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Landsat-based Phenology and Tree Ring Characterization, Eastern US Forests, 1984-2013

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Summary

This data set provides a 30-year record of Landsat TM and ETM+ derived forest phenology and the results of tree ring analyses for annual wood production and nitrogen and carbon isotopic composition at 113 selected forested sites in the eastern United States. The sites are located in four national parks: Prince William Forest Park (PRWI), Harpers Ferry National Historical Park (HAFE), Catoctin Mountain Park (CATO), and Great Smoky Mountains National Park (GRSM). Phenology and tree ring data cover 1984-2013.

From a temporal stack of >240 Landsat TM and ETM+ scenes (30-m resolution) covering the 1984-2013 period, the fraction of photosynthetic vegetation (fPV) was quantified. The fPV data were used to parameterize a dual sigmoid logistic growth curve representing seasonal patterns of fPV from which phenological parameters including spring onset and autumn offset were derived for each of the four parks.

Based on similar phenology and tree species in common, 113 sites were selected across the four parks. In total, 222 trees of three deciduous species (*Liriodendron tulipifera*, *Quercus rubra*, and *Quercus alba*) were cored. Individual rings were separated and annual wood production, carbon and nitrogen content, and δ13C, and δ15N isotope ratios were measured.

This data set includes 42 data files. There are 40 files in GeoTIFF (.tif) format; with ten files per park. These GeoTIFF files are maps of the Landsat and model-derived average phenology parameters that were used to stratify and randomly select sites for tree coring within each park. There are also two files in comma-separated (.csv) format: 1) results of individual tree ring measurements and analyses for each site; and 2) site locations and physical characteristics, and site averages of phenology parameters and tree ring analysis results.

