simulations.

Kim et al. (2020) used parameters developed above to simulate the wetland in California and determine impacts of waterfowl on water quality. By the time of this study, hydrology data was now available to add to the accuracy of the model simulations. The unit T6 has irrigation water flood in and flow through 4 units connected by weir-culvert pairs in the berm until it is drained and rereleased into the river. Summer has a brief flood, then the wetland is inundated from fall to spring. The river is relatively clean, but the water inflow to the wetland is full of nutrients and agricultural runoff. As water reaches the final unit of T6 it has been filtered by this series of wetland units. Water depth was measured by depth transducers with data loggers daily from April 2017 to September 2018 placed at the inflow and outflow of each unit. Water samples were taken in May–August 2015–2018 for total nitrogen analysis. Vegetation transects were taken 50 m apart in 2015 for every unit. Plant density was calculated for each species:

$$\text{Plant Density} = ((\text{sum of proportion coverage in quadrats})/(\#\text{quadrats}))*\ (\text{unit area}). \quad (8)$$

Plant species were sorted into the wetland functional groups described in Williams et al. (2020) as rushes and

Table 5 Nutrient values from Delmarva and North Dakota. Nitrogen (N) was measured in 2017. Phosphorus (P) was measured in 2015–2016. Repro is the entire reproductive structure. Adapted from Williams et al. (2020)

Species	Plant Part	Date 1 N(%)	P(g g^{-1})	Date 2 N(%)	P(g g^{-1})	Date 3 N(%)	P(g g^{-1})
Rushes and Sedges							
Hardstem Bulrush	Leaves	1.89	0.0020	1.35	0.0018	1.30	0.0015
	Repro	–	0.0029	1.43	0.0032	0.74	0.0024
Slough Sedge	Leaves	2.78	0.0043	1.81	0.0032	1.28	0.0025
	Repro	–	–	–	–	–	0.0030
Poverty Rush	Leaves	0.64	0.0019	0.74	0.0013	0.94	0.0011
	Repro	1.02	0.0019	0.73	0.0022	0.70	0.0008
Marsh Flatsedge	Leaves	2.48	0.0020	1.05	0.0017	0.62	0.0005
	Repro	1.83	0.0025	1.50	0.0018	1.14	–
Average	*Leaves*	*1.95*	*0.0026*	*1.24*	*0.0020*	*1.04*	*0.0014*
	Repro	*1.43*	*0.0024*	*1.22*	*0.0024*	*0.86*	*0.0021*
Forbs							
Narrowleaf Cattail	Leaves	1.75	0.0031	1.08	0.0026	1.40	0.0018
	Repro	–	–	0.68	0.0031	1.60	0.0027
Smartweed	Leaves	1.35	0.0032	2.41	0.0025	2.12	0.0022
	Stems	1.00	0.0029	1.02	0.0025	0.77	0.0021
	Repro	–	–	–	–	1.40	0.0032
Average	*Leaves*	*1.55*	*0.0031*	*1.75*	*0.0025*	*1.76*	*0.0020*
	Stems	*1.00*	*0.0029*	*1.02*	*0.0025*	*0.77*	*0.0021*
	Repro	–	–	*0.68*	*0.0031*	*1.50*	*0.0030*
Grasses							
Reed Canarygrass	Leaves	3.10	0.0044	2.12	0.0038	1.00	0.0022
	Repro	–	–	1.61	0.0064	1.10	0.0038
Sprangletop	Leaves	1.73	0.0044	1.45	0.0027	1.70	0.0016
	Repro	–	–	1.41	0.0023	1.50	–
Average	*Leaves*	*2.42*	*0.0044*	*1.79*	*0.0033*	*1.35*	*0.0019*
	Repro	–	–	*1.51*	*0.0043*	*1.30*	*0.0038*

sedges, forbs, or grasses. This site is a stop on the Pacific Flyway, a migratory route for birds, and waterfowl droppings add nitrogen to the wetland system. To address how much nitrogen is added by the influx of waterfowl, calculations were made based off waterfowl surveys for T6:1–4 and literature reviews. USFWS biologists performed waterfowl counts and

Table 6 Means of each different age group for black willow and green ash. Welch's *t* test comparison between the two age groups within each tree was performed for each variable at 0.05 significance level. Adapted from Kim et al. (2018)

	Black Willow			Green Ash		
Variables Tree age range (yrs)	BW1 3–5	BW2 6–8	Welch's *P* value	GA1 4–6	GA2 7–10	Welch's *P* value
Dry wt per tree (kg)	0.39	5.03	< 0.0001	0.62	3.75	0.0023
LAI	0.72	1.49	0.0055	0.32	0.74	0.0953
k	− 0.25	− 0.34	0.44	− 0.81	− 0.74	0.866
No. trunks tree^{-1}	3	6	0.0056	2	2	0.56
Trunk diameter (cm)	2.81	4.61	0.0019	2.67	4.5	0.0009
Height (m)	1.91	3.02	< 0.0001	2.16	3.56	< 0.0001
Volume (m^3)	0.73	6.28	< 0.0001	0.56	2.85	0.0078
Growth rate (mm yrs.$^{-1}$)	2.23	4.56	< 0.0001	2.4	3.42	0.034

