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Land-use legacies in forests at Jefferson's Monticello plantation

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Abstract

Questions: We evaluate the role of past land use on long-term forest succession and ask fundamental questions: (i) are successional patterns along a chronosequence consistent through time; (ii) is past land use or physiography a greater driver of forest composition; and (iii) does forest composition converge with age?

Location: Thomas Jefferson's Monticello plantation, Virginia Piedmont, USA.

Methods: Combining dendroecology, historical documents and a repeated vegetation survey from 1934, we reconstruct forest histories along a chronosequence that retains a temporal dimension. Tree-ring data indicate initial canopy status and canopy release events using time series analysis with intervention detection.

Results: Forest extent was lowest during Jefferson's tenure; however, tree ring and documentary evidence revealed the location of Jefferson's timber zone. Jefferson-era trees in this zone are largely on the west slope with scattered *Pinus* recruitment starting in the late 18th century, followed by *Quercus* species. *Pinus* cohorts also recruited into former agricultural fields on south and east slopes in two chronosequence stages from the 20th century. Synchronized release events were observed during the early 1800s, 1850s–1860s and 1960s, indicating periods of intense forest use. Ordination of repeated vegetation surveys showed a progression in forest age that explained more variation in forest composition than elevation and slope. The forest age gradient is also evident independently from tree-ring data, but the ordination does not show convergence in composition with forest age.

Conclusion: Past land use is a greater driver of forest composition than an inferred soil moisture gradient. The composition of the most recent chronosequence stage suggests that future forest dynamics may be novel compared to the prior two centuries because of differences in land use and species availability. These land-use legacies demonstrate how colonial-era agricultural decisions at Monticello continue to impact forest growth and composition more than two centuries later.

KEYWORDS
dendroecology, disturbance, eastern deciduous forest, southeast USA, succession

1 | INTRODUCTION

Monticello is a UNESCO World Heritage Site for its neoclassical design by Thomas Jefferson, who authored the Declaration of Independence and served as the third President of the United States. Colonial-era land use at Monticello began with a field and slave quarters by Jefferson's father after patenting the land in 1735 (Urofsky, 2001), which was later referred to as the ancient field by Thomas Jefferson.

More extensive land use occurred in 1768 when Jefferson began construction of his house (Bear & Stanton, 1997). To characterize Jefferson's land use of Monticello, scholars have previously relied on his extensive letters, land surveys and other documents (e.g. Jefferson, Betts, & Hatch, 2008). Notably, in an 1806 draft letter, Jefferson outlines his vision for an English garden landscape at Monticello:

> *the grounds which I destine to improve in the style of the English gardens are in a form very difficult to be managed. They compose the Northern quadrant of a mountain for about 2/3 of its height & then spread for the upper third over its whole crown. They contain about three hundred acres… They are chiefly still in their native woods, which are majestic (Jefferson et al., 2008).*

Visitors during Jefferson's lifetime report a similar distribution of forests. After Jefferson retired from the Presidency in 1809, Margaret Bayard Smith wrote that "the sides of the mountain covered with wood, with scarcely a speck of cultivation, present a fine contrast to its summit, crowned with a noble pile of buildings, surrounded by an immense lawn, and shaded here and there with some fine trees" (Smith, 1906). Jefferson complained how his long absence had left Monticello a "wilderness" and explained the improvements he had planned for the grounds including picturesque roads, walks, buildings and monuments (Smith, 1906). These documentary accounts of forests (and others in Appendix S1) present a potential contradiction when considered alongside extensive documentary accounts of slave-based, tobacco and wheat cultivation at Monticello. While Jefferson divided his plantation into areas of ornamental, agricultural, and forest land uses, their spatial extents have