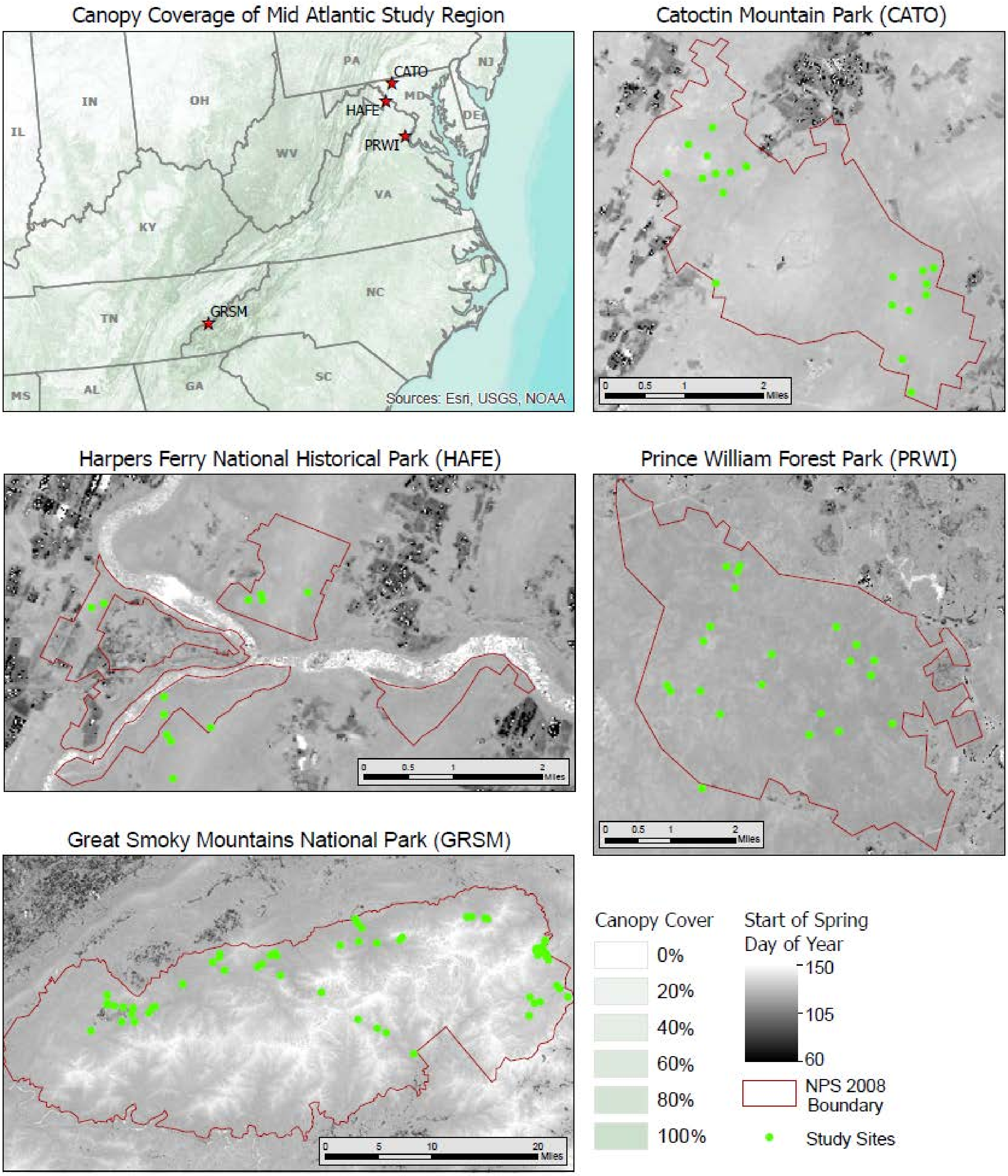

Figure 1. Location map of sites across the four study regions spanning the Appalachian Oak mesophytic forest of the eastern United States. The background maps for the park sites are the 30-year average phenology parameter, spring onset of greenness (spring_onset), as provided with this data set.

Citation

Elmore, A.J., D. Nelson, S.M. Guinn, and R. Paulman. 2017. Landsat-based Phenology and Tree Ring Characterization, Eastern US Forests, 1984-2013. ORNL DAAC, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1369

Table of Contents

1. Data Set Overview

This data set provides a 30-year record of Landsat TM and ETM+ derived forest phenology and the results of tree ring analyses for annual wood production and nitrogen and carbon isotopic composition at 113 selected forested sites in the eastern United States. The sites are located in four national parks: Prince William Forest Park (PRWI), Harpers Ferry National Historical Park (HAFE), Catoctin Mountain Park (CATO), and Great Smoky Mountains National Park (GRSM). Phenology and tree ring data cover 1984-2013.

From a temporal stack of >240 Landsat TM and ETM+ scenes (30-m resolution) covering the 1984-2013 period, the fraction of photosynthetic vegetation (fPV) was quantified. The fPV data were used to parameterize a dual sigmoid logistic growth curve representing seasonal patterns of fPV from which phenological parameters including spring onset and autumn offset were derived for each of the four parks.

Based on similar phenology and tree species in common, 113 sites were selected across the four parks. In total, 222 trees of three deciduous species (*Liriodendron tulipifera*, *Quercus rubra*, and *Quercus alba*) were cored. Individual rings were separated and annual wood production, carbon and nitrogen content, and δ13C, and δ15N isotope ratios were measured.

Project: North American Carbon Program (NACP)

The North American Carbon Program (NACP) is a multidisciplinary research program designed to improve scientific understanding of North America's carbon sources and sinks and of changes in carbon stocks needed to meet societal concerns and to provide tools for decision makers.

Related Publication:

Elmore, A. J., Nelson, D.M., and Craine, J.M. Earlier springs are causing reduced nitrogen availability in North American eastern deciduous forests, *Nature Plants* (2016). http://dx.doi.org/10.1038/nplants.2016.133

Acknowledgements:

This project was supported by the National Aeronautics and Space Administration's Terrestial Ecology Program and North American Carbon Program NNX12AK17G.

2. Data Characteristics

Spatial Coverage

The four study areas are located in the eastern US and are separated by more than 500 km: Prince William Forest Park, Harpers Ferry Historical Park, Catoctin Mountain Park, and the Great Smoky Mountains Park.

Spatial Resolution

Landsat imagery and the phenology parameter maps are at 30-m resolution. The sampling sites were randomly selected within common phenology classes at this same 30-m resolution, within the four national parks.

