The Potential of American Sycamore as a Bioenergy Feedstock

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North Carolina Forest Service, NC Board of Registration for Foresters,
NC Cooperative Extension
Online Webinar
June 28, 2022

Outline

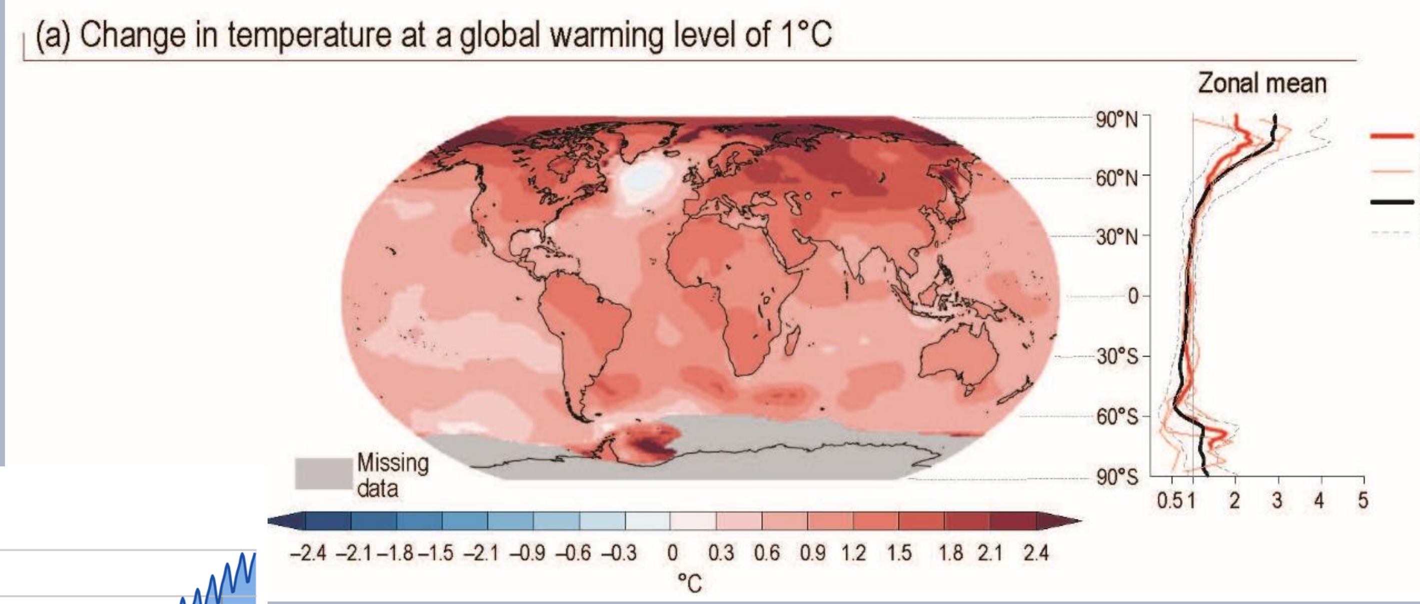
1. A rapidly changing world

2. Opportunities for integrating bioenergy into forestry and agriculture

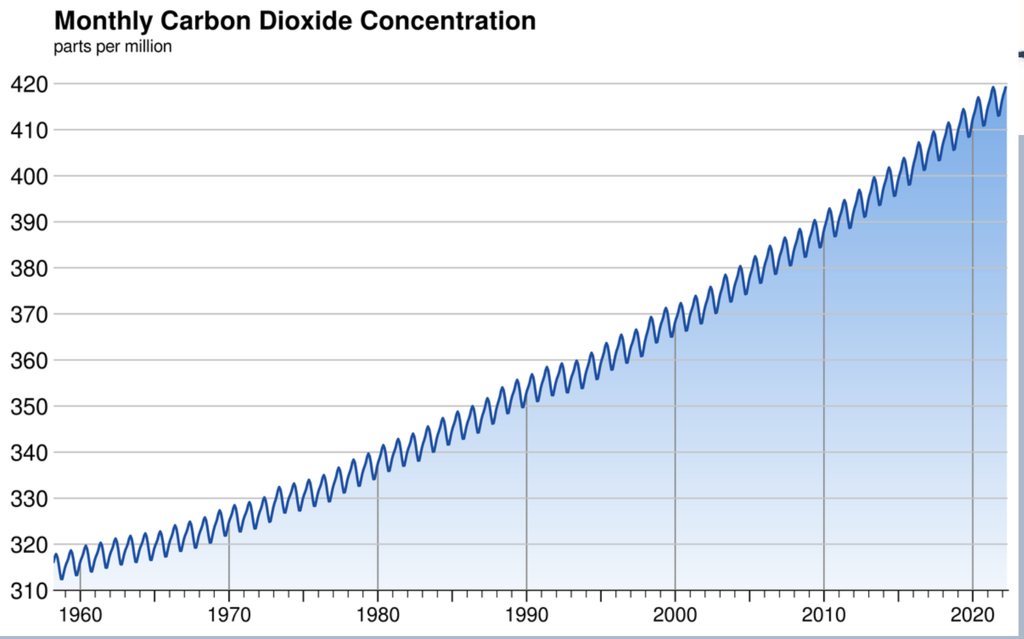
3. American sycamore: Unrecognized potential

4. The future

1. A rapidly changing world



IPCC 2021

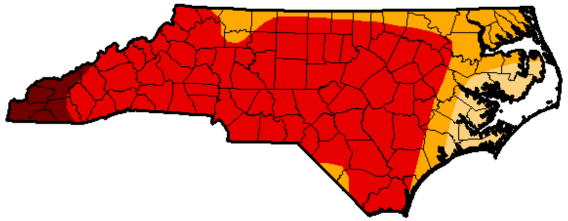


Scripps Oceanographic Inst. 2022

Recurring/intensifying droughts

U.S. Drought Monitor

North Carolina



September 25, 2007

(Released Thursday, Sep. 27, 2007)

Valid 7 a.m. EST

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.00	100.00	100.00	92.76	75.10	4.04
Last Week 9/18/2007	0.00	100.00	100.00	96.18	77.37	4.04
3 Months Ago 6/26/2007	0.01	99.99	63.41	14.72	3.88	0.00
Start of Calendar Year 1/2/2007	98.53	1.47	0.00	0.00	0.00	0.00
Start of Water Year 9/26/2006	95.48	4.52	0.00	0.00	0.00	0.00
One Year Ago 9/26/2006	95.48	4.52	0.00	0.00	0.00	0.00

Intensity:

- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

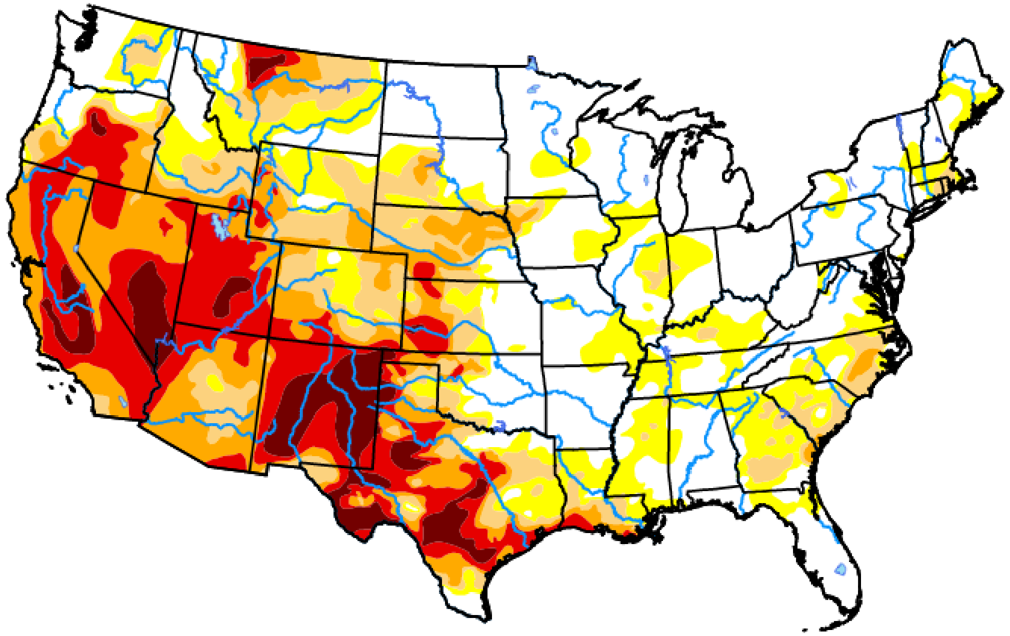
Author:
David Miskus
NOAA/NWS/NCEP/CPC

USDA National Drought Mitigation Center

http://droughtmonitor.unl.edu/

Falls Lake, 2007; Climate Justice

Contiguous U.S.