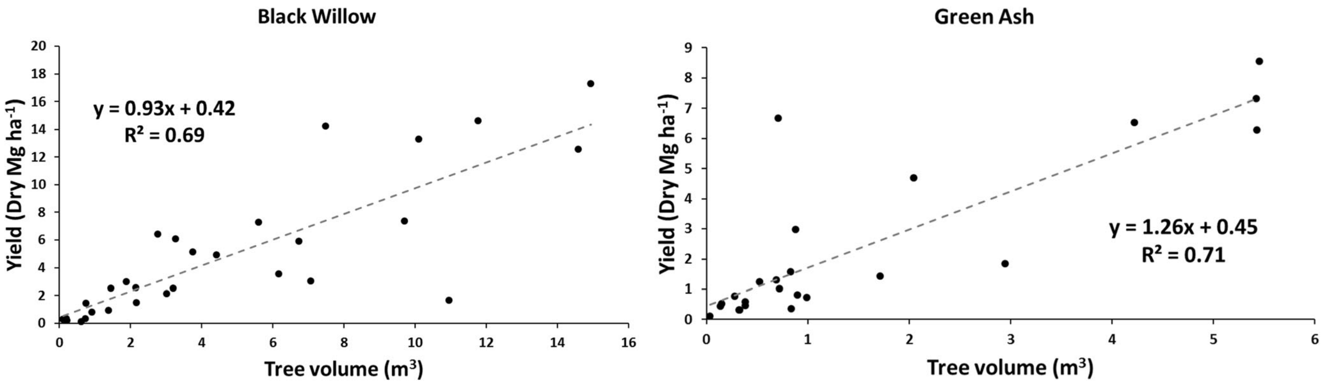

Fig. 4 Relationship between tree volume and total dry weight for black willow and green ash. The line is the fitted regression line. Adapted from Kim et al. (2018)

recorded surface area of standing water in each T6 unit monthly. Ninety eight percent of total mass of waterfowl droppings were from 9 species. Nutrient loading from waterfowl was determined on an individual species basis by month for each unit. The constants used (0.0234 and 0.0187) are the average concentration of nitrogen or phosphorus found in waterfowl droppings:

$$\begin{aligned} \text{Nitrogen} &= (\text{avg body weight of 1 bird*\#birds})* \\ &\quad (\text{dropping production})*\ (0.0234) \\ \text{Phosphorus} &= (\text{avg body weight of 1 bird*}\ \text{\#birds})* \\ &\quad (\text{dropping production})*\ (0.0187) \end{aligned} \tag{9}$$

APEX simulated the California wetland as 4 subareas flowing from one to the other with a single final outflow.

Table 7 Parameters simulated from 2013 to 2017 data. WA is radiation use efficiency (RUE) for the model calculated as RUE times 10 as a unit conversion factor. HI is harvest index. TB is maximum growing temperature in °C. TG is minimum growing temperature in °C. DMLA is maximum leaf area index (LAI). DLAI is the fraction of the growing season when leaf area declines. LAP1 is the first point on leaf area development curve, and LAP2 is the second point. PPL1 is the plant population at a low density with a fraction of maximum potential LAI, and PPL2 is the number at a higher density. RBMD is the rate of decline in WA. HMX is the maximum plant height in meters. RDMX is the maximum root depth in meters. EXT is the extinction coefficient from Beer's law. POP is the plant population per 1 m^2. PHU is the potential heat units. Adapted from Williams et al. (2020)