Temporal Coverage

1984-01-01 through 2013-12-31

Temporal Resolution

Annual

Site boundaries: (All latitude and longitude given in decimal degrees, datum: WGS84)

Site (Region)	Westernmost Longitude	Easternmost Longitude	Northernmost Latitude	Southernmost Latitude
Prince William Forest Park	-77.441	-77.322	38.6439	38.5592
Harpers Ferry Historical Park	-77.796	-77.627	39.3558	39.2881
Catoctin Mountain Park	-77.525	-77.407	39.6947	39.5422
Great Smoky Mountains National Park	-84.034	-82.983	35.8981	35.3389

Data File Information

There are 42 data files in this data set. This includes two files in comma-separated (.csv) format and 40 files in GeoTIFF (.tif) format.

File name	Description
dendrophenology_rings.csv	This file provides individual tree ring width and wood analyses of C, N, 13C, 15N, tree diameter at breast height (DBH), and calculated Basal Area Increment (BAI)
dendrophenology_sites.csv	This file provides site location and physical characteristics, species occurrence, and site averages of phenology parameters and tree ring measurement results.
XXXX_phenology_pre2013_**parameter**.tif	40 GeoTIFF files, 10 parameter files per park, of the Landsat and model-derived average phenology maps used to stratify and randomly select sites for tree coring within each park. File naming syntax described below.

Table 1. Variables in the file **dendrophenology_rings.csv**

Variable ID	Units	Description
site_id		Four letter code indicating the park unit followed by a number indicating the site number
region		Harpers Ferry Historical Park (HAFE); Catoctin Mountain Park (CATO); Prince William Forest Park (PRWI); Great Smokey Mountains Park (GRSM)
elevation	meters	Elevation
slope	degrees	Topographic slope
aspect	degrees	Topographic aspect
tree_id		The site_id, followed by the tree number. There were two trees at each site.
core_id		The tree id, followed by a core id. Each tree was cored two times but only one core was measured for isotopes.
sp_code		A four letter code indicating the tree species. QUAL = *Quercus alba*; QURU = *Quercus rubra*; LITU = *Liriodendron tulipifera*
DBH	cm	Diameter at breast height (DBH)
ring_width	mm	Ring width
BAI	mm^2	Basal Area Increment (BAI)
Year	YYYY	Year the ring grew on the tree
dC	per mil	delta 13C of carbon in the tree ring
C_wood	%	Percent carbon in ring wood
CO2_air	ppm	Atmospheric concentration of CO2. Data are from the Scripps CO2 Program, Scripps Institution of Oceanography
d13C_CO2_air	per mil	delta 13C of CO2 in air. Data are from the Scripps CO2 Program, Scripps Institution of Oceanography
d13C_wood	per mil	Carbon isotope discrimination measured in wood
Ci	ppm	The internal CO2 concentration
Ci_Ca	unitless	The seasonally integrated ratio of internal (Ci) to atmospheric (Ca) CO2 concentration.
Ca_minus_Ci	ppm	Ca minus Ci (used to calculate iWUE)
iWUE	ratio	iWUE equal to the ratio of photosynthesis (A) to stomatal conductance of water vapor (gw)
		Mean residual fraction of photosynthetic vegetation (fPV) in the early

early_sum_ann	fPV	summer. Early summer is defined as starting 20 days after the spring onset and ending on DOY 221.
late_sum_ann	fPV	Mean residual fraction of photosynthetic vegetation (fPV) in the late summer. Late summer is defined as starting on DOY 221 and ending 20 days before the autumn offset of greeness
spring_ann	days	Mean offset in the DOY direction of fPV relative to the mean fPV on that DOY across all years
autumn_ann	days	
N_wood	%	Percent nitrogen in wood
d15_N	per mil	delta 15N of nitrogen in wood