Map released: Thurs. June 23, 2022

Data valid: June 21, 2022 at 8 a.m. EDT

Intensity

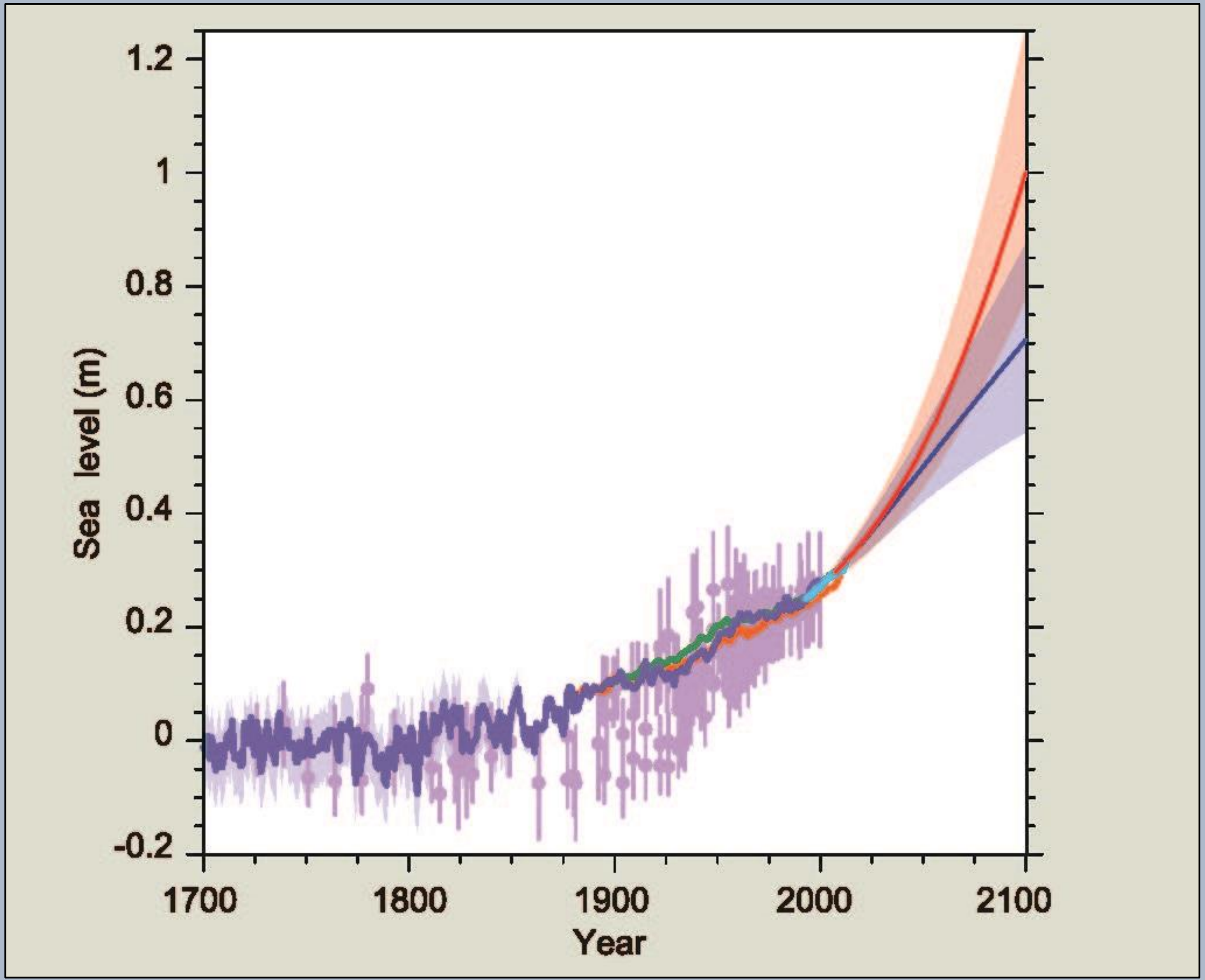
- None
- D0 (Abnormally Dry)
- D1 (Moderate Drought)
- D2 (Severe Drought)
- D3 (Extreme Drought)
- D4 (Exceptional Drought)
- No Data

Authors

United States and Puerto Rico Author(s):
Adam Hartman, NOAA/NWS/NCEP/CPC

Pacific Islands and Virgin Islands Author(s):
Denise Gutzmer, National Drought Mitigation Center

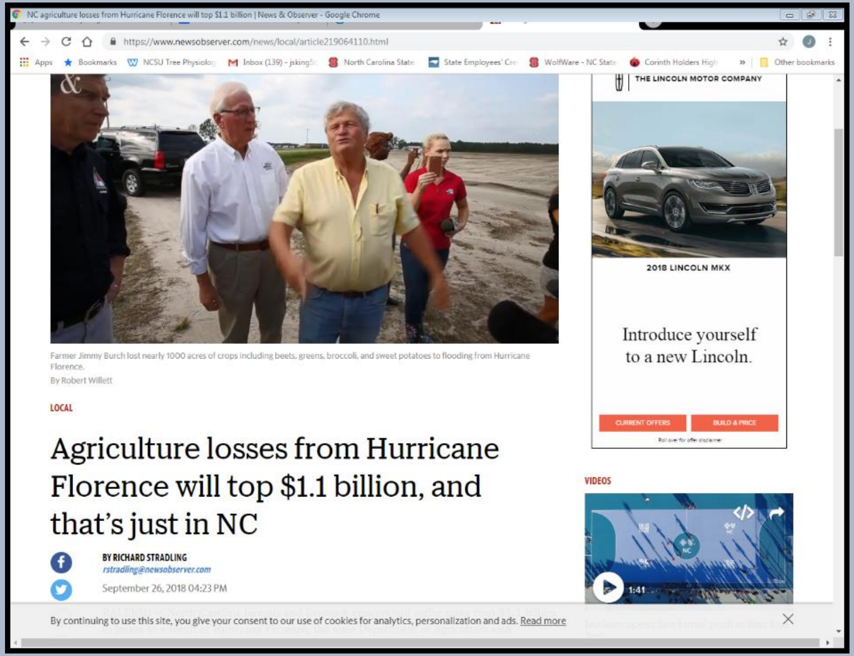
Rising seas and extreme storms



IPCC, 2013

NASA, 2018

Whiteville, NC, after Hurricane Florence, Fall 2018



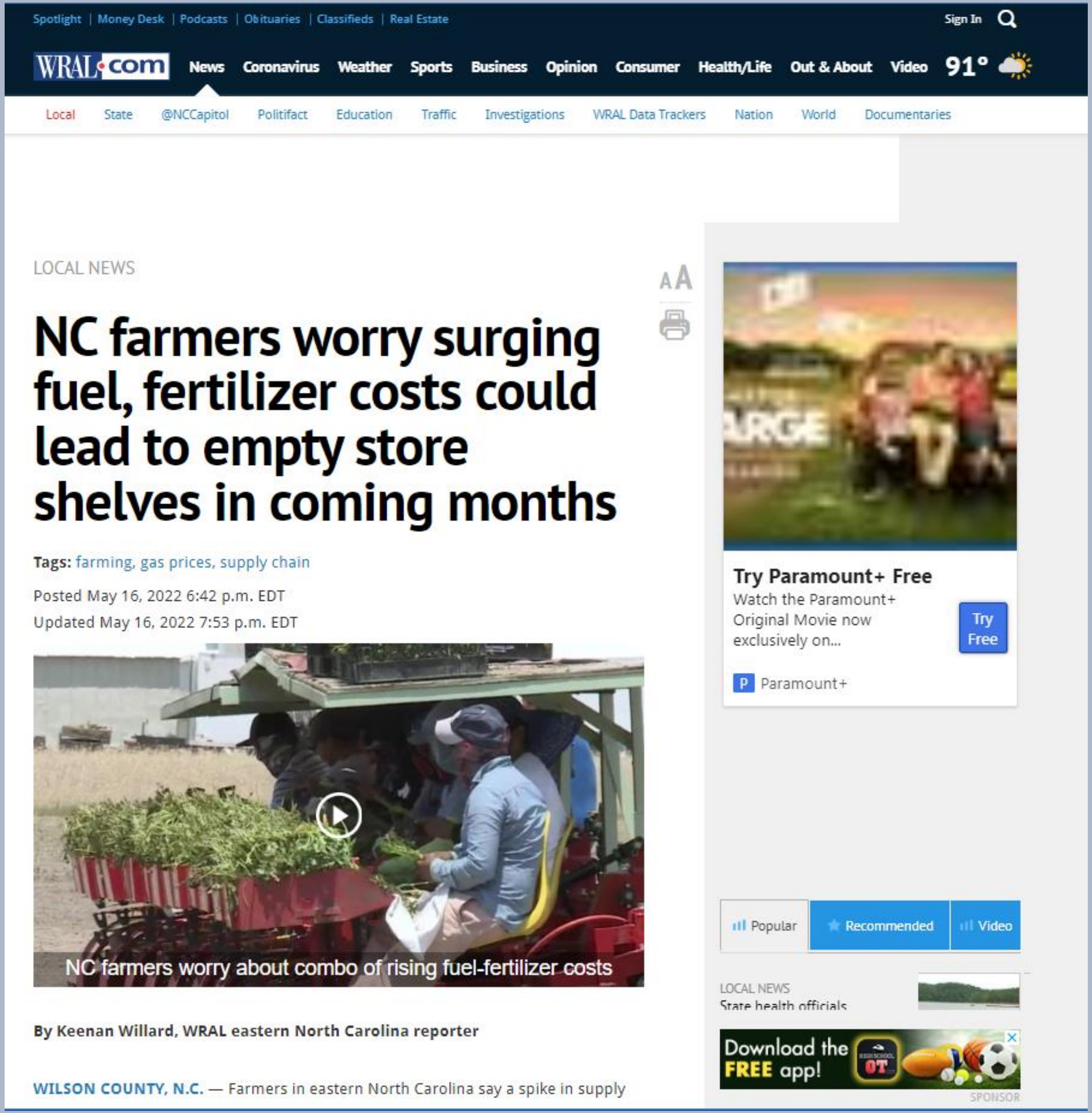
Farmer Jimmy Burch lost nearly 1000 acres of crops including beets, greens, broccoli, and sweet potatoes to flooding from Hurricane Florence.
By Robert Willett

LOCAL

Agriculture losses from Hurricane Florence will top $1.1 billion, and that's just in NC

BY RICHARD STRADLING
rstradling@newsobserver.com
September 26, 2018 04:23 PM

VIDEOS



LOCAL NEWS

NC farmers worry surging fuel, fertilizer costs could lead to empty store shelves in coming months

Tags: farming, gas prices, supply chain

Posted May 16, 2022 6:42 p.m. EDT
Updated May 16, 2022 7:53 p.m. EDT

NC farmers worry about combo of rising fuel-fertilizer costs

By Keenan Willard, WRAL eastern North Carolina reporter

WILSON COUNTY, N.C. — Farmers in eastern North Carolina say a spike in supply

land

MDPI

Article

Millennial-Scale Carbon Storage in Natural Pine Forests of the North Carolina Lower Coastal Plain: Effects of Artificial Drainage in a Time of Rapid Sea Level Rise

Maricar Aguilos [1,*], Charlton Brown [1], Kevan Minick [1], Milan Fischer [2], Omoyemeh J. Ile [1], Deanna Hardesty [1], Maccoy Kerrigan [1], Asko Noormets [3] and John King [1]

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Abstract: Coastal forested wetlands provide important ecosystem services along the southeastern region of the United States, but are threatened by anthropogenic and natural disturbances. Here, we examined the species composition, mortality, aboveground biomass, and carbon content of vegetation and soils in natural pine forests of the lower coastal plain in eastern North Carolina, USA. We compared a forest clearly in decline (termed "ghost forest") adjacent to a roadside canal that had been installed as drainage for a road next to an adjacent forest subject to "natural" hydrology, unaltered by human modification (termed "healthy forest"). We also assessed how soil organic carbon (SOC) accumulation changed over time using ^{14}C radiocarbon dating of wood sampled at different depths within the peat profile. Our results showed that the ghost forest had a higher tree density at 687 trees ha^{-1}, and was dominated by swamp bays (*Persea palustric*), compared to the healthy forest, which had 265 trees ha^{-1} dominated by pond pine (*Pinus serotina* Michx). Overstory tree mortality of the ghost forest was nearly ten times greater than the healthy forest ($p < 0.05$), which actually contributed to higher total aboveground biomass (55.9 ± 12.6 Mg C ha^{-1} vs. 27.9 ± 8.7 Mg ha^{-1} in healthy forest), as the dead standing tree biomass (snags) added to that of an encroaching woody shrub layer during ecosystem transition. Therefore, the total aboveground C content of the ghost forest, 33.98 ± 14.8 Mg C ha^{-1}, was higher than the healthy forest, 24.7 ± 5.2 Mg C ha^{-1} ($p < 0.05$). The total SOC stock down to a 2.3 m depth in the ghost forest was 824.1 ± 46.2 Mg C ha^{-1}, while that of the healthy forest was 749.0 ± 170.5 Mg C ha^{-1} ($p > 0.05$). Carbon dating of organic sediments indicated that, as the sample age approaches modern times (surface layer year 2015), the organic soil accumulation rate (1.11 to 1.13 mm $year^{-1}$) is unable to keep pace with the estimated rate of recent sea level rise (2.1 to 2.4 mm $year^{-1}$), suggesting a causative relationship with the ecosystem transition occurring at the site. Increasing hydrologic stress over recent decades appears to have been a major driver of ecosystem transition, that is, ghost forest formation and woody shrub encroachment, as indicated by the far higher overstory tree mortality adjacent to the drainage ditch, which allows the inland propagation of hydrologic/salinity forcing due to SLR and extreme storms. Our study documents C accumulation in a coastal wetland over the past two millennia, which is now threatened due to the recent increase in the rate of SLR exceeding the natural peat accumulation rate, causing an ecosystem transition with unknown consequences for the stored C; however, much of it will eventually be returned to the atmosphere. More studies are needed to determine the causes and consequences of coastal ecosystem transition to inform the modeling of future coastal wetland responses to environmental change and the estimation of regional terrestrial C stocks and flux.