Plant	WA	HI	TB	TG	DMLA	DLAI	LAP1	LAP2	PPL1	PPL2	RBMD	HMX	RDMX	EXT	POP	PHU
Bulrush	54[b]	0.13	30	10	2.8[b]	0.6	15.13	75.99	5.12	20.96	0.1	2.99[b]	0.36	0.8	9	780
BulrushCA	41[b]	0.13	30	10	2.8[b]	0.2	17.13	18.99	5.12	20.96	1	2.99[b]	0.36	0.8	20	1000
Cattail[a]	50[b]	0.2	30	10	4[b]	0.74	16.51	75.99	1.12	10.9	0.1	2.04	0.36	0.7	6.7, 4, 10	825, 865, 1000
Smartweed[a]	18[b]	0.03	27	10	2.2[b]	0.6	17.25	60.73	3.12	15.96	0.1	1.2[b]	0.36	1.15	17, 8	700, 900
Reed Canarygrass	22[b]	0.12	25	3	2.84	0.5	13.17	36.99	1.12	6.96	0.1	1.89	0.36	0.75	9	1600
Sprangletop	21.35	0.07	25	12	1.61	0.4	13.31	58.99	1.12	6.96	0.1	1.49[b]	0.41	1.26	9	1600
Marsh Flatsedge	20[b]	0.3	25	12	1.3[b]	0.7	3.4	73.6	3.12	20.96	0.1	0.83	0.25	1.27	9	1100
Poverty Rush	96.01	0.16	25	12	4.31	0.4	3.18	33.99	1.12	6.96	3	1.61	0.15	0.48	8	800
Joint Grass	16[b]	0.07	25	10	5.45	0.65	38.74	51.99	1.12	6.96	0.1	0.8	0.10	0.68	8	1300
Watergrass	20[b]	0.11	25	10	2.65	0.8	8.57	99.99	1.12	25.96	0.1	1.5	0.36	0.55	30	1700
Swamp Timothy	19.12	0.2	25	12	3.44	0.4	69.62	80.67	1.12	6.96	0.1	0.75	0.36	1	10	1300
Rushes/Sedges	33.36	0.19	25	12	1.9	0.4	9.12[c]	50.75[c]	4.12[c]	17.96[c]	0.5[c]	1.59	0.20	0.76	20	900
Forbs	26.95	0.11	25	12	1.38	0.4	17.38[c]	68.86[c]	2.12[c]	13.93[c]	0.1	1.01	0.36	0.7	16	900
Grasses	19.694[c]	0.11[c]	25	9.4[c]	3.2[c]	0.55[c]	28.48[c]	65.93[c]	1.12	6.96	0.1	1.16	0.28	0.75	9	1500

[a] Note: Cattail and smartweed have different values for POP and PHU based on location. The numbers listed are for North Dakota first, followed by Delmarva, then California, if applicable

[b] Note: These parameters were higher than measured values

[c] Note: Functional group parameters from simulated species instead of calculated values

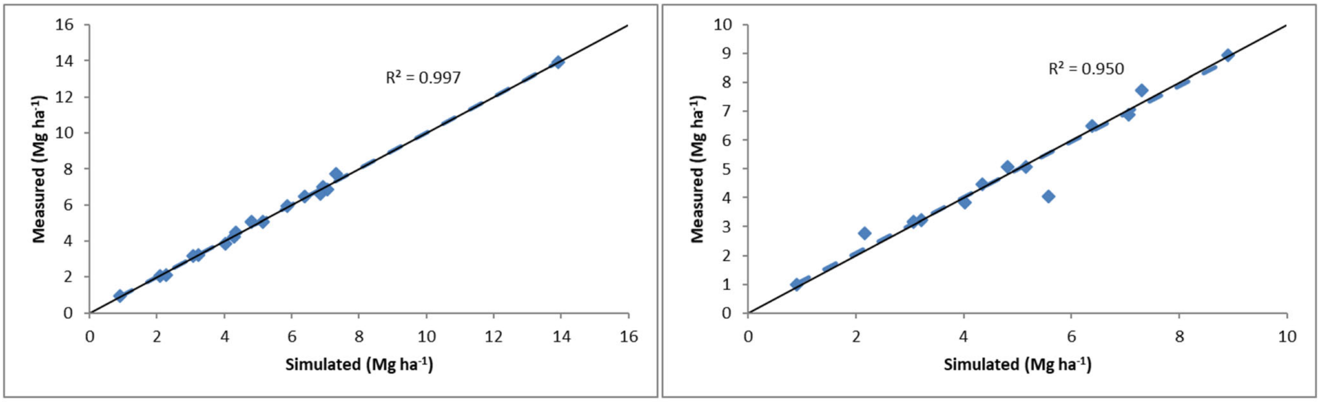

Fig. 5 Comparing measured and simulated plant yields for all data using singles site runs, runs for the functional groups, and using (**a**) runs of individual sites of the multi-site species or (**b**) multi-site species average value instead of runs from each site of the multi-site species. Adapted from Williams et al. (2020)

Irrigation was applied twice per year following reported field data, once in summer, and once in winter. Management is shown in Table 3. The functional groups were planted March 1st using the density calculated with field measurements. APEX was calibrated for water levels by comparing simulations to field data from April 2017–May 2018 and validated comparing simulation outputs with field data from June 2018–September 2018. Each unit in T6 was assumed flat and to not divert hydrologic flow within the unit. Data loggers had a recording error for T6:4, the final unit before release back into the river. Due to this, data was compared to T6:1–3 to each simulated T6:1–3 unit. APEX was calibrated for nitrogen using data from 2017 to 2018, and then validated with data from 2015 to 2016. Nitrogen from precipitation and the canal

Table 8 Derived plant parameter values of black willow (BW1 and BW2) and green ash (GS1 and GS2) used to calibrate the ALMANAC and APEX models. Adapted from Kim et al. (2018)