Table 2. Variables in the file **dendrophenology_sites.csv**

Variable ID	Units	Description
site_id		Four letter code indicating the park unit followed by a number indicating the site number
region		Harpers Ferry Historical Park (HAFE); Catoctin Mountain Park (CATO); Prince William Forest Park (PRWI); Great Smokey Mountains Park (GRSM)
easting	meters	Spatial location east of the meridian of the UTM zone identified in the srid
northing	meters	Spatial location north of the equator
Datum_srid		EPSG code which corresponds to the WGS 84 / UTM zone 18N or 17N. The values are 32617 or 32618
slope	degrees	Topographic slope
aspect	degrees	Topographic aspect
elevation	meters	Elevation
LITU	binary	Indicates presence of *Liriodendron tulipifera* among the tree species cored at the site.
QURU	binary	Indicates presence of *Quercus rubra* among the tree species cored at the site.
QUAL	binary	Indicates presence of *Quercus alba* among the tree species cored at the site.
av_min_veg_cover	fraction	The average minimum vegetation cover. fPV is the fraction of photosynthetically active vegetation
av_cover_amplitude	fraction	The vegetation cover amplitude, achievable only when the rate of greendown during the summer growing season equals 0.
spring_inflection_point	days	The day of year (DOY) of the spring inflection point (i.e., days since Jan 1).
greenness_increase_max_greeness	days	Proportional to the length of the spring greenup period. Approximately equal to 1/3 of the length of time (in days) between the onset of greenness increase and the onset of greenness maximum.
autumn_inflection_point	days	The day of year of the autumn inflection point
autumn_greendown	days	Proportional to the length of the spring greenup period
greendown_fPV	fPV/day	Rate of greendown during the summer growing season
d15N_slope	per mil/yr	Trend over time in delta 15N
d15N_p_value		P-value for the trend over time in delta 15N
d15N_mean	per mil	Site mean delta 15N
D13C_slope	per mil/yr	Trend over time in carbon isotope discrimination (Delta 13C)
D13C_p_value		P-value for the trend over time in Delta 13C
D13C_mean	per mil	Site mean Delta 13C
BAI_slope	mm^2/yr	Trend over time in Basal Area Increment (BAI)
BAI_p_value		P-value for the trend over time in BAI
BAI_mean	mm^2	Site mean BAI

iWUE_slope	unitless ratio/yr	Trend over time in intrinsic Water Use Efficiency (iWUE)
iWUE_p_value		P-value for the trend over time in iWUE
iWUE_mean	unitless ratio	Site mean iWUE

Note: The Elmore et al., 2012 study did not include the Great Smoky Mountains National Park site.

GeoTIFF Files

There are 40 GeoTIFF files with this data set. The files are Landsat and model-derived average phenology parameter maps used to stratify and randomly select sites for tree coring within each park.

The files are named **XXXX_phenology_pre2013_"parameter".tif**

Where:

XXXX = park [Harpers Ferry Historical Park (HAFE); Catoctin Mountain Park (CATO); Prince William Forest Park (PRWI); Great Smokey Mountains Park (GRSM)]; and

"parameter"= phenology parameters.

Example file name: **cato**_phenology_pre2013_**autumn_offset**.tif

[The "_pre2013_" element denotes that the files contain data from 1984 to 2013.]

Table 3. Descriptions of parameters provided in the GeoTIFF files. There are 10 files/parameters per park. Note cross references to corresponding variables in the *_sites.csv data file and bootstrapping parameter numbers in Section 4.

"parameter" Phenology parameter in respective map file.	Units	Description	Corresponding variable in *_sites.csv data file	Corresponding parameter number. See Section 4.
autumn_offset	days	Equals the day of year of the autumn inflection point.	autumn_inflection_point	m5
autumn_offset_slope	days	Proportional to the length of the autumn greendown period.	autumn_greendown	m6
min_veg_cover	fraction	The average minimum vegetation cover. fPV is the fraction of photosynthetically active vegetation.	av_min_veg_cover	m1
model_iterations		The number of model iterations required to calculate the phenology parameters	Not applicable	NA
model_misfit		Model misfit, calculated using Equation 8 in Elmore et al., 2012	Not applicable	NA
num_landsat_images		The number of Landsat images used for that pixel (the value changes across the image due to cloud cover that obscures some pixels but not all)	Not applicable	NA
potential_amplitude	fraction	Equals the vegetation cover amplitude, achievable only when **"summer_greendown"** equals 0.	av_cover_amplitude	m2
spring_onset	days	Equals the day of year (DOY) of the spring inflection point (i.e., days since Jan 1)	spring_inflection_point	m3
spring_onset_slope	days	Proportional to the length of the spring greenup period. Approximately equal to 1/3 of the length of time (in days) between the onset of greenness increase and the onset of greenness maximum.	greenness_increase_max_greeness	m4
summer_greendown	fPV/day	Rate of greendown during the summer	greendown_fPV	m7

Feedback

		growing season		

Attributes of the *.tif files

All files contain the following attributes:

File type	File format	Map units	Resolution	Number of bands	Data type	Fill value
raster	GeoTiff	meter	30	1	Float32	3.4E+38

The table below provides file names and attributes of the individual files. Minimum and maximum values may reflect the values the model derived for non-forest land areas.The phenology parameter files are unfiltered.