Keywords: ghost forest; forested wetland; aboveground biomass; soil carbon; carbon dating

Citation: Aguilos, M.; Brown, C.; Minick, K.; Fischer, M.; Ile, O.J.; Hardesty, D.; Kerrigan, M.; Noormets, A.; King, J. Millennial-Scale Carbon Storage in Natural Pine Forests of the North Carolina Lower Coastal Plain: Effects of Artificial Drainage in a Time of Rapid Sea Level Rise. *Land* **2021**, *10*, 1294. https://doi.org/10.3390/land10121294

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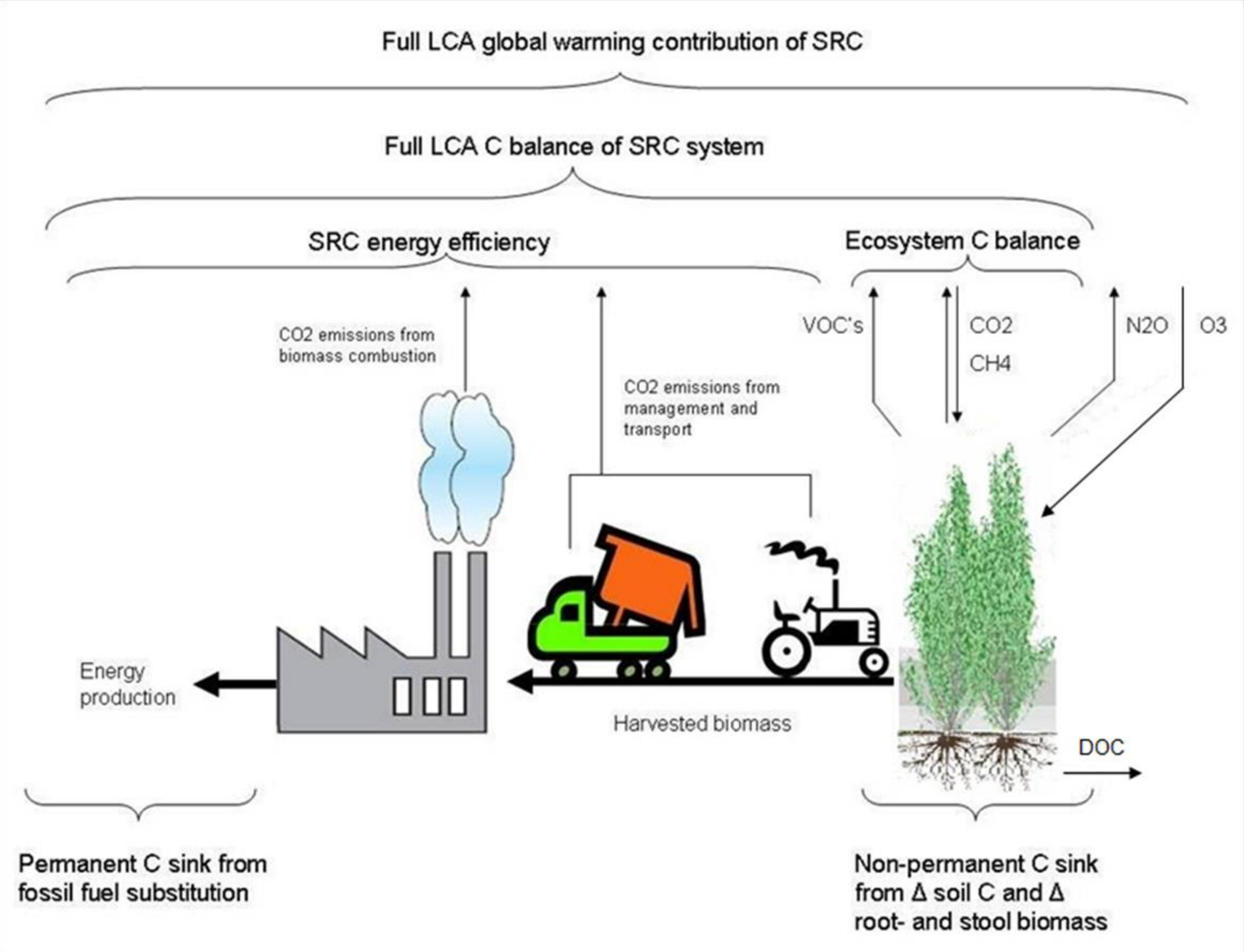
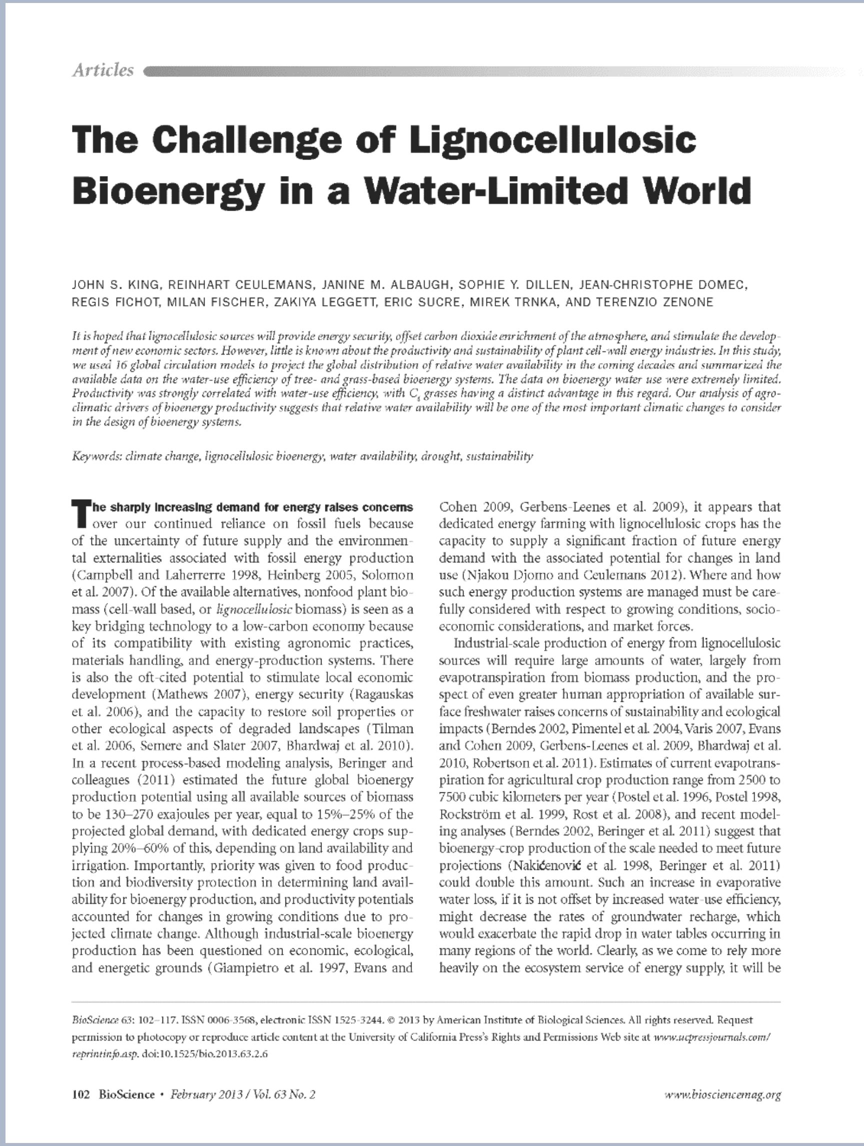
Bioenergy in an increasingly STRESSFUL world!



POPFULL Project, University of Antwerp, R. Ceulemans



The Challenge of Lignocellulosic Bioenergy in a Water-Limited World

JOHN S. KING, REINHART CEULEMANS, JANINE M. ALBAUGH, SOPHIE Y. DILLEN, JEAN-CHRISTOPHE DOMEC, REGIS FICHOT, MILAN FISCHER, ZAKIYA LEGGETT, ERIC SUCRE, MIREK TRNKA, AND TERENZIO ZENONE

It is hoped that lignocellulosic sources will provide energy security, offset carbon dioxide enrichment of the atmosphere, and stimulate the development of new economic sectors. However, little is known about the productivity and sustainability of plant cell-wall energy industries. In this study, we used 16 global circulation models to project the global distribution of relative water availability in the coming decades and summarized the available data on the water-use efficiency of tree- and grass-based bioenergy systems. The data on bioenergy water use were extremely limited. Productivity was strongly correlated with water-use efficiency, with C_4 grasses having a distinct advantage in this regard. Our analysis of agro-climatic drivers of bioenergy productivity suggests that relative water availability will be one of the most important climatic changes to consider in the design of bioenergy systems.

Keywords: climate change, lignocellulosic bioenergy, water availability, drought, sustainability

The sharply increasing demand for energy raises concerns over our continued reliance on fossil fuels because of the uncertainty of future supply and the environmental externalities associated with fossil energy production (Campbell and Laherrerre 1998, Heinberg 2005, Solomon et al. 2007). Of the available alternatives, nonfood plant biomass (cell-wall based, or *lignocellulosic* biomass) is seen as a key bridging technology to a low-carbon economy because of its compatibility with existing agronomic practices, materials handling, and energy-production systems. There is also the oft-cited potential to stimulate local economic development (Mathews 2007), energy security (Ragauskas et. al. 2006), and the capacity to restore soil properties or other ecological aspects of degraded landscapes (Tilman et. al. 2006, Semere and Slater 2007, Bhardwaj et. al. 2010). In a recent process-based modeling analysis, Beringer and colleagues (2011) estimated the future global bioenergy production potential using all available sources of biomass to be 130–270 exajoules per year, equal to 15%–25% of the projected global demand, with dedicated energy crops supplying 20%–60% of this, depending on land availability and irrigation. Importantly, priority was given to food production and biodiversity protection in determining land availability for bioenergy production, and productivity potentials accounted for changes in growing conditions due to projected climate change. Although industrial-scale bioenergy production has been questioned on economic, ecological, and energetic grounds (Giampietro et al. 1997, Evans and Cohen 2009, Gerbens-Leenes et al. 2009), it appears that dedicated energy farming with lignocellulosic crops has the capacity to supply a significant fraction of future energy demand with the associated potential for changes in land use (Njakou Djomo and Ceulemans 2012). Where and how such energy production systems are managed must be carefully considered with respect to growing conditions, socioeconomic considerations, and market forces.