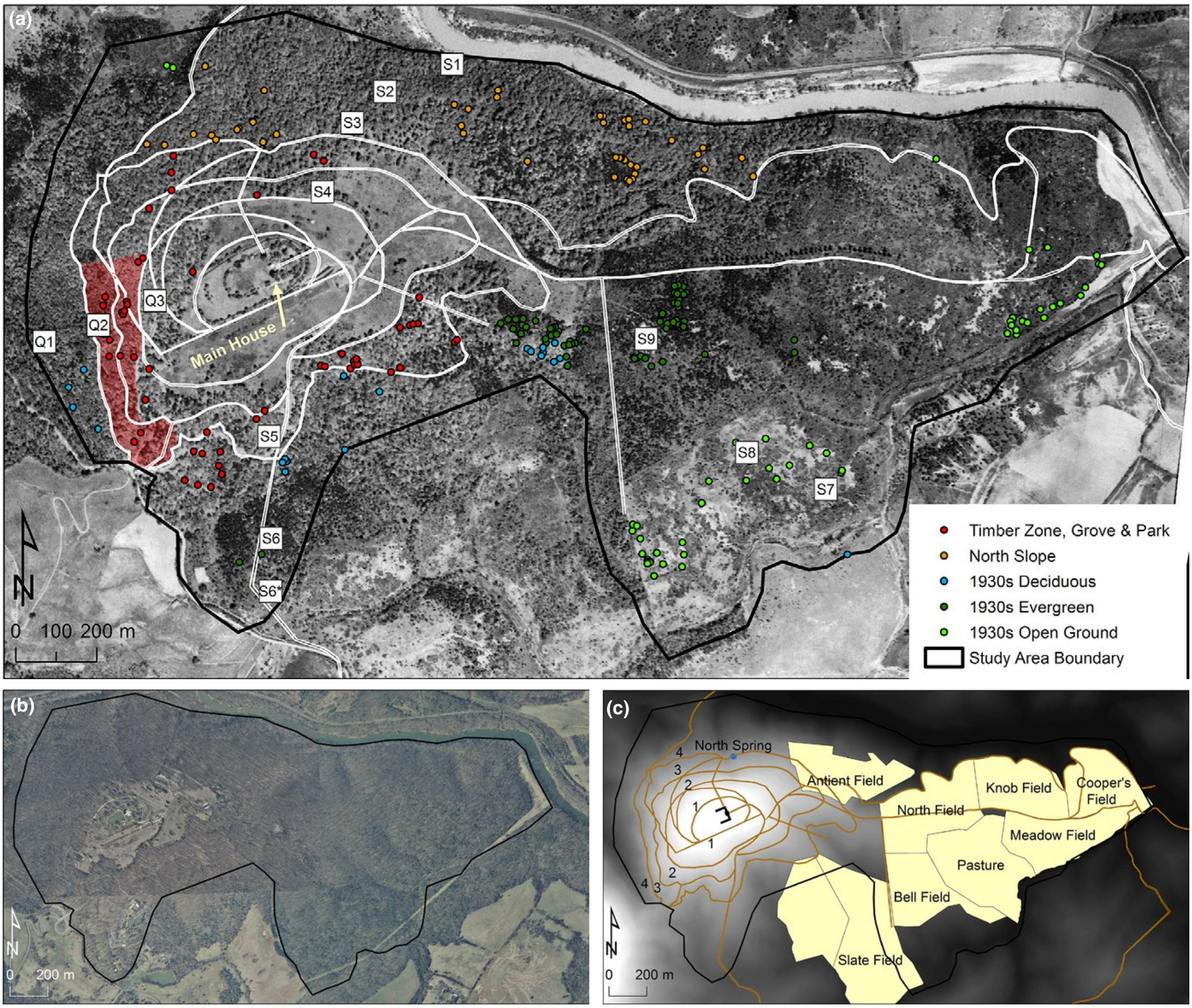

FIGURE 1 Land cover at Monticello through time. 1937 aerial photograph with locations of tree ring sampling by chronosequence stage and re-surveyed vegetation plots (stands (S) and quadrats (Q) shown with white squares). Red polygon highlights an additional 17 trees found in an initial sampling within the timber zone. Plot S6* was relocated south of a parking lot present in 2004 (a). 2013 orthophotograph showing extensive forest cover (b). Colonial-era features including Jefferson's house, spring, fields and four roundabout roads depicted in his surveys and located by archaeological surveys (c)

been unclear. Additionally, some areas, such as Jefferson's timber zone, may have provided both forest resources and ornamental design at Monticello.

Almost 200 years after the death of Jefferson, the majority of this mountain is now forested, obscuring much of this colonial-era land use (Figure 1a–c). However, this progression of time frames an observational study of the resulting extent and composition of forests at Monticello. In addition to historical interpretation for Monticello, these observations also provide broader insights into colonial-era land-use legacies and forest succession in the Virginia Piedmont, as slave-based agriculture for tobacco and wheat were common at that time. Even though Jefferson's landscape design may have been unique within the ornamental area of Monticello, Jefferson was bound by the same economic and environmental realities as other piedmont plantation owners in needing large extents of arable land for the production of tobacco and wheat (Neiman, 2008).

Widespread patterns of succession on former agricultural lands can persist for centuries as land-use legacies (Rhemtulla, Mladenoff, & Clayton, 2009); however, the long time scales of succession often lead to the use of chronosequences as space-for-time substitutions (Walker, Wardle, Bardgett, & Clarkson, 2010). Using tree rings, repeated vegetation surveys and historical documents, this study analyses the responses of forests at Jefferson's Monticello plantation to past land use using a chronosequence that retains a temporal dimension at annual resolution. The long-term perspective of these data sets provides an opportunity to investigate forest chronosequences, succession and resulting land-use legacies in a region that was intensively studied during the past century.

Early research on forest succession in the southeast piedmont by Oosting (1942) followed Clements' (1916) theory of climax communities. While Gleason's individualistic concept supplanted Clements' theory, sites with similar soils, topography and past land use generally showed a consistent forest composition (Keever, 1983). Typically, pines established after agricultural abandonment (McQuilkin, 1940). Oak (*Quercus*) establishment, generally white oak (*Q. alba*), black oak (*Q. velutina*) and northern red oak (*Q. rubra*), initiated after approximately 20 years (Barrett & Downs, 1943; Billings, 1938; Oosting, 1942). Canopies transitioned to deciduous species 70–80 years after abandonment, with release events from pine mortality (Oosting, 1942; Peet & Christensen, 1987). Christensen and Peet (1981) tested Clements' prediction that vegetation composition should converge through time (i.e. decreased β-diversity). In a repeated vegetation survey over 50 years, β-diversity remained constant (Christensen & Peet, 1981), and in a chronosequence study with forests extending over 80 years, β-diversity increased (Christensen & Peet, 1984).

Unlike North Carolina piedmont forests, early 20th century succession in central Virginia occurred during the chestnut blight (Gravatt, 1914). Prior to the blight, American chestnut (*Castanea dentata*) was a dominant component of inner piedmont forests around Monticello described by Braun (1950) as the Oak–Chestnut Association. Braun (1950) found it difficult to predict post-chestnut succession with the scarcity of primary forests and research on these forests. Subsequently Johnson and Ware (1982) reported that composition varied by elevation and soil moisture availability, but found no clear trends in the species replacing chestnut.