Table 4. Attributes of the GeoTIFF files.

Filename	crs_proj4	West	East	South	North	Min value	Max value
cato_phenology_pre2013_autumn_offset.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-75.7	648.9
cato_phenology_pre2013_autumn_offset_slope.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-33.7	48.9
cato_phenology_pre2013_min_veg_cover.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-0.1	0.6
cato_phenology_pre2013_model_iterations.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	2	101
cato_phenology_pre2013_model_misfit.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	21.8	779.8
cato_phenology_pre2013_num_landsat_images.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	32	161
cato_phenology_pre2013_potential_amplitude.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-2.6	6.3
cato_phenology_pre2013_spring_onset.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-241.9	596.3
cato_phenology_pre2013_spring_onset_slope.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-23.6	43.8
cato_phenology_pre2013_summer_greendown.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.525	-77.407	39.5422	39.6947	-0.0174	0.033
grsm_phenology_pre2013_autumn_offset.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-508.9	795.3
	+proj=utm +zone=17						

grsm_phenology_pre2013_autumn_offset_slope.tif	+ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-40.9	66.3
grsm_phenology_pre2013_min_veg_cover.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-0.8	0.8
grsm_phenology_pre2013_model_iterations.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	2	101
grsm_phenology_pre2013_model_misfit.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	0	3414.1
grsm_phenology_pre2013_num_landsat_images.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	1	177
grsm_phenology_pre2013_potential_amplitude.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-7	8.2
grsm_phenology_pre2013_spring_onset.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-578.1	817.6
grsm_phenology_pre2013_spring_onset_slope.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-69.6	59.8
grsm_phenology_pre2013_summer_greendown.tif	+proj=utm +zone=17 +ellps=WGS84 +units=m +no_defs	-84.034	-82.983	35.3389	35.8981	-0.0494	0.04794
hafe_phenology_pre2013_autumn_offset.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-217.6	806.3
hafe_phenology_pre2013_autumn_offset_slope.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-33.8	48.7
hafe_phenology_pre2013_min_veg_cover.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-0.1	0.6
hafe_phenology_pre2013_model_iterations.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	2	101
hafe_phenology_pre2013_model_misfit.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	18.7	970.4
hafe_phenology_pre2013_num_landsat_images.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	25	171
hafe_phenology_pre2013_potential_amplitude.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-3.2	6.3
hafe_phenology_pre2013_spring_onset.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-626.8	532.3
hafe_phenology_pre2013_spring_onset_slope.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-30.3	48.4
hafe_phenology_pre2013_summer_greendown.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.796	-77.627	39.2881	39.3558	-0.0208	0.0387
	+proj=utm +zone=18						

prwi_phenology_pre2013_autumn_offset.tif	+datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	456.8
prwi_phenology_pre2013_autumn_offset_slope.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	38.6
prwi_phenology_pre2013_min_veg_cover.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	0.6
prwi_phenology_pre2013_model_iterations.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	101
prwi_phenology_pre2013_model_misfit.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	699.2
prwi_phenology_pre2013_num_landsat_images.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	189
prwi_phenology_pre2013_potential_amplitude.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	1.4
prwi_phenology_pre2013_spring_onset.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	555.5
prwi_phenology_pre2013_spring_onset_slope.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	37.5
prwi_phenology_pre2013_summer_greendown.tif	+proj=utm +zone=18 +datum=WGS84 +units=m +no_defs	-77.441	-77.322	38.5592	38.6439	-3.4	0.007

3. Application and Derivation

These data are useful for climate change studies. Advances in remote sensing and dendroecological methods present opportunities to acquire information retrospectively to advance understanding of how phenological changes and resource availability to trees have been affecting forest productivity. This study provides a 30 year record of remotely-sensed forest phenology (Elmore et al., 2016).