Industrial-scale production of energy from lignocellulosic sources will require large amounts of water, largely from evapotranspiration from biomass production, and the prospect of even greater human appropriation of available surface freshwater raises concerns of sustainability and ecological impacts (Berndes 2002, Pimentel et al. 2004, Varis 2007, Evans and Cohen 2009, Gerbens-Leenes et. al. 2009, Bhardwaj et al. 2010, Robertson et al. 2011). Estimates of current evapotranspiration for agricultural crop production range from 2500 to 7500 cubic kilometers per year (Postel et al. 1996, Postel 1998, Rockström et al. 1999, Rost et al. 2008), and recent modeling analyses (Berndes 2002, Beringer et al. 2011) suggest that bioenergy-crop production of the scale needed to meet future projections (Nakićenović et al. 1998, Beringer et al. 2011) could double this amount. Such an increase in evaporative water loss, if it is not offset by increased water-use efficiency, might decrease the rates of groundwater recharge, which would exacerbate the rapid drop in water tables occurring in many regions of the world. Clearly, as we come to rely more heavily on the ecosystem service of energy supply, it will be

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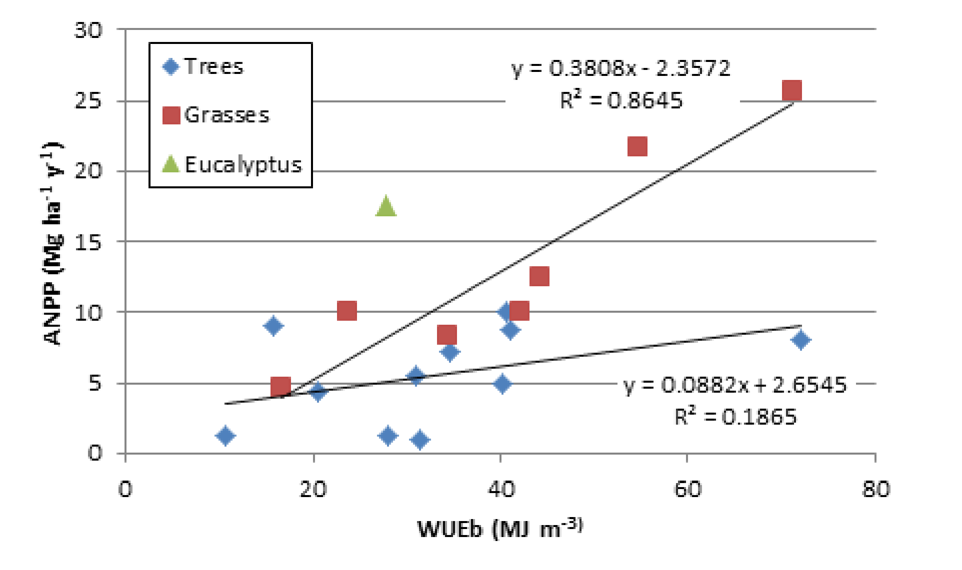
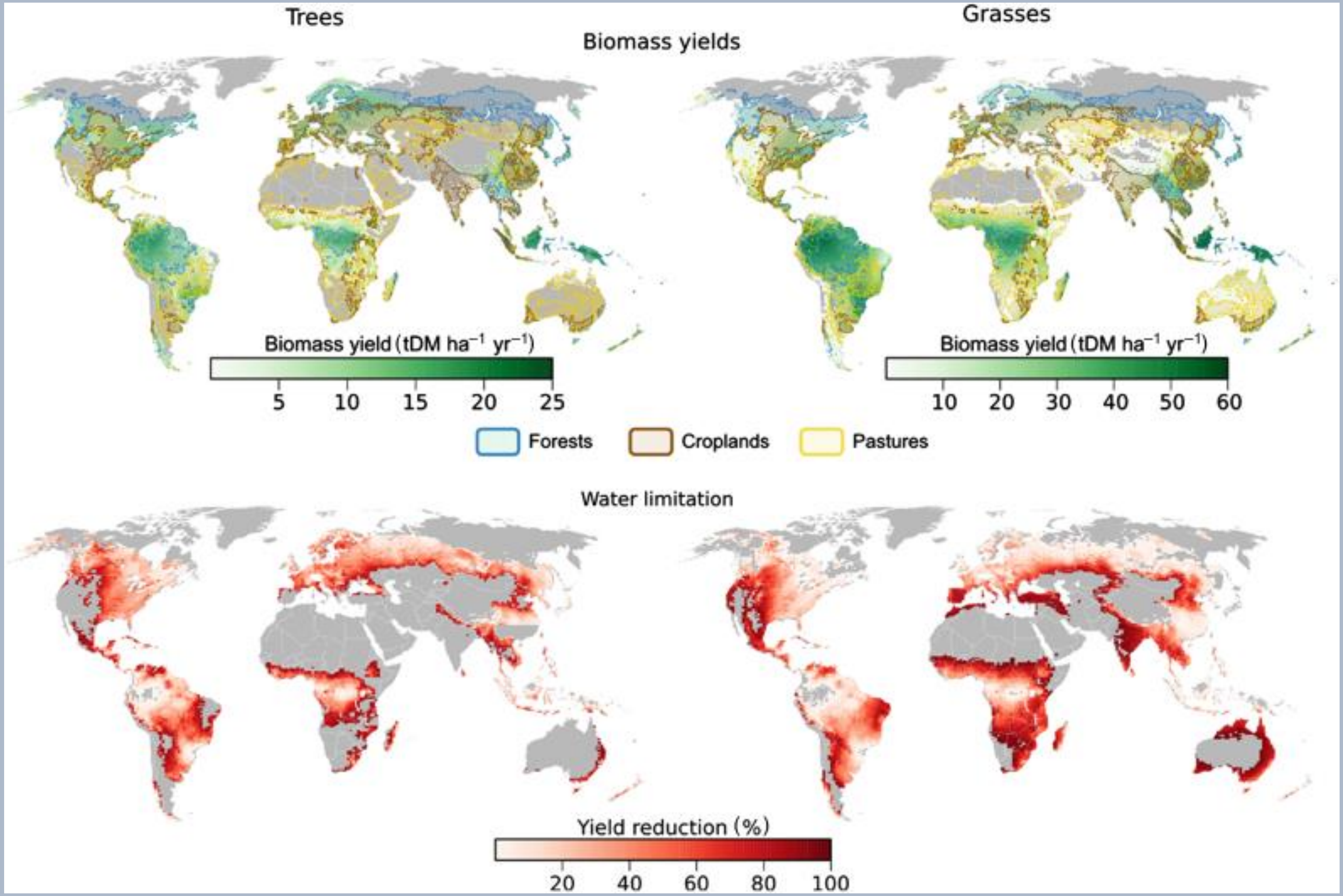
Ecophysiology as an applied science

Taxa	Avg Ps (umol per m² per s)	Avg gs (mmol per m² per s)	Avg WUEi £ (µmol per mmol)	δ¹³C	Avg Tree ANPP (Mg per ha per y)	Avg Under-story ET (mm per y)	Avg Stand T (mm per y)	Avg Stand WUE* (kg per mm)	Bio energy WUE** (MJ per m³)	Avg MAT (°C)	Avg MAP (mm)
Acer pseudopl.	6.5	165.2	0.039	-	1.2	-	-	-	-	10.0	877
Acer rubrum	7.7	175.2	0.044	-	1.3	-	-	-	-	9.2	1186
Alnus	7.9	81.0	0.097	-28.8	9.0	230.0	538.0	16.8	28.1	11.3	1305
Eucalyptus	16.8	396.0	0.042	-27.3	17.5	-	1054	16.5	27.7	20.5	1309
Larix	7.0	56.0	0.125	-26.4	1.0	62.0	101.0	6.3	10.6	-8.7	230
Liquidambar	8.6	280.0	0.031	-27.4	4.4	205.0	462.5	9.4	15.8	15.7	1304
Liriodendron	8.9	102.1	0.087	-	0.9	-	-	-	-	13.0	1692
Pinus	4.7	99.0	0.047	-27.3	5.0	251.8	410.0	12.3	20.5	16.6	1145
Platanus	9.5	286.5	0.033	-	5.5	-	293.8	18.9	31.5	18.4	1019
Populus-pure sp	13.7	303	0.045	-28.0	10.1	117.0	419.2	24.0	40.2	11.4	607
Populus-hybrids	12.7	343	0.037	-28.1	8.1	142.5	439.1	18.5	30.9	10.2	753
Quercus	10.4	185.5	0.056	-27.8	7.2	-	294.8	24.3	40.6	13.6	913
Robinia	9.7	296.7	0.033	-24.3	8.8	370.0	204.5	43.2	72.2	10.9	700
Salix-pure sp	13.7	316.0	0.043	-27.9	8.4	240.1	403.8	20.7	34.6	5.7	661
Salix-hybrids	20.6	378.0	0.054	-	8.0	119.4	324.9	24.5	41.1	6.6	703



Spatially-explicit representation of forest-ag land biotic structure and process rates, linked to climate driven models for regional integration