Parameters	ALMANAC		APEX	
	Black Willow	Green Ash	Black Willow	Green Ash
WA	30	30	30	30
HI	0.01	0.01	0.01	0.01
DMLA	3.17	1	3.17	1
DLAI	0.99	0.99	0.99	0.99
DLAP1	30.15	30.15	30.15	30.15
DLAP2	54.84	54.84	54.84	54.84
COSD (tree 1)	30.31	40.35	30.31	40.35
PRY (tree 2)	70.5	80.6	70.5	80.6
CLAIYR	9	10	9	10
HMX	3.74	4.01	3.74	4.01
EXTINC	0.31	0.84	0.31	0.84
RTPRT1	0.7	0.7	0.7	0.7
RTPRT2	0.3	0.3	0.3	0.3
PLANTPO	12	11	1200	1100
PHU/OPV1	3000	3000	a	a
If tree ages are	*BW1 (< 5 yrs)*	*GA (All)*	*BW1 (< 5 yrs)*	*GA (All)*
PPL1	10.13	10.23	1500.35	1500.83
PPL2	15.35	15.83	1000.13	1000.23
If tree ages are	*BW2 (> 6 yrs)*	–	*BW2 (> 6 yrs)*	–
PPL1	10.23	–	1500.85	–
PPL2	15.85	–	1000.23	–

a PHU in APEX was parameterized based on simulated LAI observed from the ALMANAC model.

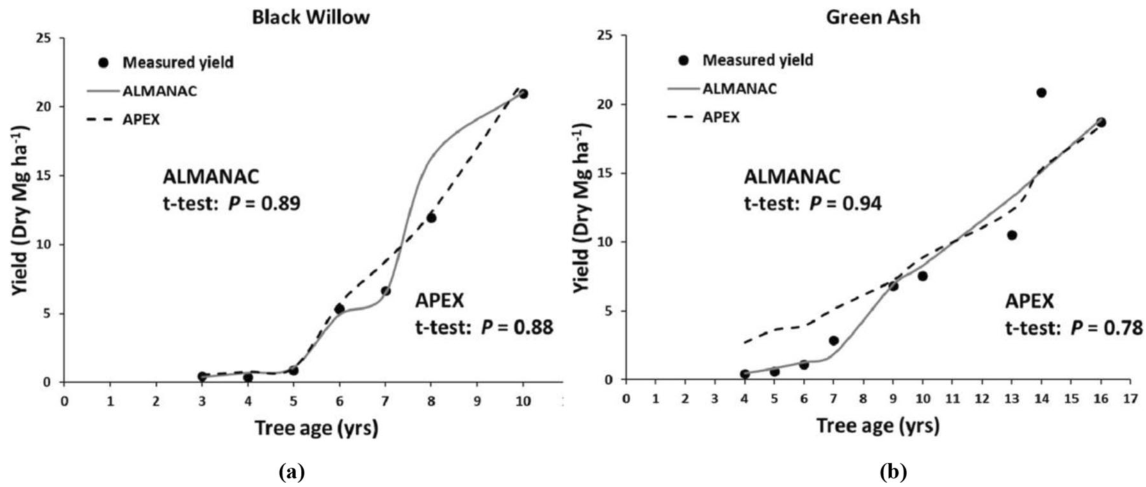

Fig. 6 Measured yields and simulated yields by ALMANAC and APEX for (**a**) black willow and (**b**) green ash across different ages. Measured and each of simulated yields were statistically compared using t test at alpha = 0.05. Adapted from Kim et al. (2018)

were included in the simulation, and nutrient addition by waterfowl was manually input based on earlier calculations. Nitrogen removal rates are influenced by water, soil, and plant uptake; data that are unavailable at this site. Removal percentages were adjusted by reducing amount in sediment, water, and runoff by unit T6:1 52.3%, T6:2 51.7%, T6:3 53.1%, T6:4 63.1%. After these simulations, APEX was used to model variations of irrigation rates and climate change scenarios. Climate was changed by increasing temperatures from 2015 to 2018 by 5.56 °C for the four years. Irrigation rates were the current rate, decreased by 0.5 times, increased by 1.5 and 3.0 times.

Results

Wetland Plant Growth

Results of measured data from the 5 year Wetland CEAP project concluded with 3 functional groups and 17 plants parameterized. FIPAR, maximum LAI, k, total above ground dry weight, seed weight, harvest index (HI), and RUE are listed in Table 4 arranged by functional group. Dry weight was averaged from the end of season harvest each year. Seed weight and HI were averaged from the date with the highest seed weight. Seed weight, HI, and RUE were only from 2016 to 2017. The grasses functional groups had higher values than the other 2 groups for most values (FIPAR 0.65, max LAI 2.92, and dry weight 507 g m^{-2}). Plant nutrient concentrations from North Dakota and Delmarva are listed in Table 5. Nitrogen (N) was sampled in 2017, and phosphorus (P) was sampled in 2015–2016. Samples were tested by plant part, green leaves or reproductive structures, and were from 3 dates, early season, mid-season, and end of season. Grasses had higher values than the other 2 functional groups for nutrients. Values for all generally decreased as the season progressed. Exceptions were found such as with the forb group, which only contained cattail and smartweed. This could be due to their later greenup compared to the other plant species that were measured for nutrients. For example, smartweed was still submerged in the wetland when other species were above the water level and being measured.