As described in Elmore et al. (2016), all data were organized in a PostgreSQL object-relational database and queried for statistical analysis in the R statistical programing language. Two types of models were used to test for the effects of spring and autumn timing on resource availability and wood production. The first type of model used all available observations across trees and time. These models tested for the effects of time, spring anomaly and autumn anomaly on BAI, δ15N and Δ13C from tree rings, and included the main effects of region (GRSM, PRWI, HAFE and CATO) and species (QUAL, QURU and LITU) as blocking factors. Because the different measurements were made at different frequencies, the sample size available for each model varied. Observations of spring (n = 2,143) and autumn (n = 2,911) anomaly were sparse because of low availability of appropriately timed Landsat data. Further, these observations did not always line up with measurements of δ15N, resulting in n = 967 for models comparing spring anomaly with δ15N and n= 1,229 for models comparing autumn anomaly with Δ13C.

In the second set of models, the rate of change (slope) of trends was calculated in tree-ring-based measurements over time and rates were compared across sites. These models aid the interpretation of causal relationships between correlated variables identified in the first set of models. Sample sizes for these models equaled the number of sites (n = 113). Region and three nominal variables were also included in these models indicating the presence or absence of each of the three tree species at the site.

To augment exploration of regression statistics in tabular form, the relationship between δ15N and spring anomaly was visualized in scatterplot form. The scatterplot was generated by first modeling the effects of region and species on δ15N, then modeling the effect of spring anomaly on the model residuals. From the data used to construct this model, the annual mean spring anomaly and annual mean δ15N were calculated (Elmore et al., 2016).

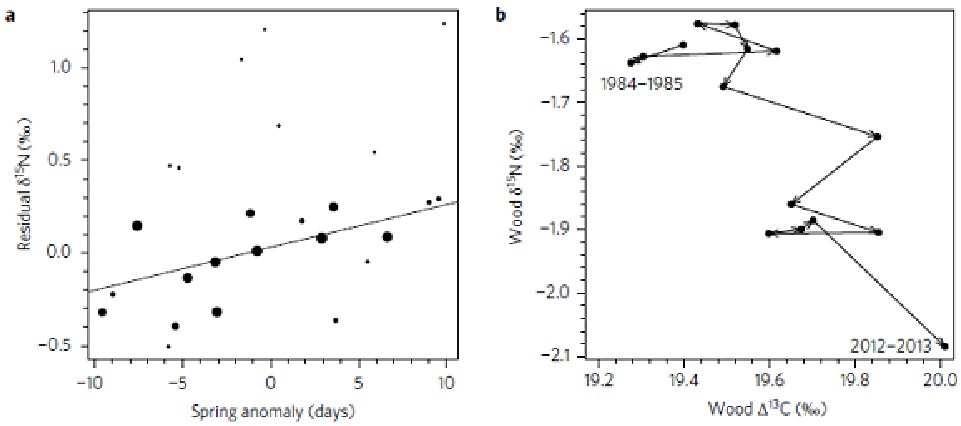

Figure 2. Relationships between mean δ15N, Δ13C, and spring anomaly: a, Years exhibiting an early spring phenology anomaly are associated with low δ15N (r2 = 0.21; P = 0.02), after accounting for region and species effects. Symbol sizes represent sample sizes of paired δ15N and spring anomaly observations in each year, which range from 2 to 93; b, Averaged biennially across all 222 trees, Δ13C has increased and δ15N has decreased over time (Elmore et al., 2016).

4. Quality Assessment

Uncertainty in the average phenology parameters

Bootstrapped resampling was used to calculate uncertainty in the average phenology observations. These were reported in Elmore et al. 2012. Others have compared the annual phenology anomaly with in situ observations (Melaas et al., 2013, Melaas et al., 2016). Analytical precision (1 sigma) of an internal wood standard analyzed alongside samples was 0.1 per mil for del 13C and 0.3 per mil for del 15N. Uncertainty estimates are referenced in Elmore et al. 2016.

Table 3. Summary of bootstrapping results (Elmore et al., 2012). This study did not include the Great Smoky Mountains National Park site.