Only a few dendroecological studies have investigated forest succession in the Virginia Piedmont (Abrams & Copenheaver, 1999; Ambers, Druckenbrod, & Ambers, 2006; Copenheaver, Grinter, Lorber, Neatrour, & Spinney, 2002; Druckenbrod & Shugart, 2004; Orwig & Abrams, 1994). Furthermore, while forest succession studies in the piedmont have typically focused on land abandonment beginning in the 1930s, little research exists on earlier piedmont forests (Skeen, Doerr, & van Lear, 1993). Studies that synthesize disparate ecological and documentary data sources are also rare (Ireland, Oswald, & Foster, 2011), but combining these data within a chronosequence enables a reconstruction of long-term dynamics in each stage even while substituting space for time (Walker et al., 2010). Using repeated surveys, tree rings and documents, this study considers (i) the consistency of forest succession along a chronosequence of forest histories at Monticello extending over centuries, (ii) whether physiography or past land use explains more variation within current forest composition at this former agricultural plantation, and (iii) whether forest composition converges through time.

2 | METHODS

Tree age and growth history was reconstructed using increment cores from live trees and cross-sections from fallen trees from 2002 to 2015 across five chronosequence stages at Monticello (Figure 1a). GPS locations were recorded for all trees except for an initial subset within the western slope of the timber zone. Trees were sampled selectively by species and size to reconstruct forest histories back to Jefferson's ownership (*sensu* Pederson, 2010). Samples were extracted at approximately 1-m height as saplings of this height likely indicate that a site had transitioned to a forest at that time. Oaks and pines were preferentially sampled because of their prevalence and potential age. Tree-ring widths were cross-dated and verified using COFECHA (Speer, 2010). Recruitment dates were estimated geometrically by extrapolating the mean width of the earliest five rings to the centre of the stem, as determined using a compass only if <20 additional rings were estimated (see Frelich & Graumlich, 1994; Pirie, Fowler, & Triggs, 2015). Initial cohorts were defined by the sixth oldest tree in each chronosequence group to minimize outliers from remnant older trees.

Tree rings have been extensively applied in archaeological and climatological studies; however, their use in ecological applications is more recent (Fritts & Swetnam, 1989). Tree-ring widths vary in response to a growth curve, climate and canopy disturbances (Cook & Kairiukstis, 1990). Growth releases indicate increased light availability after canopy disturbance events and have often been identified using radial growth averaging (Rubino & McCarthy, 2004); however, time series analysis with intervention detection provides an alternative, statistical approach to identifying these events (Druckenbrod, 2005). Druckenbrod, Pederson, Rentch, and Cook (2013) demonstrated that time series analysis with intervention detection could not only detect past release events, but also quantify their impacts on a tree's subsequent growth rate. This paper modifies the combined step and trend

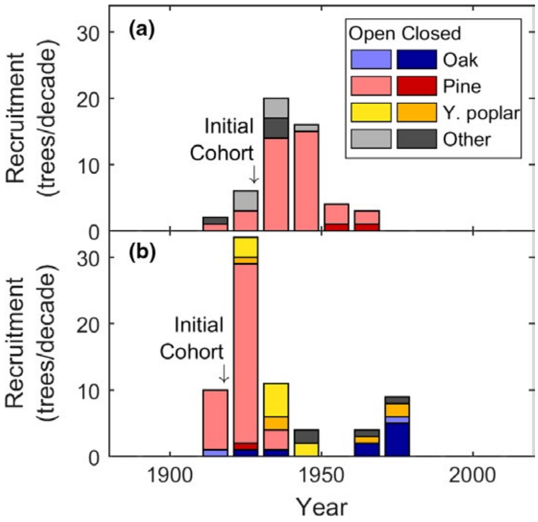

FIGURE 2 Forest history of two youngest chronosequence stages at Monticello. Canopy recruitment (number of trees per decade) in open ground (a) and evergreen cover (b) on the 1937 aerial photograph. Lighter shade of each colour indicates trees recruiting under open canopy conditions

(CST) method to specifically detect release events for reconstructing forest history using curve intervention detection (CID).

When a positive outlier is detected in the CID method, a series is disturbance detrended by fitting a Hugershoff curve (Cook & Kairiukstis, 1990), which has been previously used for disturbance detrending by Warren (1980). Unlike the step change in Druckenbrod et al. (2013), CID identifies release events in which a positive trend in growth may be transient or sustained depending surrounding canopy conditions forming a disturbance growth index for each tree-ring series. The CID method is evaluated using surviving trees from a documented 1967 logging event on the north slope of Monticello. Mean disturbance growth indices used the oldest ring-width series per tree and are shown during years with a minimum of six oak trees.

This study also uses an indicator of canopy openness based upon the shape of the initial growth curve, informing whether recruitment occurred into either an open or closed canopy environment. Growth curves of trees in open canopy environments typically fit an exponential decline, resulting from the addition of annual growth around an increasingly larger stem circumference (Cook & Kairiukstis, 1990). Unlike open-grown trees, trees recruiting under a closed canopy often show slower initial growth rates. Previous metrics of canopy status at recruitment include calibrated measures of initial growth rates from trees sampled within and outside of gaps (Lorimer, Frelich, & Nordheim, 1988), qualitative assessments of a tree's initial growth curve shape (Rentch, Fajvan, & Hicks, 2003) and hybrid methods that consider both growth rates and shapes (Hart, Clark, Torreano, & Buchanan, 2012; Pederson, Varner, & Palik, 2008). The indicator used in this study, iterative growth detrending (IGD), is similar except that it is not dependent on a calibration sample nor the entire tree-ring series.