Kim et al. (2018) saw distinct differences in two tree age groups for both black willow and green ash (Table 6). Black willow aged 3–5 years were referred to as BW1, and ages 6–8 years were BW2. The same age groups were used for green ash and referred to as GA1 and GA2. This split was chosen due to the two ages having different growth rates and morphological differences. All the values shown in Table 6 were shown to have significant differences between the two age groups excluding k in black willow, and LAI, k, and number of trunks per tree in green ash (P >0.05). Tree yield (dry aboveground biomass) and tree volume had a positive linear relationship (Fig. 4).

Wetland Plant Simulation

Studies from Williams et al. (2017) and Williams et al. (2020) resulted in the parameters in Table 7 used for wetland plant simulations. Ten plant species and 3 functional groups were simulated. Plant population (POP), and PHU were different based on species and location (Table 7). Figure 5 compares the measured to simulated above ground biomass of all simulations (single species, multi-site species, and functional groups), and Fig. 5b switches from comparisons of multi-site species at a single site (ex cattail at Delmarva measured to cattail simulated at Delmarva) to all multi-site species averages (ex average cattail measured to average cattail simulated). Single site species were within 6% of measured values, multi-site species were within 7% compared to measured data

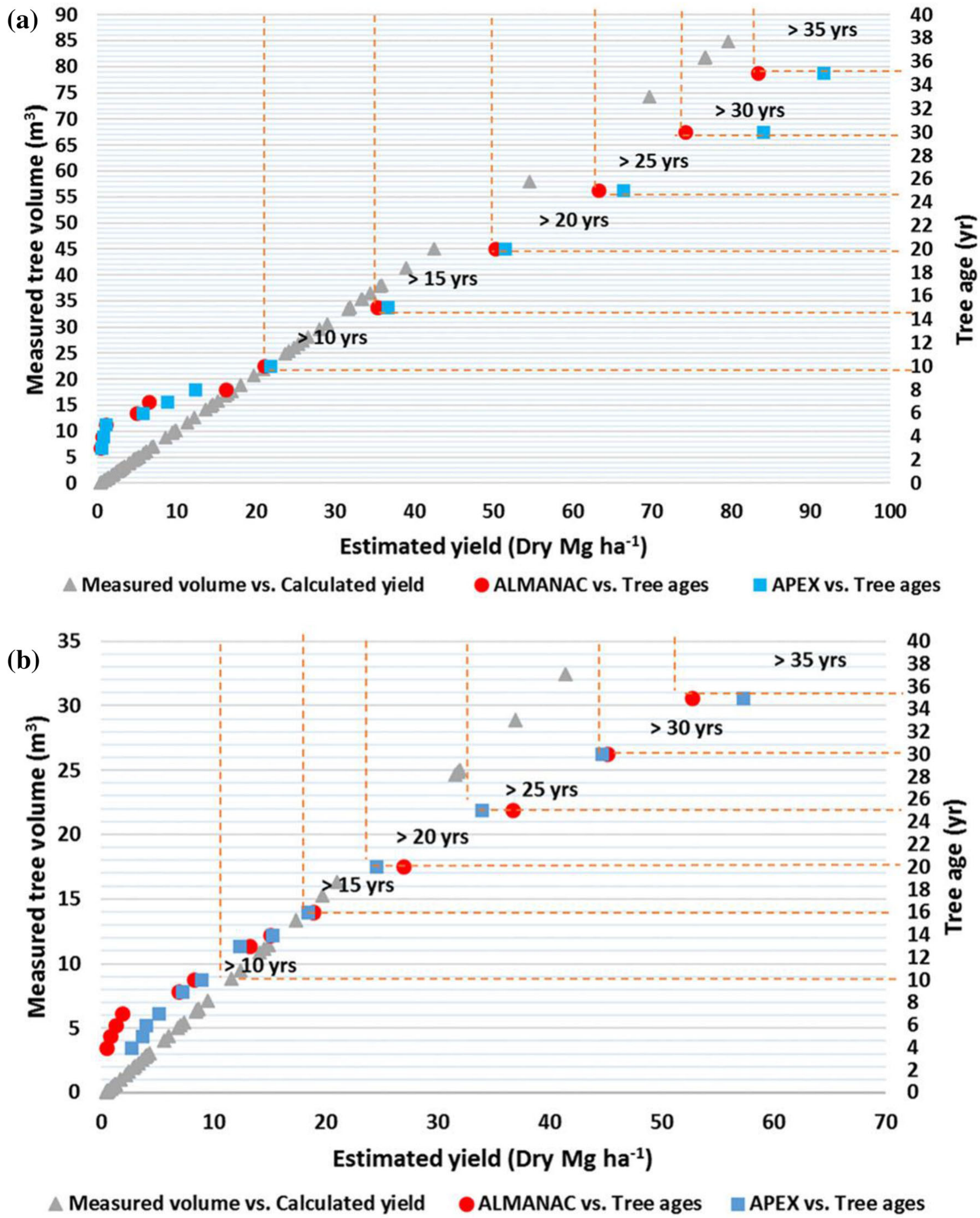

Fig. 7 Relationship between calculated biomass using simple linear equation and measured tree volumes (gray triangle), relationship between ALMANAC simulated biomass and trunk age (red circle), and relationship between APEX simulated biomass and trunk age (blue rectangle) for (**a**) black willow and (**b**) green ash. The simple linear equation is derived from Fig. 4 showing relationship between measured tree volumes and measured dry biomass of black willow and green ash. The orange dot lines indicate threshold lines for tree ages estimated based on simulated biomass from both ALMANAC and APEX. Adapted from Kim et al. (2018)