King et al. 2013



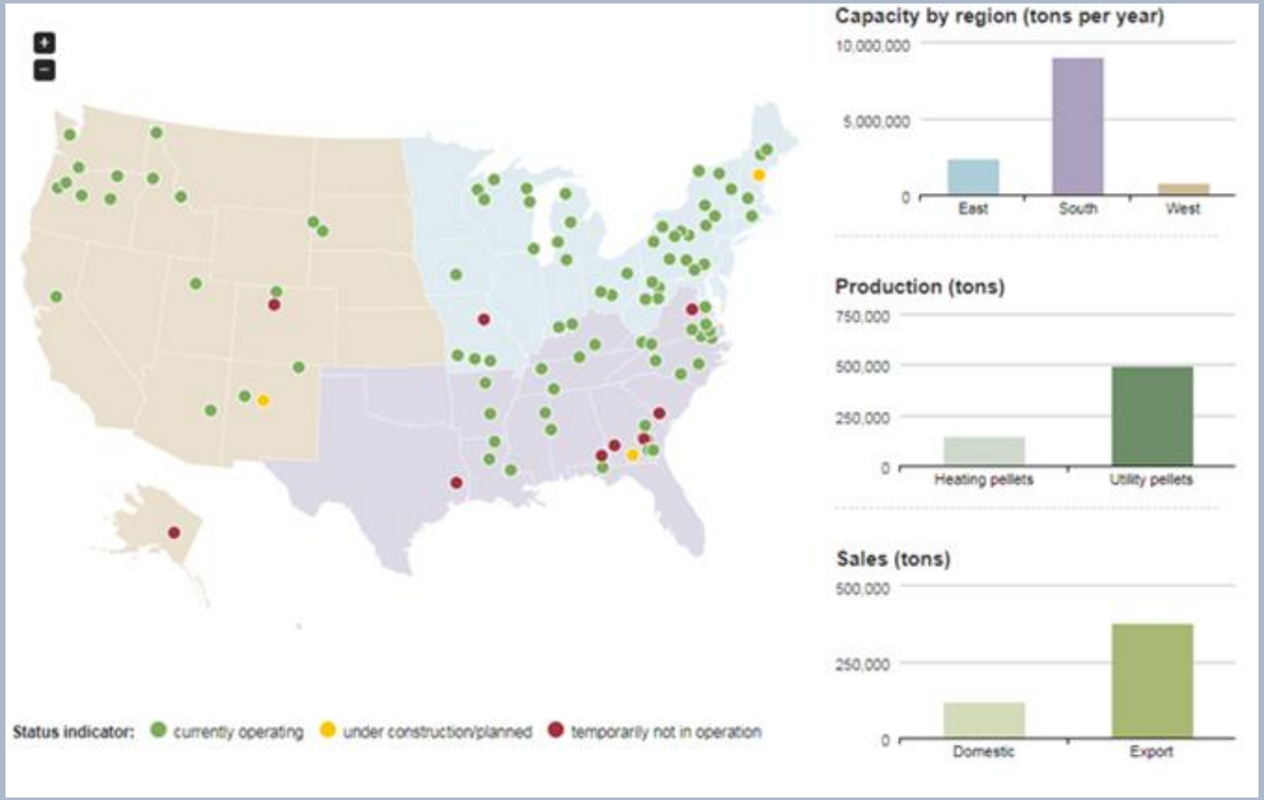
Beringer et al. 2011

2. Opportunities for integrating bioenergy into forestry and agriculture

- Bioenergy intercropping as an example
  - Economic diversification
    - Rural economic development (harvesting, handling, processing bioenergy)
    - Integrate bioenergy cropping with agriculture
      - More research is needed
      - Development of markets
    - Added product streams for farmers
  - Restoration of soil properties and biodiversity
    - SOC, nutrients, soil structure, decreased nematodes, etc.
    - Increase biodiversity of agricultural landscapes
    - Improve climate profile of agricultural landscapes
  - Regional and national C balance, impacts on water
    - Fossil fuel offsets
    - Energy security
    - C sequestration in soils
    - Must understand effects on regional water cycling

Photo credit: R. Ceulemans, POPFULL, U Antwerp

Strong and growing demand



US densified biomass (wood pellets) production facilities by state, region, and capacity, March, 2018 (US EIA).

FORISK, 2022

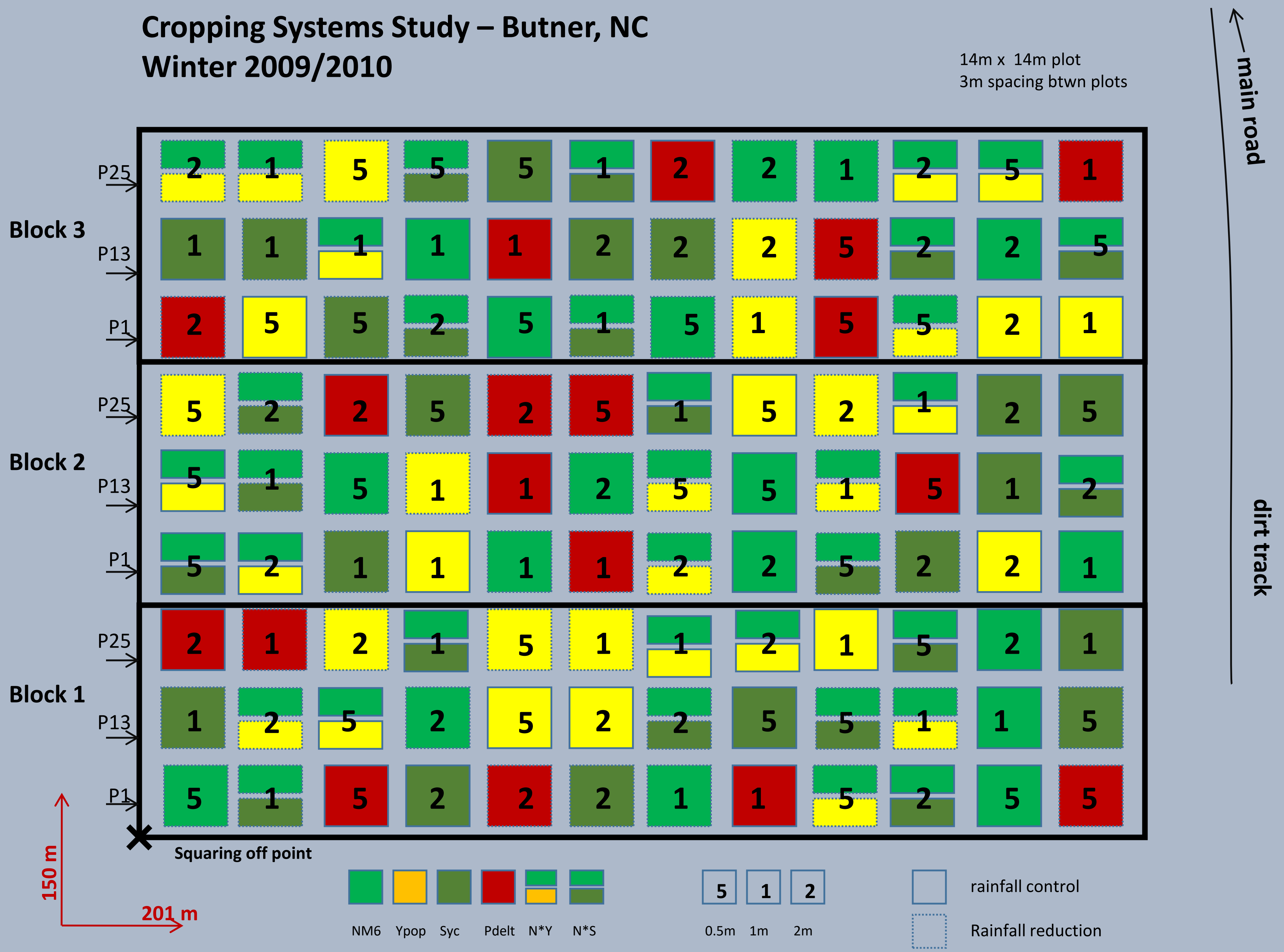
3. American sycamore: Unrecognized potential

- Native species with wide range of environmental tolerances
- HIGH tolerance of biotic and abiotic stress
  - Tolerates both drought and flooding, not many pests
- Moderate to very good productivity with LOW INPUT culture
- Seedling production capacity at scale available
- Reliable, low cost establishment with existing technology
- Excellent coppicing and ability to outcompete weeds
- Great potential for tree improvement programs – productivity, drought tolerance, salt tolerance(?), resistance to diseases
- Excellent wood properties and uniformity for bioenergy feedstock at scale
  - Good energy content (19-20 MJ kg^{-1}), dries well, thin bark/low ash content
- Capacity to improve agricultural soil health and biodiversity
  - Chemical, physical and biological properties
- Improves farm-scale and regional carbon and water cycling

Seed source and establishment

NC Forest Service Claridge Nursery
Goldsboro, NC

Cropping Systems Study – Butner, NC
Winter 2009/2010



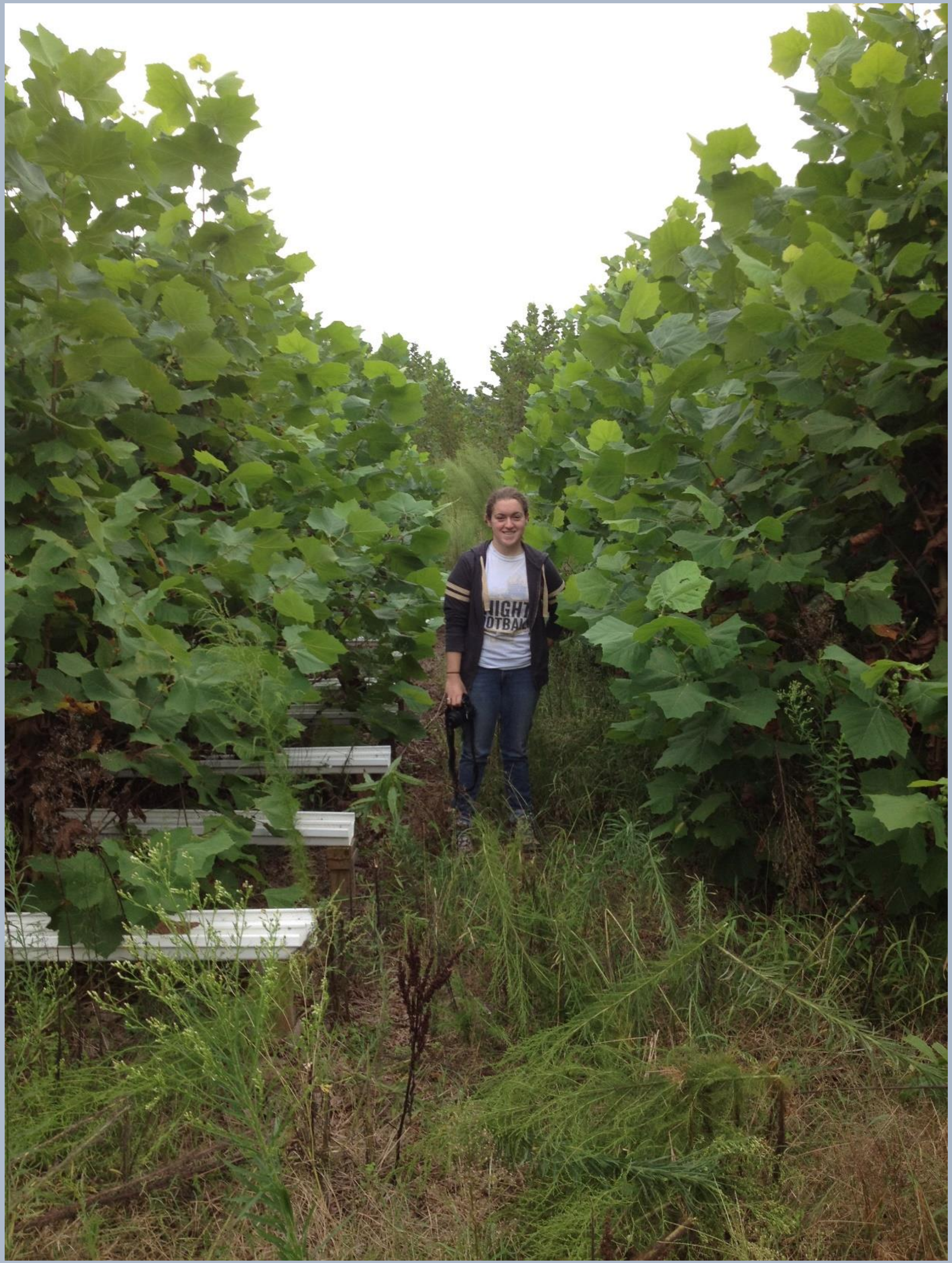
July 2010

Note low input culture

Winter Harvest 2013/2014

Harvest and Coppice

September, 2014



Winter/Spring Harvest 2019

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journal homepage: http://www.elsevier.com/locate/biombioe