In IGD, a tree-ring time series is iteratively fit to a negative exponential curve from the first 30 years to the entire series. The negative exponential curve with the best fit is then selected as the growth curve and indicates that a tree was recruited into an open canopy environment. If a negative exponential curve does not fit, then the series is detrended with a linear regression, indicating closed canopy conditions (sensu Cook & Kairiukstis, 1990). The IGD approach reconstructs a tree's canopy environment at recruitment and is evaluated using trees that recruited into the open land chronosequence stage.

In his 1934 vegetation surveys, Gregory (1935) used both quadrats and stands in surveying forest communities at Monticello (Figure 1a). Using Gregory's descriptions and map, our repeated survey estimated locations for three quadrats and six stands where we measured trees ≥1.37-m tall. Chronosequence stages were defined by land cover present on a 1937 aerial photograph. Three additional stands were surveyed to capture more recent land use along the east slope, which was not forested in 1937. In his quadrats, Gregory provided both the number of trees sampled by species and the area of each quadrat (523 m^2) but he used a variable plot area in six stands. As the tallies of all categories of trees from the stands were approximately half of those in the quadrats, 225 m^2 plots were used in re-surveying stands from 2004–2015.

Nonmetric Multidimensional Scaling (NMDS) ordinated tree species across plots and sampling intervals using the vegan community ecology package in R (v 2.3-2; R Foundation for Statistical Computing, Vienna, Austria). Function metaMDS follows Minchin (1987) using a Wisconsin double standardization, a Bray-Curtis dissimilarity index and a rotation of the first axis to align with the largest variance of the data. Species composition was compared with slope, elevation and transformed aspect (Beers, Dress, & Wensel, 1966) derived from a 30-m DEM using ArcGIS Desktop Advanced 10.3 (Environmental Systems Research Institute, Redlands, CA, USA) and convergence was tested using an F-test in Matlab 2014b (MathWorks, Natick, MA, USA). Slope values were extracted using Whitebox GAT 3.2.2 (University of Glasgow, Glasgow, UK).

3 | RESULTS

3.1 | Evaluation of tree-ring methods

Trees recruited into the open ground chronosequence stage on the 1937 aerial showed a predominance of open-grown conditions from IGD, particularly for pines (Figure 2, Appendix S2). The initial cohort in this stage began in 1928 and pines recruited over several decades. Surviving trees from the 1967 logging on the north slope showed the largest number of release events during the 1960s (Figure 3). The mean disturbance growth index increased by 1 mm and gradually declined over several decades, representing the largest forest disturbance during the 20th century at Monticello.

3.2 | Forest histories along chronosequence

A total of 292 trees were sampled across chronosequence stages, including pines (114) oaks (106), yellow poplars (*Liriodendron tulipifera*, 30) and eastern red cedars (*Juniperus virginiana*, 15). Tree recruitment dates for the initial cohorts increased along the chronosequence, with the youngest cohort (86 years old) found in open land on the 1937