at the site, while comparing multi-species measured averages to the simulated average at all sites was 37%. This is likely due to the discrepancy between the number of measured sites and the number of simulated sites for multi-site species. Functional groups simulated yields that were within 5% of measured values. Williams et al. (2020) paper shows the success ALMANAC has, R^2>0.95, when simulating not only individual species, but also wetland plant functional groups.

Kim et al. (2018) paper shows the success ALMANAC has with wetland trees simulations. Table 8 shows the

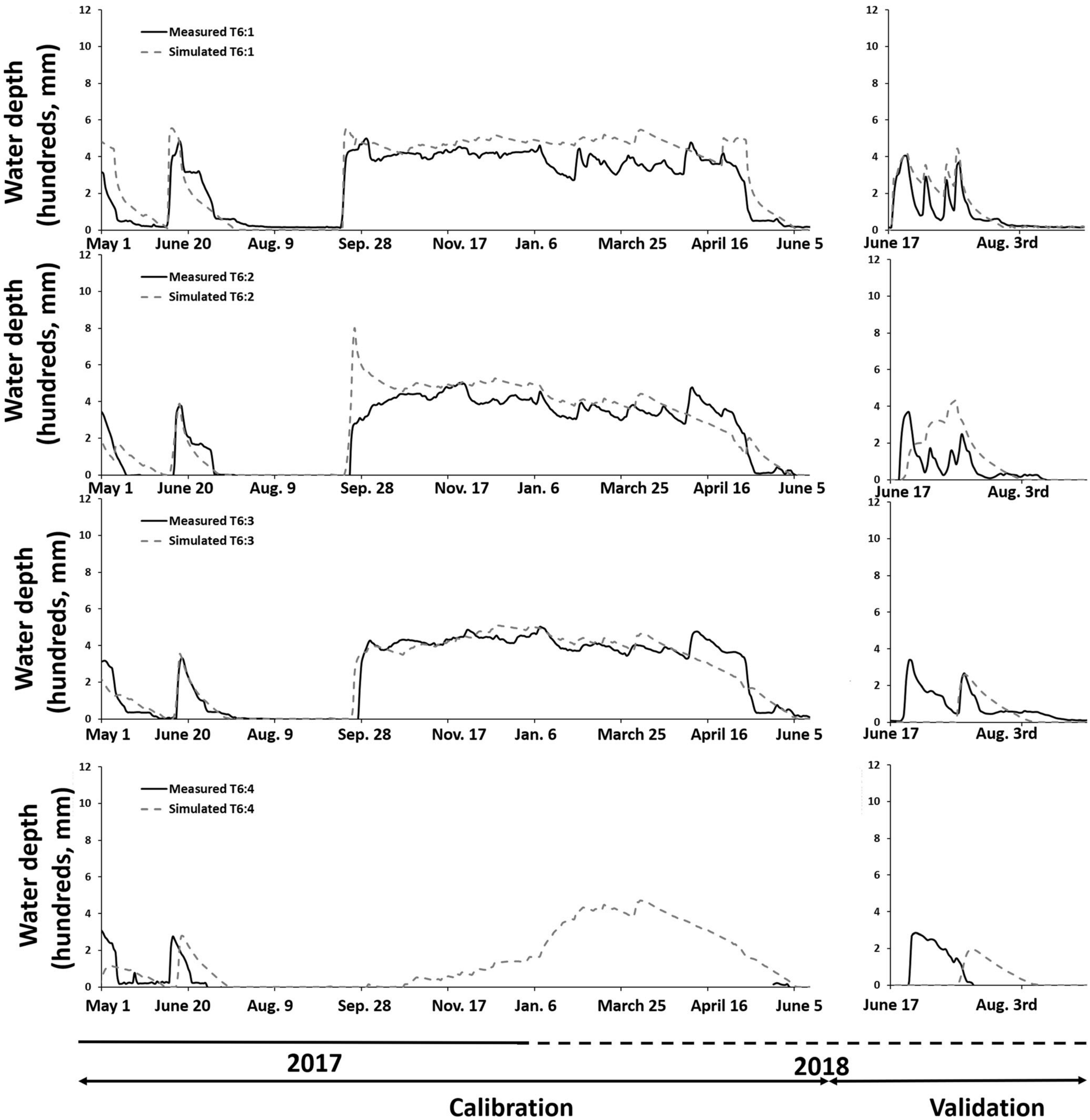

Fig. 8 This Comparison of daily measured and simulated wetland water depth (mm) for calibration (April 2017 – May 2018) and validation (June 2018 – August 2018) in T6:1–4 at CNWR (Colusa National Wildlife Refuge), Colusa CA. There are missing measured water depth values for T6:4 between July 2017 and May 2018. Adapted from Kim et al. (2020)