Productivity of low-input short-rotation coppice American sycamore (*Platanus occidentalis* L.) grown at different planting densities as a bioenergy feedstock over two rotation cycles

Omoyemeh J. Ile[a,*], Maricar Aguilos[a], Suna Morkoc[b], Kevan Minick[a], Jean-Christophe Domec[c], John S. King[a]

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A R T I C L E I N F O

Keywords:
Sustainable bioenergy
Low silvicultural input
Degraded land
Woody biomass partitioning
Short rotation woody crops

A B S T R A C T

Short rotation coppice culture of woody crop species (SRWCs) has long been considered a sustainable method of producing biomass for bioenergy that does not compete with current food production practices. In this study, we grew American sycamore (*Platanus occidentalis* L.) for nine years corresponding to two rotation cycles (first rotation (FR) = 2010–2014, second rotation (SR) = 2015–2019). This was done at varying tree planting densities (1250, 2500, 5000, and 10,000 trees per hectare (tph)) on a degraded agricultural landscape under low-input (e.g. no fertilizer and low herbicide application) culture, in the Piedmont physiographic region of eastern North Carolina. Tree productivity was proportional to planting density, with the highest cumulative aboveground wood biomass in the 10,000 tph treatment, at 23.2 ± 0.9 Mg ha^{-1} and 39.1 ± 2.4 Mg ha^{-1} in the first and second rotations, respectively. These results demonstrate increasing productivity under a low-input SRWC management regime over the first two rotations. Biomass partitioning was strongly affected by planting density during FR, allocating less biomass to stems relative to other plant parts at low planting density (44–59% from 1250 to 10,000 tph, respectively). This effect disappeared during SR, however, with biomass partitioning to stems ranging from 74 to 79% across planting densities. Taken together, our results suggest that American sycamore has the potential to be effectively managed as a bioenergy feedstock with low input culture on marginal agriculture lands.

1. Introduction

Renewable energy such as solar energy, wind energy and bioenergy derived from biomass are alternative sources that could reduce GHG emissions, thereby supporting goals of the Paris Agreement [1]. This agreement aims to mitigate climate change in the 21st century by decreasing CO_2 from the atmosphere and limiting temperature increase in this century to 2 °C [2,3]. The focus of the current study is on cellulosic bioenergy, a renewable energy source produced from a variety of plant materials including herbaceous perennial crops, crop residues and woody bioenergy species. Biomass-based energy can offset the effects of GHG emissions on the environment, as well as enhance domestic economic development by supporting rural communities and industries involved in bio-based products [4].

There are long-term data on the biomass productivity of corn and perennial grasses because of extensive research on these species compared to woody bioenergy species [5,6]. However, when corn and perennial grasses are grown solely for ethanol production, this can increase production costs greatly, add carbon to the atmosphere during fertilization and tillage, and can stress water resources [5,7,8]. A more sustainable bioenergy feedstock would be plants that can be grown with minimal agricultural/silvicultural inputs, which decreases costs and the environmental footprint. Trees, especially species that coppice vigorously after harvesting, have great potential as bioenergy feedstocks. Trees produce deep, extensive root systems to access soil resources and withstand many environmental stresses. Fine root mortality and turnover provide biochemically complex carbon inputs to the soil, in contrast to the shallow root systems of many annual crops [5,9,10].

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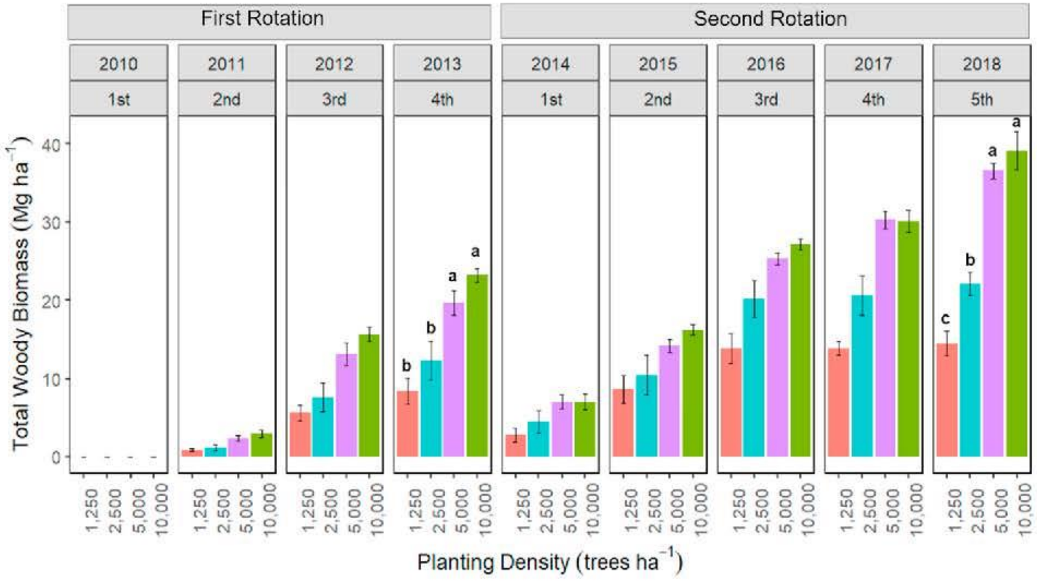
Table 1
Biomass regression equation used to estimate productivity of American sycamore.

Estimated variable	Biomass regression equation	R^2
Total tree	$0.0013(BA)^{1.0922}$	0.9594
Total stem weight	$0.0015(BA)^{1.0447}$	0.9751
Total live Branches	$0.00002(BA)^{1.3088}$	0.6649
Total dead Branches	$0.00002(BA)^{1.0426}$	0.7466

Adapted from Boone, 2017 [57].



ulative American sycamore total (means, ±SE) woody biomass (Mg ha^{-1}) for each year by planting density. Trees were coppiced winter of 2013/2014 to rotation (FR). The second rotation ended with a harvest in winter 2018/2019. Differing letters on bars indicate statistical significance ($P < 0.05$) at the end of the FR and SR.

Table 2
Average (standard error) Aboveground Net Primary Productivity (ANPP) (Mg ha^{-1} y^{-1}) for each planting density (trees per hectare, tph). Year 2013 ends the first rotation (FR = 2010–2013) and year 2014 begins the second rotation (SR = 2014–2018). 2010 represents the year of establishment, hence, there are no available data for that year.

Planting density (tph)	ANPP							
	First Rotation (2010–2013)			Second Rotation (2014–2018)				
	2011	2012	2013	2014	2015	2016	2017	2018
10,000	2.98 (0.45)	12.69 (0.74)	7.49^{a} (0.82)	7.00 (0.70)	9.27 (0.70)	10.84 (0.75)	2.98 (1.40)	9.03^{a} (1.70)
5000	2.34 (0.37)	10.83 (1.21)	6.46^{a} (1.24)	7.00 (0.50)	7.20 (0.51)	11.11 (0.47)	4.96 (1.11)	6.25^{a} (0.50)
2500	1.18 (0.34)	6.45 (1.60)	4.69^{b} (1.16)	4.48 (0.80)	5.99 (1.00)	9.70 (0.66)	0.46 (0.21)	1.42^{b} (1.00)
1250	0.88 (0.21)	4.76 (0.99)	2.80^{c} (0.92)	2.82 (0.50)	5.85 (0.91)	5.14 (1.09)	0.06 (0.01)	0.61^{b} (0.40)

Different superscript letters indicate significant differences between planting density treatments ($P < 0.05$) at the end of each rotation.

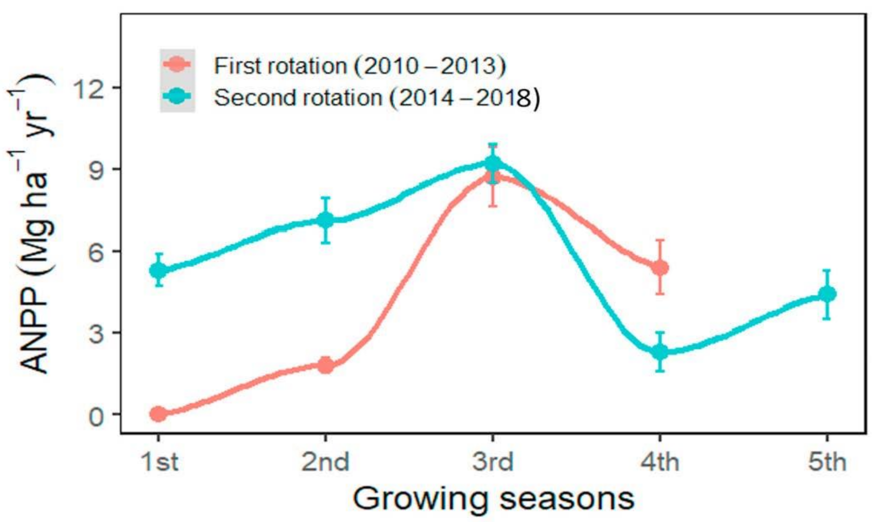


Fig. 4. Average ANPP (Mg ha^{-1} yr^{-1}) across the four planting densities for each growing season of the first and second rotations. In both rotations, there was a decline in productivity after the third growing season. Vertical bars represent the standard error of the mean.