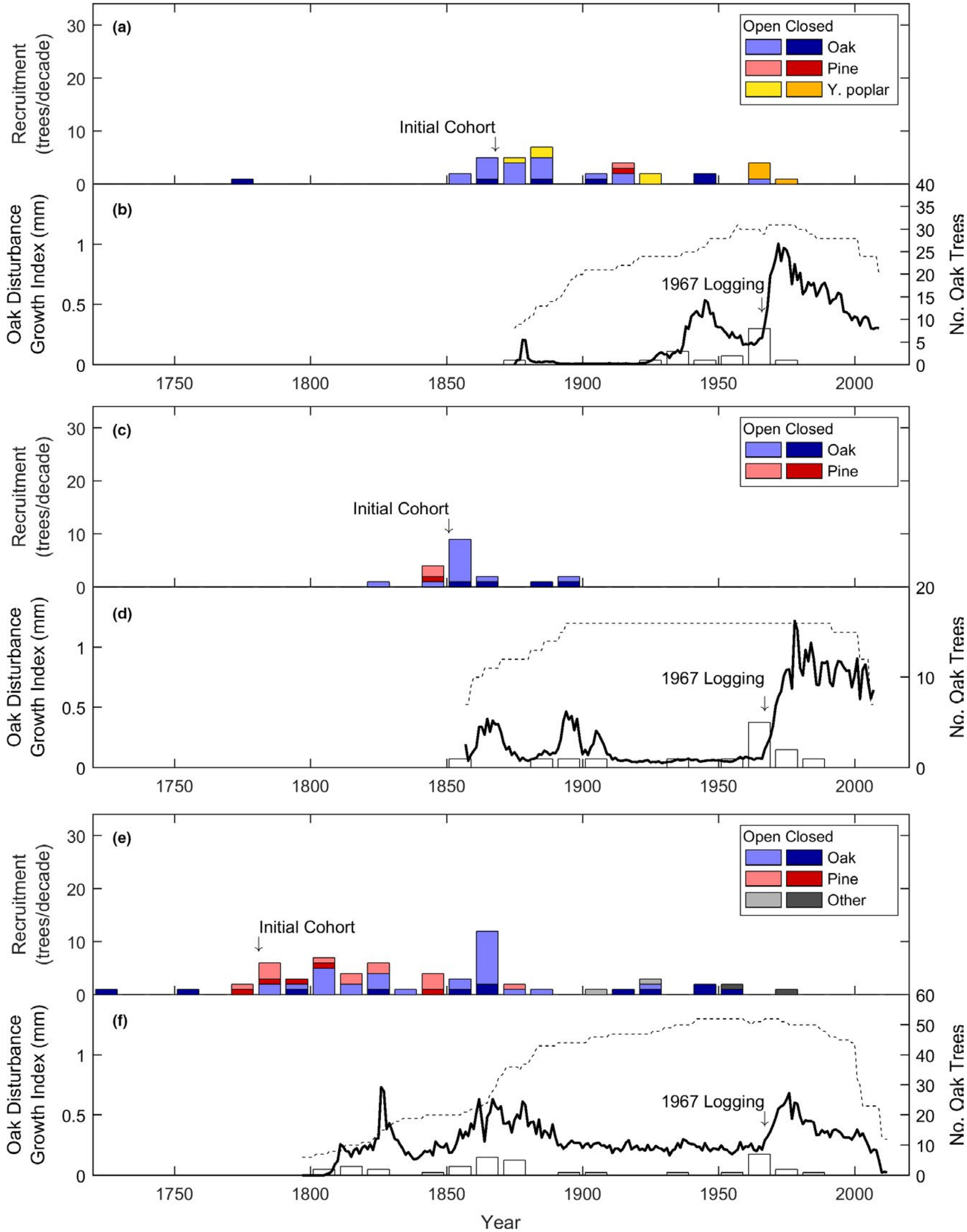

FIGURE 3 Forest history of three oldest chronosequence stages at Monticello. Tree recruitment in north slope (a), deciduous cover (c) and historical ornamental zone (e) on the 1937 aerial photograph. Lighter shade of each colour indicates trees recruiting under open canopy conditions. Mean disturbance growth index (bold line) along with sample size (dashed line) in north slope (b), deciduous cover (d) and ornamental zone (f) with bars showing release events per decade

aerial photograph, followed by evergreen cover (Figure 2) and then deciduous cover (Figure 3). The oldest cohort (223 years old) was present in the historical ornamental zone of Monticello (including the timber zone, park and grove) with a chestnut oak (*Q. montana*) dating to 1727 (Figure 3). Transitions from open-grown pine to oak recruitment were observed in the evergreen, deciduous and ornamental zone stages.

The 1967 logging disturbance was also evident in mean disturbance growth indices from the ornamental zone and deciduous cover stages. Tree recruitment from this more recent event was underrepresented by the study design, which focused on sampling larger and older trees; however, substantial recruitment (mostly oaks) was also evident across the north slope, deciduous cover and ornamental zone stages from the 1850s to 1880s. Disturbance growth indices also indicate canopy release events during that time period, although the magnitude and duration of elevated growth rates are smaller than the 1967 logging disturbance.

Forest cover, estimated from tree rings and documents, was lowest during Jefferson's lifetime (45%) but increased to 57% by 1937 and 90% by 1994 (Appendix S3). During Jefferson's time, agricultural fields (excluding the Ancient field abandoned by Jefferson) were located in areas with significantly less steep slopes than forested areas (Kolmogorov-Smirnov two-sample test, $p = .02$).

3.3 | Changes in tree species abundance along a re-surveyed chronosequence

The NMDS of repeated forest surveys ordinated species with a stress <0.2 on three axes. The ordination had a significant relationship to slope ($p = .016$) and elevation ($p = .041$), but not transformed aspect ($p = .123$) on the first two axes (Figure 4a). Species distributions across this ordination space include early successional species at positive values on axis 1 with mid- to late successional species at negative values. Mesic species occur at positive values on axis 2. While environmental factors correlated significantly with forest communities along axis 2, axis 1 explains the most variation. Non-native tree species including tree of heaven (*Ailanthus altissima*), Chinese privet (*Ligustrum sinense*), princess tree (*Paulownia tomentosa*) and sweet cherry (*Prunus avium*), were also not present during the initial 1934 vegetation survey.

Ages of initial cohorts in each chronosequence stage also varied from youngest to oldest along axis 1 (Figure 4b). The variance along axis 2 for plots with a positive axis 1 value (younger forests) was not significantly different than plots with a negative axis 1 value (older forests; $p = .89$). North slope forests have negative values on axis 1 when surveyed in 1934, but these values are more positive when resurveyed after the 1967 logging. The timber zone plots also slightly shift to more positive values after the 1967 logging (Figure 4c).

3.4 | Comparison tree-ring analysis with Jefferson-era and more recent documents

Documentary evidence corroborates the extent and magnitude of the 1967 logging disturbance. Prior to the logging, a State Forester report