Parameter	Description	Inversion estimate using d_{obs}	Mean bootstrap estimate	Bootstrap 95% lower bound	Bootstrap 95% upper bound
m1	Minimum vegetation cover	0.1023	0.9977	0.08046	0.1210
m2	Potential amplitude	0.8802	0.8779	0.6917	1.042
m3	Spring onset of greenness	108.2	108.5	100.0	115.7
m4	Slope of spring onset	7.596	8.600	6.182	11.45
m5	Autumn offset of greenness	311.4	311.4	301.6	321.5
m6	Slope of autumn offset	7.473	6.971	4.657	8.742
m7	Summer greendown	0.002250	0.002231	0.001499	0.002898

Sensitivity analysis of effect size on core chronology

To evaluate the sensitivity of our results to the potential for missing or false tree rings, or any other sources of error in core chronology (e.g., the possibility for N translocation between tree rings), a sensitivity analysis was performed in which 1%, 5%, and 10% of the cores were sampled at random for artificial tampering. For each sampled core a ring was either added or taken away from the bark end of the core. This procedure changed the alignment between measurements of ring width, δ13C and δ15N in ring wood, and year and phenology for the cores sampled for tampering. Any of the results that are sensitive to the exact alignment of these measurements will be influenced by this sensitivity analysis. 100 Monte Carlo simulations were performed at each of the three random sampling levels, repeatedly modeled the effects of year, spring anomaly, region, and species on δ15N and constructed histograms of the resulting effects of year and spring anomaly on δ15N.

This sensitivity analysis revealed that the effects of year and spring anomaly are robust to a range of core tampering. As the fraction of cores sampled for tampering increases some random permutations result in either an increase or a decrease in the effect size (both effects). However, the trend of δ*15N* with time is always negative and the effect of an earlier spring is always positive.

5. Data Acquisition, Materials, and Methods

Site description

The study sites were located in four national parks: Prince William Forest Park, Harpers Ferry Historical Park, Catoctin Mountain Park, and Great Smoky Mountains Park. These parks, referred to as 'regions' in this study are within the Appalachian Oak sub-region of the mesophytic forest region extending from New England to Tennessee. The mean annual temperature is 11.76 degrees C and the mean annual precipitation is 1,595 mm across the sampling regions. Elevation ranges from 30 m to more than 1,400 m, which influences temperature and precipitation patterns (Elmore et al., 2016).

Methods

Remotely sensed phenology data

Landsat scenes (>240 depending on location; Thematic Mapper (TM) and Enhanced Thematic Mapper plus +, 30 m pixel, path15/row33) were processed to reflectance using the Landsat Ecosystem Disturbance Processing System (LEDAPS), and analyzed for the photosynthetic vegetation fraction, fPV, using spectral mixture analysis and image end members. Observations of fPV were organized by DOY and fit with two sigmoid logistic growth curves, one increasing in spring and a second decreasing in autumn.

- To evaluate changes in phenology, spring and autumn scenes were identified that were positioned within 20 days of the spring and autumn inflection points, greater than 20% of the site average annual minimum fPV, and less than 20% (spring) and 40% (autumn) of the maximum fPV.
- These spring- and autumn-timed Landsat observations of fPV were compared against the 30-year average date of spring onset and autumn offset, respectively, to calculate anomalies. For any given location, between 5 and 16 spring fPV observations and 7 and 18 autumn fPV observations were identified (mean of 9.7 and 13.4, respectively).
- Residual vegetation cover was also calculated after accounting for the mean vegetation phenology.

Site selection

Maps of average phenology were used to stratify and randomly select locations for tree coring within each park. An ISODATA clustering algorithm was used to identify 20 phenology classes that differed primarily in growing season length and the amplitude of annual fPV. The standard deviation in phenology parameters (3 × 3 pixel neighbor rule) was also calculated and used to further constrain the extent of each phenology class to areas of low spatial variability in phenology. Six randomly located sites were then identified in each phenology class. Alternative sites for each phenology class were also identified; if trees of the target species were not identified at any given site an alternative site was used. Similar methods were employed at all park units used in the study; however, at GRSM we applied two further constraints that (1) all sites must be located below 1,400 m to ensure access to trees of the target species, and (2) sites were located within 250 m of a designated trail to facilitate site access. One hundred and twenty sites were initially identified (60 at northern parks (PRWI, HAFE, and CATO) and 60 at GRSM), but because of access and the availability of the target species only 113 were ultimately included in the study.