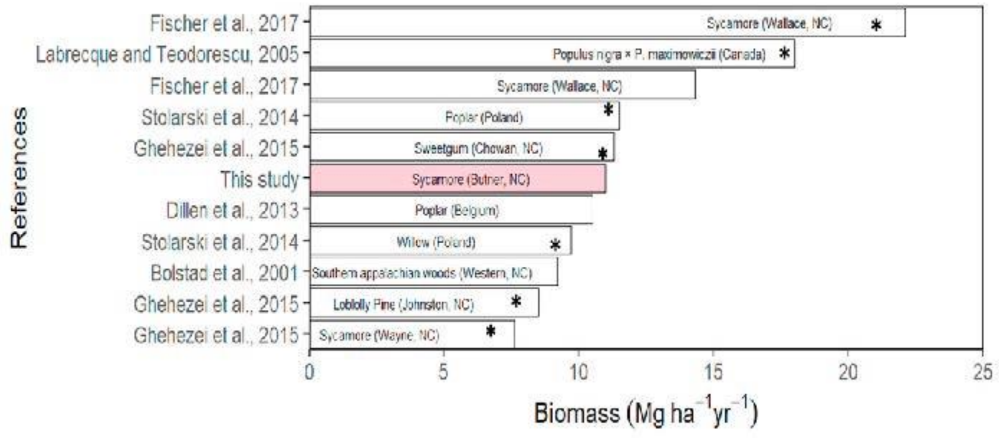
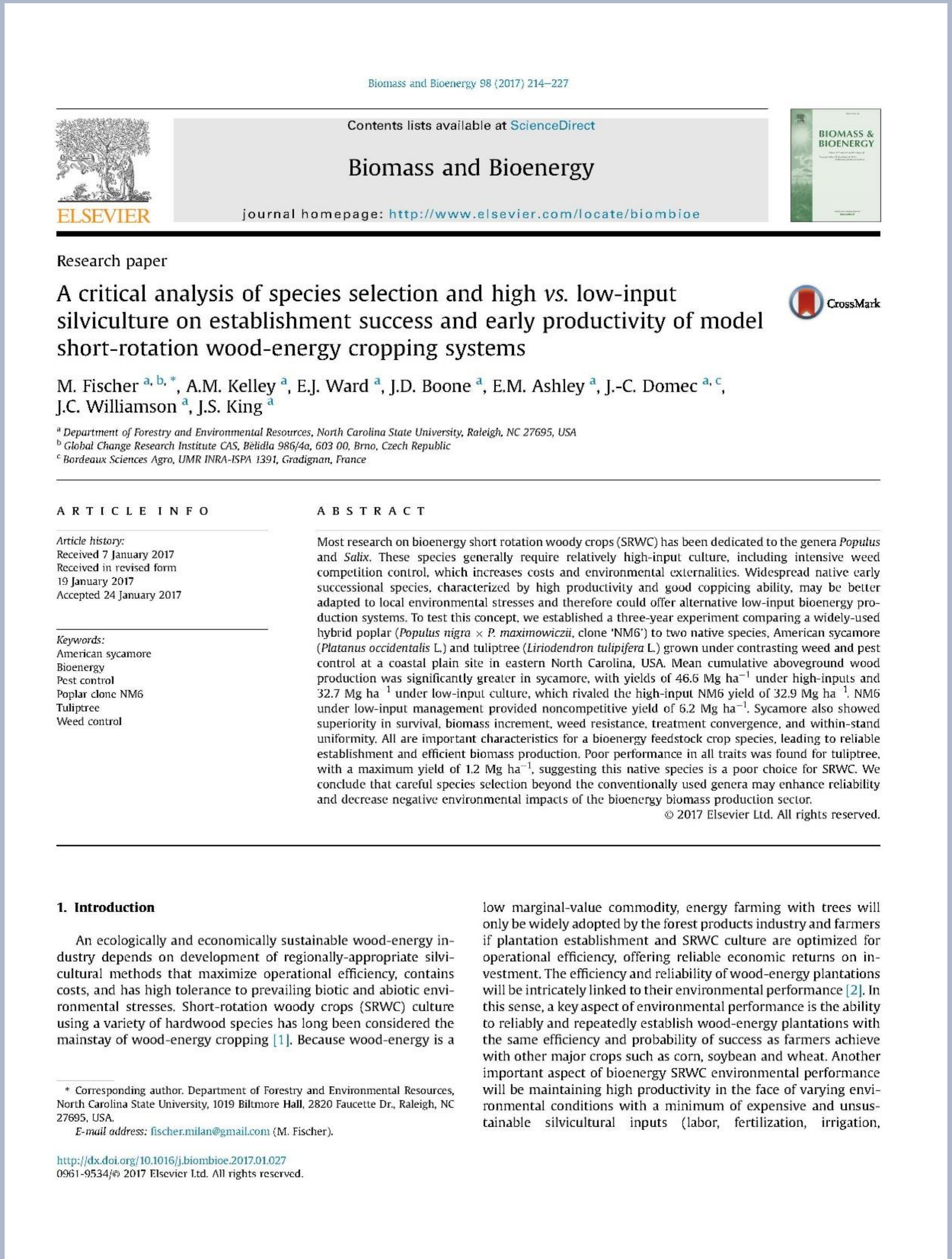


Fig. 7. Annual biomass productivity (third growing season of the second rotation, year 2016) of American sycamore trees planted on marginal land with low input (this study), compared to other woody species. Asterisks (*) depicts studies that incorporated fertilizers, herbicides and/or irrigation.

This experience has been repeated multiple times, at multiple sites in eastern and central NC



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Research paper

A critical analysis of species selection and high *vs.* low-input silviculture on establishment success and early productivity of model short-rotation wood-energy cropping systems

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ABSTRACT

Most research on bioenergy short rotation woody crops (SRWC) has been dedicated to the genera *Populus* and *Salix*. These species generally require relatively high-input culture, including intensive weed competition control, which increases costs and environmental externalities. Widespread native early successional species, characterized by high productivity and good coppicing ability, may be better adapted to local environmental stresses and therefore could offer alternative low-input bioenergy production systems. To test this concept, we established a three-year experiment comparing a widely-used hybrid poplar (*Populus nigra* × *P. maximowiczii*, clone 'NM6') to two native species, American sycamore (*Platanus occidentalis* L.) and tuliptree (*Liriodendron tulipifera* L.) grown under contrasting weed and pest control at a coastal plain site in eastern North Carolina, USA. Mean cumulative aboveground wood production was significantly greater in sycamore, with yields of 46.6 Mg ha^{-1} under high-inputs and 32.7 Mg ha^{-1} under low-input culture, which rivaled the high-input NM6 yield of 32.9 Mg ha^{-1}. NM6 under low-input management provided noncompetitive yield of 6.2 Mg ha^{-1}. Sycamore also showed superiority in survival, biomass increment, weed resistance, treatment convergence, and within-stand uniformity. All are important characteristics for a bioenergy feedstock crop species, leading to reliable establishment and efficient biomass production. Poor performance in all traits was found for tuliptree, with a maximum yield of 1.2 Mg ha^{-1}, suggesting this native species is a poor choice for SRWC. We conclude that careful species selection beyond the conventionally used genera may enhance reliability and decrease negative environmental impacts of the bioenergy biomass production sector.

1. Introduction

An ecologically and economically sustainable wood-energy industry depends on development of regionally-appropriate silvicultural methods that maximize operational efficiency, contains costs, and has high tolerance to prevailing biotic and abiotic environmental stresses. Short-rotation woody crops (SRWC) culture using a variety of hardwood species has long been considered the mainstay of wood-energy cropping [1]. Because wood-energy is a low marginal-value commodity, energy farming with trees will only be widely adopted by the forest products industry and farmers if plantation establishment and SRWC culture are optimized for operational efficiency, offering reliable economic returns on investment. The efficiency and reliability of wood-energy plantations will be intricately linked to their environmental performance [2]. In this sense, a key aspect of environmental performance is the ability to reliably and repeatedly establish wood-energy plantations with the same efficiency and probability of success as farmers achieve with other major crops such as corn, soybean and wheat. Another important aspect of bioenergy SRWC environmental performance will be maintaining high productivity in the face of varying environmental conditions with a minimum of expensive and unsustainable silvicultural inputs (labor, fertilization, irrigation,

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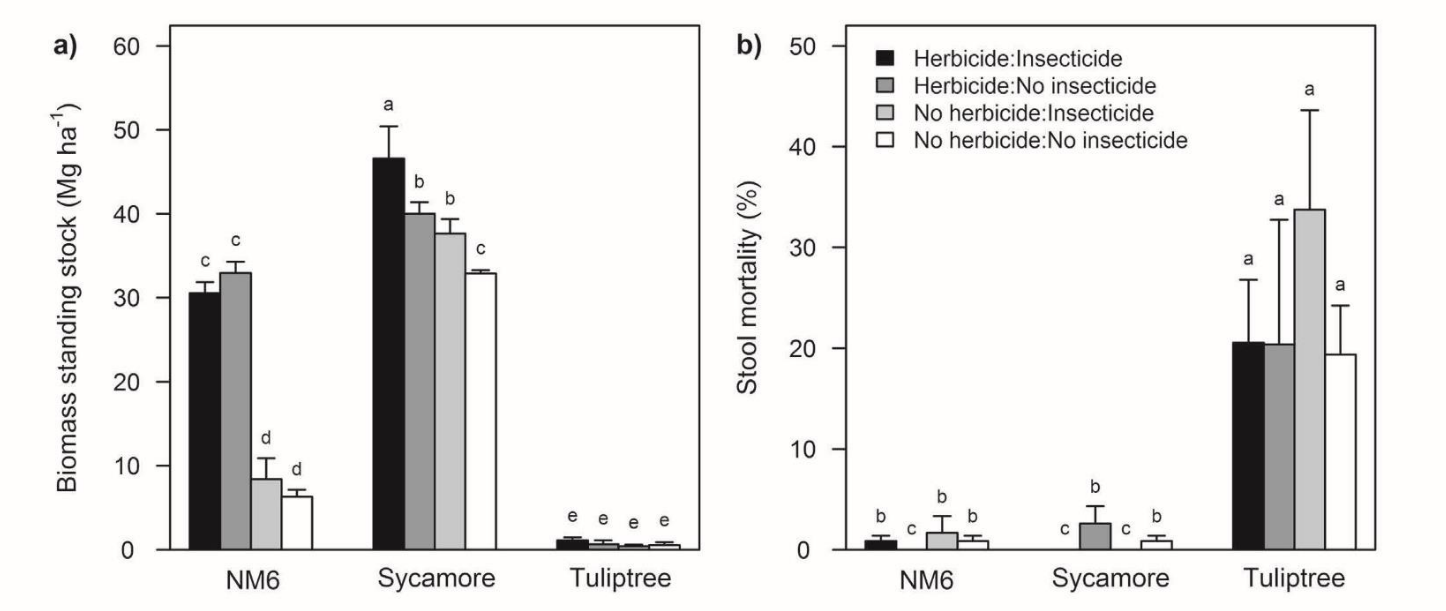

Fig. 5. Mean ± SE (3 replicates) total aboveground woody biomass standing stock cumulated during the 3 years (a) and mortality (b) at the time before harvest in 2014. Bars associated with the same letters are not significantly different (P > 0.05) from each other.