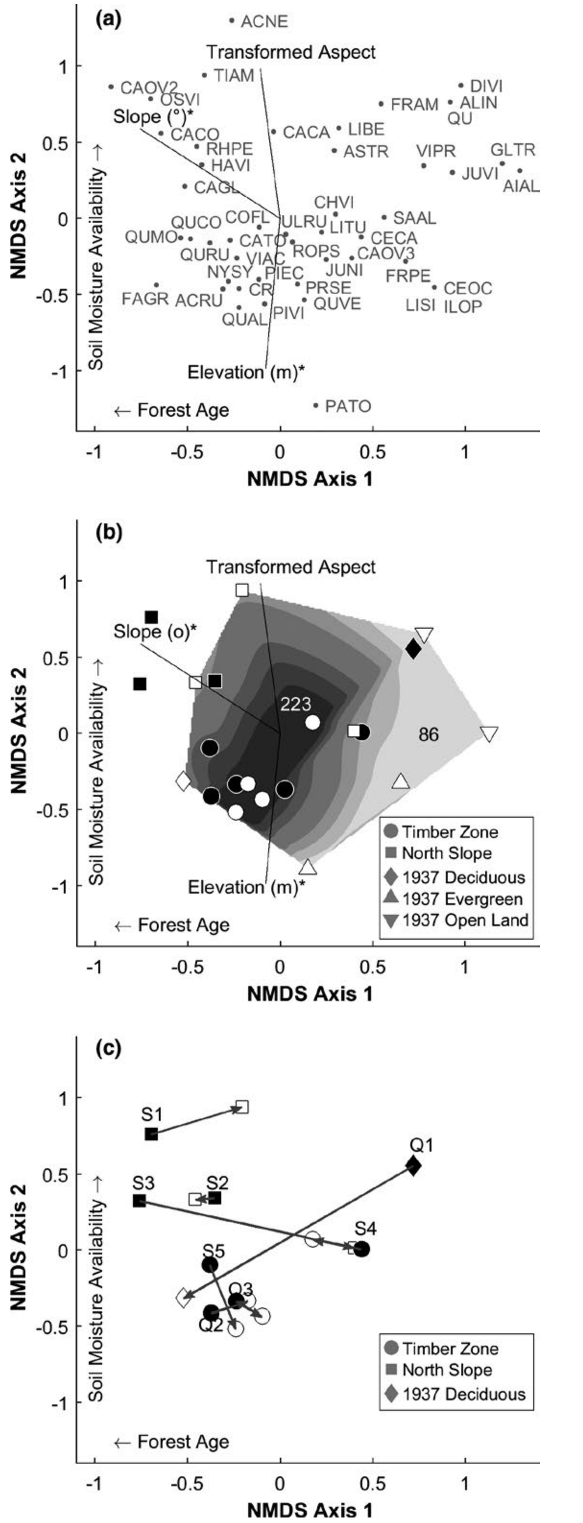

FIGURE 4 NMDS of repeated forest surveys showing species codes (see Appendix S4 for species names) with environmental variables (a). Original sites (black) and resurveyed sites (white) with environmental variables by chronosequence stage (symbols), with dendrochronological ages of initial cohorts as grey-shaded contours ranging from 86 to 223 years old (b). Change in ordination space for resurveyed sites from 1934 (grey arrows) (c)

recorded that forest composition on the north slope was mostly "[yellow] poplar, with red oak, chestnut oak, white oak, hickory, Virginia Pine, and a few walnut [*Juglans nigra*]…" with diameters averaging 66 cm, with a maximum of 107 cm (Lyon, 1943). When the forests were logged in 1967, 312,000 board feet (736 m^3) of oak, yellow poplar and hickory were removed. A subsequent report (Tice, 1980) found that over 100 ha of forests across Monticello were selectively logged, with portions of on the north slope more heavily cut, appearing almost clear-cut with frequent white oak and yellow poplar stump sprouts (Wieboldt, 1981). Wieboldt (1981) noted that the eastern portion of this slope had a higher abundance of fallen American chestnuts and suggested that rock outcroppings prevented more extensive logging. Tree-ring analysis supports this inference, with the presence of older trees dating to the mid-1800s.

For the open land cover on the 1937 aerial photograph, evidence of posts for wire fencing along with abundant eastern red cedar suggests that these fields were last used as pasture (see Braun, 1950). For the evergreen land cover, a 1927 photograph supports the presence of its initial cohort dating to 1918 (Appendix S1). In the deciduous land cover, oak trees dating to the 1850s generally show an open-grown growth curve, suggesting this stage was reforested during the larger recruitment pulse contemporaneous with the Civil War.

In contrast, forests in the historic ornamental zone stage show no documentary evidence of agricultural land use. Tree-ring reconstructions show episodic pine establishment beginning in the late 1700s followed by oak recruitment. This disturbance is contemporaneous with the construction of the house and may have been the result of selective logging or fire. While fire was used as a means to remove forests for tobacco farming in central Virginia (Tice, 1987), unintentional fires were also frequent around Monticello during the colonial era, as reported by a former slave (Jefferson, 1951). By 1800–1809, the increases in tree recruitment and disturbance growth indices reflect the wilderness that Jefferson returned to after his presidency. The locations of trees dating to Jefferson's lifetime (1743–1826) are not only within the forested area of ornamental land use of Monticello reconstructed by historical documentary records (Appendix S3), they are also within or adjacent to Jefferson's timber zone, further supporting that Jefferson used this oldest chronosequence stage for his interpretation of an English garden, limiting the extraction of wood as a resource. The north spring (Fig. 1c, Appendix S1) drains the timber zone and is the only spring without a sediment retaining wall dating to Jefferson's time. Other springs down-slope of agricultural fields have Jefferson-era retaining walls to prevent sedimentation from up-slope erosion on agricultural fields.

Tree-ring data support that the area of ornamental land use, including the timber zone but not the grove, remained forested after 1826; however, disturbance growth indices record more release events and oak open-grown recruitment from 1850 to 1870, when Monticello's ownership was disputed. Jefferson's documents suggest that the north slope remained forested with only selective logging during his lifetime (Appendix S1). The open-grown recruitment of oaks during the mid-19th century indicates that logging continued after Jefferson's death instead of abandoned from past agriculture. Appendix S1 also shows additional portions of the timber zone circa 1927–1928 remaining as a partial ring around the mountain. Prior to the 1967 logging, the disturbance growth indices also record an earlier release event during the 1930s that is only present within the north slope forests. This event coincides with the chestnut blight and remaining chestnut trunks and sprouts were noted only on the north slope (Wieboldt, 1981).

4 | DISCUSSION

Gregory (1935) cites Cowles (1911) to support his conclusion that topography controls the distribution of plant associations at Monticello, a conclusion that predates Whittaker's (1956) concept of complex gradients. His original and our repeated survey support the presence of a complex moisture gradient, with mesic conditions for forests on the north slope (Figure 4c). Yet, we find that this indirect gradient explains less variation than a forest age gradient (axis 1), showing that past land use from agriculture and logging is more important for driving variation in forest composition at Monticello than physiographic variables over the past two centuries. This gradient of time since past land use is also evident from the ages of initial cohorts independently derived from tree ring data. Similar ordinations of Virginia forests have also expressed a successional sequence and a moisture gradient along opposing axes (Orwig & Abrams, 1994) or correlations with soil and site factors, including slope (Cole & Ware, 1997).