parameters derived from field measurements used for the ALMANAC and APEX models. Both trees started with slow growth until ages 6 or 7 years when growth began to be exponential. Black willow was split into two ages for simulation, because as the tree aged it grew more trunks, while green ash did not have a significant increase in trunk number between the two age groups. ALMANAC simulated tree biomass and growth at the local level while APEX numbers are based on the entire subarea, not just the tree area sampled. As such, both model values for biomass had no significant difference from measured values as seen in Fig. 6 (*t*-test $P>0.7$). The relationship between tree ages, biomass yield and volume shown in Fig. 7 are based on field data and both model simulations

Table 9 Measured and simulated nitrogen (N) concentration (mg L^{-1}) in surface of water body in T6:1–4 at Colusa NWR (including T6:1–4), late spring/summer periods between 2015 and 2018 and relative ratio between simulated and measured values. Adapted from Kim et al. (2020)

Cell	N content (mg L^{-1})		
	Measured	Simulated	Simulated Measured $^{-1}$
T6:1	0.89	0.80	0.90
T6:2	2.11	1.48	0.70
T6:3	2.30	2.45	1.07
T6:4	3.05	3.24	1.06

for ALMANAC and APEX. As the trees age, yield and volume increase. By the time trees are 35 years old the linear relationship derived from field values is greater than that simulated for both models with ALMANAC more closely resembling field-based values than APEX.

Wetland Simulation

Kim et al. (2018) tree paper shows success APEX has with wetland simulation using black willow and green ash simulation. As stated above, the simulated tree biomass for the wetland matched well with measured data. No measured data was available to compare water runoff or stream flow from the area. Results from APEX runoff were compared to measured rainfall from 2007 to 2016 and found to be reasonable. For example, the heavy rainfall events of 2007 had more simulated flow, and during the drought of 2011 very few runoff events were simulated.

APEX has shown success and encouraging results in simulating wetlands in the past with a multi-model approach. The Kim et al. (2020) California paper is significant because it is the first to include data from both plants and water for wetland simulation comparison, and projects water nutrient levels from various water levels, climate scenarios, and waterfowl nutrient addition.