Tree cores

At each site, the two largest specimens (occupying the largest portion of the canopy) of three species were targeted for coring: *Quercus alba* (QUAL), *Quercus rubra* (QURU) or *Liriodendron tulipifera* (LITU). If only one of the three species was present, two trees of the same species were cored. Across all 113 sites, 222 trees were cored using a 5.15-mm diameter increment borer at ~1.4 m (breast height) above the forest floor. Two cores positioned at right angles to each other were extracted and stored in paper straws. The species and diameter at breast height (DBH) were recorded.

Core analyses

The cores were dried at 60 degrees C for at least 48 hours, sanded, and then scanned at 472 dots per centimeter. The images were analyzed for ring width using Cybis CDendro Software (Saltsjobaden) and ages assigned to each ring following close visual examination of the increment core. To ensure data quality, cores were visually cross-dated from the same tree and trees from the same site using plots of normalized ring widths and, for a subset of cores, a second researcher collected ring coordinates. One core from each tree was sectioned into annual increments using a razor blade.

Approximately 1 mg of wood from each increment from each core was analyzed for δ13C using a Carlo Erba NC2500 elemental analyser (CE Instruments) interfaced with a ThermoFinnigan Delta V+ isotope ratio mass spectrometer (IRMS). For δ13C analysis, a MgClO4 trap was used to remove water vapor before the transfer of sample gases to the IRMS.

Approximately 10 mg of wood from alternate increments was analyzed for δ15N using the same instruments. Alternate increments were sampled to limit any effects of nitrogen mobility that might have occurred between adjacent tree rings. A Carbosorb trap was used to remove CO2 in advance of removing water vapor with MgClO4 before the transfer of sample gases to the IRMS.

The δ13C and δ15N data were normalized to the VPDB and AIR scales, respectively, using a two-point normalization curve with internal standards calibrated against USGS40 and USGS41. Analytical precision (1σ) of an internal wood standard analyzed alongside samples was 0.1‰ for δ13C and 0.3‰ for δ15N. Carbon isotopes were normalized for trends in atmospheric δ13C resulting from fossil fuel use to arrive at carbon isotope discrimination against 13C (Δ13C).

As a metric of wood production, the Basal area increment (BAI) was calculated from the measured DBH and annual ring widths. The DBH was initially calculated for each year over the past 30 years by subtracting annual ring widths (×2) from the DBH at the time of coring ($DBH_{t)}$. To account for bark thickness 1 cm was subtracted from the measured DBH. The BAI_t was then calculated for each year as follows:

$$BAI_t = \pi[DBHt/2]^2 - \pi[DBH_{t-1}/2]^2$$

6. Data Access

These data are available through the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

Landsat-based Phenology and Tree Ring Characterization, Eastern US Forests, 1984-2013

Contact for Data Center Access Information:

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- Telephone: +1 (865) 241-3952

7. References

Elmore, A. J., Nelson, D.M., and Craine, J.M. Earlier springs are causing reduced nitrogen availability in North American eastern deciduous forests, *Nature Plants* (2016). http://dx.doi.org/10.1038/nplants.2016.133

Elmore, A. J., Guinn, S. M., Minsley, B. J. & Richardson, A. D. Landscape controls on the timing of spring, autumn, and growing season length in mid-Atlantic forests. Glob. Change Biol. (2012). 18, 656–674. http://dx.doi.org/10.1111/j.1365-2486.2011.02521.x

Melaas, E. K., Friedl, M. A. and Zhu, Z. Detecting interannual variation in deciduous broadleaf forest phenology using Landsat TM/ETM plus data. Remote Sens. Environ. (2013) 132, 176–185. http://dx.doi.org/10.1016/j.rse.2013.01.011

Melaas, E. K., Friedl, M. A. and Richardson, A.D. Multiscale modeling of spring phenology across Deciduous Forests in the Eastern United States. Global Change Biology (2016) 22, 792–805. http://dx.doi.org/10.1111/gcb.13122