The 1967 logging disturbance also affected the ordination of plots through time, particularly with positive (younger) shifts on axis 1 for plots S1 and S3 on the north slope in areas where logging was more extensive. This ordination does not show a convergence in composition with forest age, as the variance of plots in younger forests (with axis 1 values >0) was not significantly different to plots in older forests (with axis 1 values <0), similar to previous results in the Virginia Piedmont (Christensen & Peet, 1981, 1984).

Whittaker's (1956) observations of complex gradients contributed to the individualistic concept of vegetation dynamics (Shipley & Keddy, 1987). Whittaker (1956) and Pickett (1976) also proposed that succession is simply another gradient that occurs as species' life history attributes respond to environmental changes through time instead of space (Peet, 1992), implying that forest composition has no consistent successional direction or endpoint (Pickett, Cadenasso, & Meiners, 2009). Our results support this greater focus on temporal ecology (Wolkovich, Cook, McLauchlan, & Davies, 2014). Although oak-dominated communities have been considered a successional endpoint in many early studies set in the piedmont, concurrent changes in species composition, fire frequency, land use and climate (McEwan, Dyer, & Pederson, 2011) suggest that Virginia Piedmont forests may transition to a composition dominated by mixed mesophytic species including red maple, beech, yellow poplar and blackgum (Abrams & Copenheaver, 1999; Rose, 2008). These regional trends suggest that these current drivers may portend an altered future forest composition when compared to the last two centuries, particularly with the loss of American chestnut.

Colonial agricultural land use was pervasive in the Virginia Piedmont as settlers often found it easier to clear new land than to maintain the fertility of existing fields (Nelson, 2008; Appendix S1). Our spatial analysis at Monticello showing forest cover on steeper slopes than agricultural fields is directly supported by an 1807 letter to an overseer, Edmund Bacon, who Jefferson instructs to cut down woods along a field near the bottom of Monticello in places where the slope is not too steep for agriculture (Pierson, 1862). The location of Jefferson's timber zone along the steeper slopes of Monticello was likely a decision made as much by the economic necessity of farming lands with less steep slopes than Jefferson's vision to adapt the design of English landscapes.

By 1806, within the timber zone, Jefferson was "unwilling to have a single tree fallen in that inclosure which can be done without" directing Bacon to replace fencing on Monticello with wood from an adjacent hill (Jefferson et al., 2008) and to deliver wood to his "servants" weekly during the winter (Pierson, 1862). This separation between ornamental land use surrounding the main house and wood resources likely imposed additional constraints on Jefferson's land use as fuel wood and timber were generally transported from elsewhere up the slopes of Monticello.

Whether for aesthetic or practical reasons, the extent to which forests remained on other colonial-era agricultural plantations in Virginia deserves greater attention for their potential impact on regional forest dynamics and biodiversity. For example, surviving trees in a nearby National Natural Landmark forest at James Madison's Montpelier plantation also date to the colonial era (Druckenbrod & Shugart, 2004). Across the piedmont, Oosting (1942) observed that past land use had removed most old forests except for 200- to 300-yr-old hardwood stands of small spatial extent on sites not conducive for agriculture because of topography and soils.

5 | CONCLUSION

Jefferson's use of the land at Monticello for agriculture, wood and ornamental design are land-use legacies that have affected the resulting distribution and composition of its forests more than two centuries later. These legacies are apparent in both long-term vegetation surveys and also from dendrochronological methods, CID and IGD, which reconstruct the disturbance and successional histories of these forests. In the past, Monticello's forests have followed a successional pattern with increased oak abundance; however, more recently abandoned fields may follow different patterns because of changes in species availability and land use.

While the causal mechanisms underlying succession have been intensely studied since Clements (Pulsford, Lindenmayer, & Driscoll, 2016), the importance of succession as a pattern has only increased globally with greater anthropogenic disturbance (Prach & Walker, 2011). Old-field succession results from the individual interactions of species, site factors and past land use, which when spatially extensive gives rise to patterns that are predictable regionally (Keever, 1983). The conditions of widespread land abandonment in the piedmont during the 20th century resulted from large-scale changes in agricultural land use producing successional patterns that were broadly consistent (see Barrett & Downs, 1943). The longer-term perspective of this study reconstructing forest succession from the colonial period to the present shows that land use outweighs physiography in the composition of these forests and that its legacy can persist for over two centuries. These conclusions echo those reported elsewhere across North America where long-term studies have shown the importance of past land use on forests (Foster et al., 2003; Rhemtulla et al., 2009; Thompson, Carpenter, Cogbill, & Foster, 2013). Comprised of long-lived individuals, the sensitivity of forests to environmental variation across gradients through time or space suggests that ecologists should continue to focus on their successional dynamics at a range of scales (Walker & Wardle, 2014), particularly at large scales to best test predictions (Meiners, Cadotte, Fridley, Pickett, & Walker, 2015). Studying succession in different environments is more essential than ever to conserve and restore forests in the face of increased anthropogenic impacts (Christensen, 2014). As agricultural land use and other impacts become more intense, it is more likely that the response of vegetation will follow novel pathways than those observed previously (Cramer, Hobbs, & Standish, 2008).