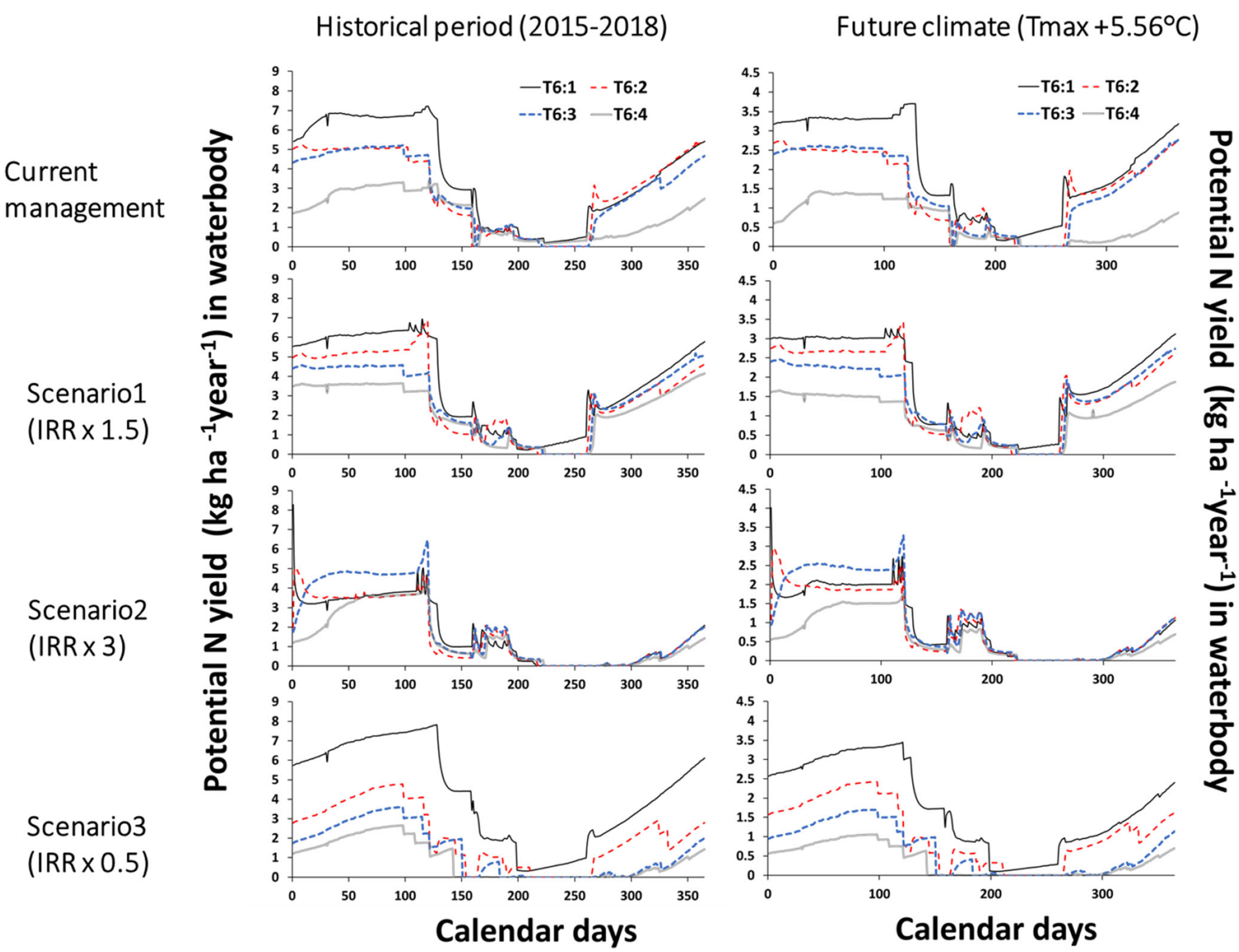

Fig. 9 Mean simulated nitrogen (N) yields (kg ha^{-1}) in waterbody in T6:1–4 at Colusa NWR, of current irrigation management and 3 scenarios during historical (2015–2018) and future periods (historical Tmax +5.56 °C). In scenarios 1 and 2, the current irrigation volume was increased by 1.5 and 3 times, respectively. In scenario 3, the current irrigation volume was decreased by 0.5 times. Adapted from Kim et al. (2020)

Wetland plant parameters from data at that site listed in Williams et al. (2020) were used to simulate the wetland plants in Kim et al. (2020). Water levels and nitrogen concentration in the water were measured at the site for comparison to simulations (Fig. 8 and Table 9). Simulation results of different irrigation treatments and future climate scenarios on nitrogen yield in water are shown in Fig. 9. Increasing temperatures will delay fall and winter waterfowl migration in the Pacific flyway. This predicted decline in waterfowl population would result with 50% less nitrogen loads but would continue to follow historic cycles.

Discussion

Results from this work will greatly improve the model-based evaluation of wetlands in the landscape. The parameters developed in this study will be of much value in the use of process-based models for assessing the impacts agriculture is having on wetlands and the assessment of water quality and quantity leading to and coming from wetlands. The parameters will be valuable for application of the ALMANAC and APEX models for determining effective agriculture practices related to wetlands as part of the CEAP project.

Simulation models have been used for decades by agronomists to simulate crop growth. Much interest has arisen in agricultural interactions with ecosystems and agronomists have just recently begun to focus on wetlands. The first bridge between these two systems is to use an already proven crop model to help simulate how they are interacting. Wetlands are now being more accurately simulated with better field data measurements from wetland plant growth parameters. More realistic landscape scale simulations can be achieved with more reliable vegetation data. This helps expand the Wetland CEAP mission and allows for simulations of more complex field managements. Realistic simulation of plant growth in wetlands is a new addition to this project. Past simulations had focused on soil loss, sediment yield, and hydrology(Water Quality Information Center NAL, Agricultural Research Service, U.S. Department of Agriculture 2006). Daniel et al. (2014) and Daniel et al. (2015) show that the vegetation type affects the rate of erosion and sediment buildup in playa wetlands. This filling impacts the playa as new flooding events increase the playa area while the depth is decreased allowing for quicker evaporation of these water sources and shorter hydroperiods impacting biota, water storage, and aquifer recharge. This is why it is important for simulated plant growth to be accurate, allowing for better assessments of the impacts on field and landscape scale upland/wetland interactions. The examples shown here of parameter derivation, single and multi-site species simulation, functional group simulation, and wetland simulation with waterfowl nutrient inputs under climate and irrigation changes are just the beginning. With these simulation tools, many more conservation practice interactions can be explored, and best management combinations under a changing future will be recommended. The next challenge in plant wetland growth modeling will be to include factors impacting emergence, reproduction, survivability, and diversity such as waterlogging, inundation, depth, duration, frequency, and timing in which data may be limited for specific species such as discussed by Webb et al. (2012). These models already include an aeration stress factor and competition, but this could be refined to include effects of water depth or timing on various aspects of plant growth.

In conclusion. Plant parameters developed in this study realistically describe diverse wetland functional groups. The parameters, when used in ALMANAC, APEX, or similar process-based models, will be effective for assessing impacts of various scenarios related to wetlands and their interaction with adjacent croplands. The parameters provide meaningful descriptions of the most important wetland functional groups, allowing reasonable description of plant growth, water use, and nutrient cycling.

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Code Availability Not applicable.

Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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