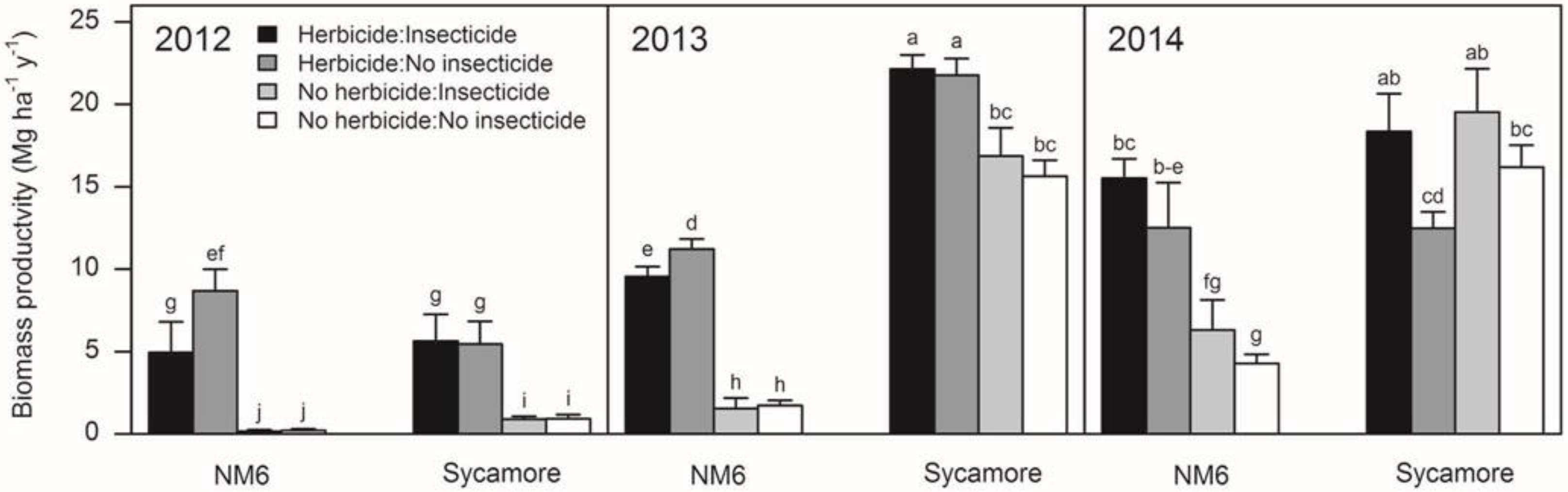

Fig. 4. Mean ± SE (3 replicates) annual aboveground woody biomass productivity. Bars associated with the same letters are not significantly different (P > 0.05) from each other across all years.

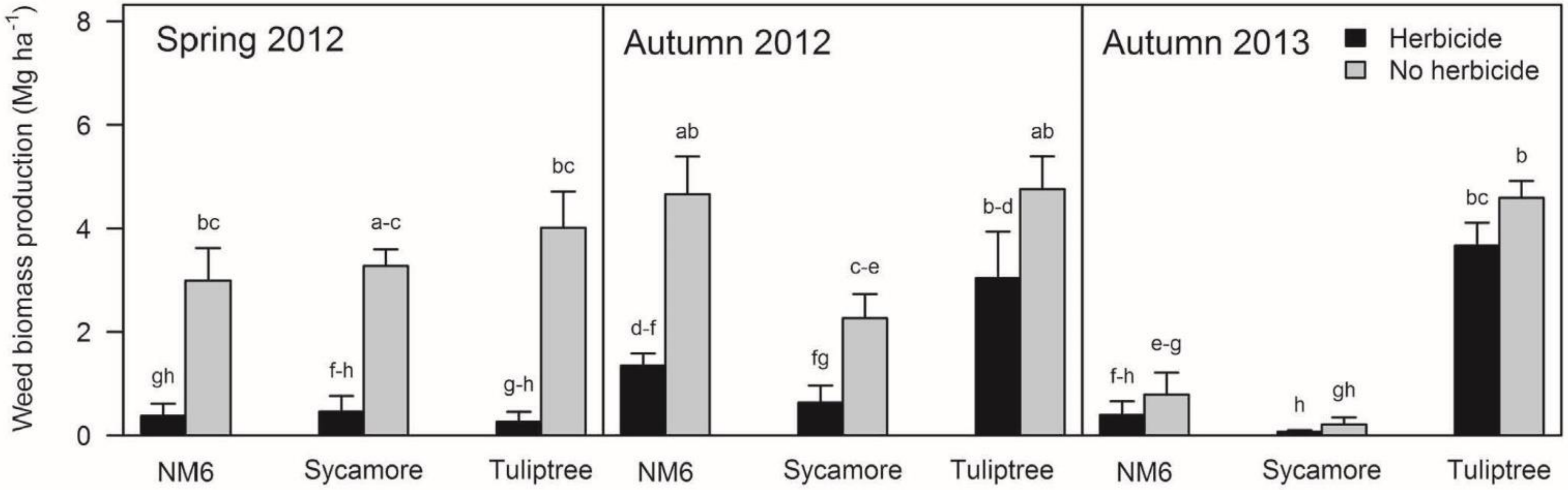

Fig. 3. Mean ± SE (6 replicates) weed biomass productivity. Bars associated with the same letters are not significantly different (P > 0.05) from each other across all periods. Spring refers to mid-May, and autumn to end of November.

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4. Future directions

Quantify ecosystem services provisioning

- Soil chemical, physical and biological properties

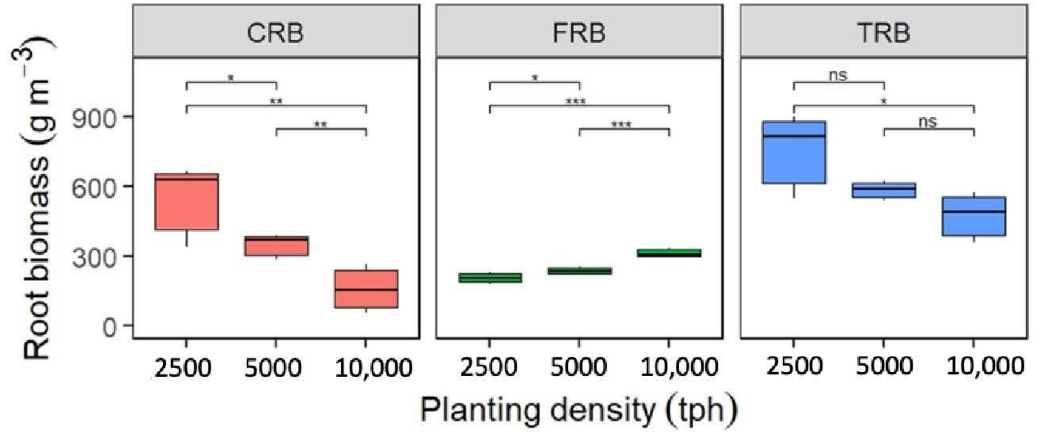

Figure 2. Variation in coarse root biomass (CRB), fine root biomass (FRB), and total root biomass (TRB) across the three different planting densities (2500 trees per hectare (tph), 5000 tph, and 10,000 tph). In the boxplots, the thick line shows the median; the box extends to the upper and lower quartiles; and dashed lines indicate the nominal range. Significant p values at *** < 0.001, ** < 0.05, and * < 0.1).

Table 1. Mean values of soil physical properties in the three planting densities.

Planting Density (tph)	Field Capacity ($m^3\ m^{-3}$)	Drainable Porosity ($m^3\ m^{-3}$)	Permanent Wilting Point ($m^3\ m^{-3}$)	Plant Available Water (%)	Total Porosity ($m^3\ m^{-3}$)	Bulk Density ($Mg\ m^{-3}$)
10,000	0.21 ± 0.01 [a]	0.16 ± 0.03 [a]	0.03 ± 0.00 [a]	18	0.38 ± 0.01 [a]	1.59 ± 0.02 [a]
5000	0.28 ± 0.01 [b]	0.09 ± 0.01 [b]	0.05 ± 0.00 [b]	23	0.37 ± 0.01 [a]	1.60 ± 0.02 [a]
2500	0.30 ± 0.02 [b]	0.10 ± 0.03 [b]	0.05 ± 0.00 [b]	25	0.40 ± 0.01 [a]	1.58 ± 0.03 [a]

Same lowercase letters within a column indicate no significant difference between treatments. Values are means and SEs of field capacity (FC), drainable porosity (DP), permanent wilting point (PWP), plant available water (PAW), total porosity, and bulk density for three planting density treatments in the study at $p < 0.05$.

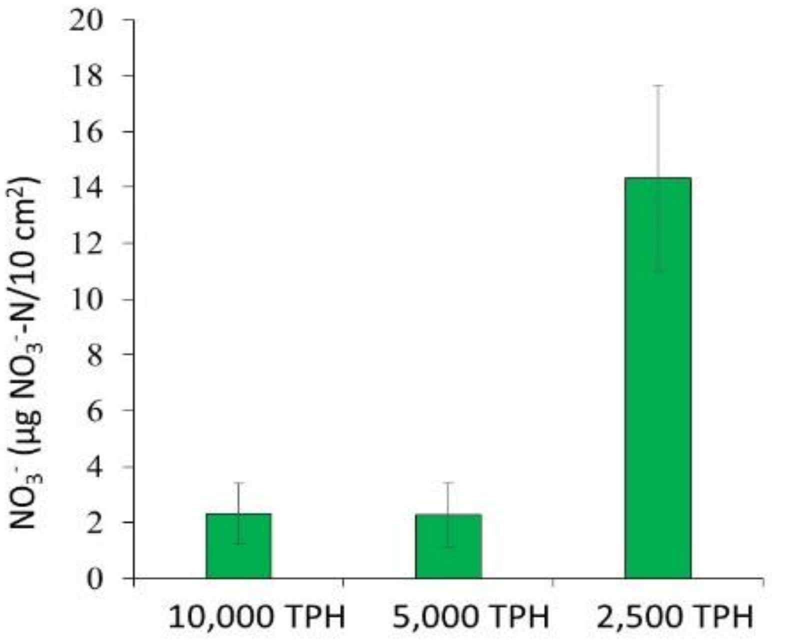

Figure 4. Growing season soil NO3- concentration under different density plantings of bioenergy SRC sycamore at Butner, NC. Minick, unpublished data.

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- Carbon and water cycling with Bowen ratio and eddy covariance studies

Planted at Butner in Winter 2021, experienced significant drought spring/summer, and intense weed competition, captured site by fall

Outreach and extension

- North Carolina Bioenergy Research Initiative/NCDACS
  - New project to work with farmers in eastern NC to operationally integrate sycamore (Winter 2022/2023) and get the word out
  - Quarterly and Annual Field Days
    - Fall 2023-Williamsdale Bioenergy Research Station (Duplin County)
  - Surveys to identify barriers to adoption

- NC Forest Service, seedling production/tree improvement
- NC Cooperative Extension, technology transfer
- Wood products industry, especially along lower coastal plain
- Pellet manufacturers and other constituencies/economic sectors

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