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Appendix S1 Document-based reconstruction of land use and forest cover at Monticello circa 1826

Appendix S2 Example time series analyses of tree-ring series

Appendix S3 Historical land use and estimates of forest cover at Monticello through time

Appendix S4 Species aames in NMDS ordination

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Appendix S1: Document-Based Reconstruction of Land Use and Forest Cover at Monticello circa 1826

Jefferson enabled access across Monticello by constructing a series of roundabout roads that were at increasing distances (1st through 4th roundabouts) from the main house at the summit (shown by shaded relief). These roundabout roads were interconnected to allow movement up and down the mountain (Fig 1).

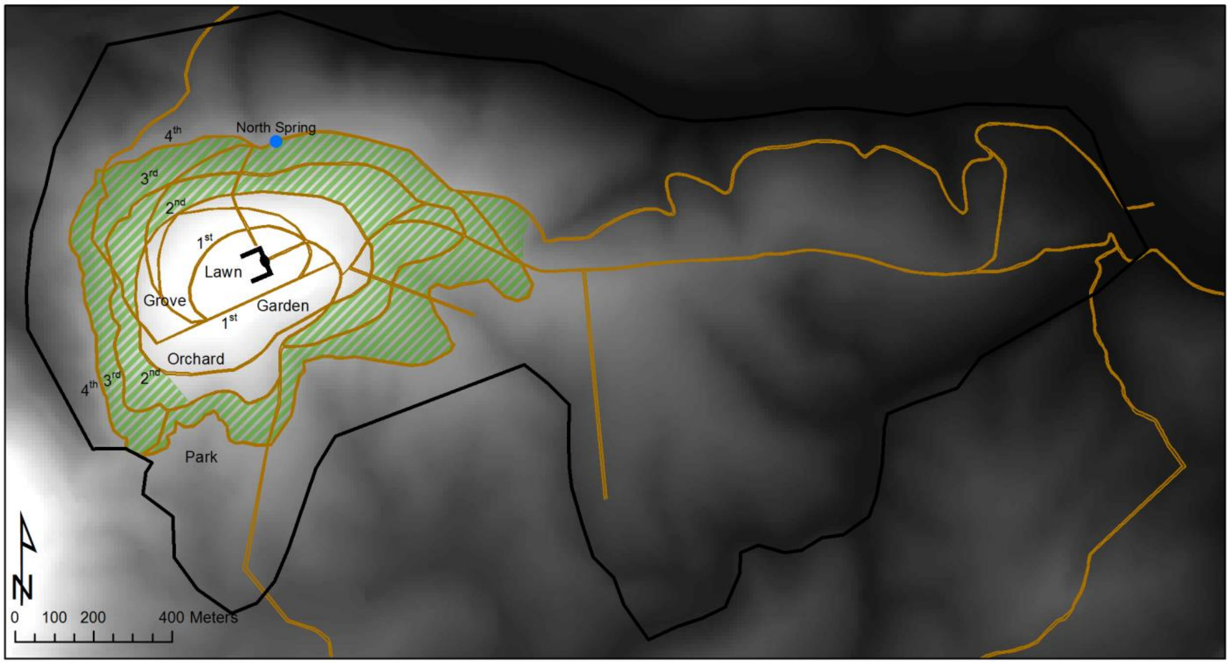

Fig. 1. Ornamental land use showing roundabout roads reconstruction from archaeological surveys and the timber zone (green cross-hatching) as interpreted by Jefferson documents.

Within the second roundabout, Jefferson constructed orchards, gardens, and wide lawn as part of his aesthetic design for Monticello following the conventions of English gardens (Beiswanger 1984). He also clearly noted the location of his Grove and Park, both which remained in forest cover. On the back of a survey, Jefferson alludes to the dimensions of his timber zone; however, interpreting its location has been uncertain prior to this documentary analysis using GIS:

> above the Timber zone are 80. acres.
>
> The circuit of the Timber zone at its upper limit is 400.po.
> at its lower limit 600.po.
> it‘s breadth must be 31½ po.=173¼ yds which will to make it's
> contents 100 acres. but instead of making it of equal breadth
> lay off its lower edge level from the spring or rather with just
> so much descent as will carry the water of the spring all around
> the mountain. the zone at the spring will be but 137 yds wide; but
> the hill there being excessively steep, it will soon spread out
> to a much greater breadth so as to make up what it loses
> in breadth there. (Jefferson 2016)

Assuming that Jefferson was referring to the North Spring, the closest spring to the main house, these calculations suggest that the shape of the timber zone with its inner and outer limits, or boundaries, approximated by the circumference of two circles forming a ring around the summit. A circle with a circumference of 400 poles (2000 m) has an area of 80 acres (30 ha) while a circle with a circumference of 600 poles (3000 m) has an area of 180 acres (70 ha). These calculations suggest that Jefferson was simply roughly estimating, or perhaps idealizing, the areal extent of his timber zone in a manner that could be easily solved using the equation for a circle's area. These upper and lower circuits are approximately congruent with Jefferson's second and forth roundabouts, which have circumferences of 1890 m and 3790 m, respectively, and delineate an area of 100 acres (40 ha) (Fig. 1). Additionally, the distance from the North Spring southward to the second roundabout is approximately 130 m, similar to Jefferson's measurement of 137 yards (125 m) on the north side of the mountain, where the slope is steepest.

This interpretation of the ornamental land use of Jefferson's timber zone is also supported by reading further in his 1806 draft letter to William Hamilton, Jefferson discusses how trees form part of his aesthetic interpretation of English Gardens in Virginia:

> Their [England's] sunless climate has permitted them to adopt what is certainly a beauty of the very first order in landscape. Their canvas is of open ground, variegated with clumps of trees distributed with taste. They need no more of wood than will serve to embrace a lawn or glade. But under the beaming, constant and almost vertical sun of Virginia, shade is our Elysium. In the absence of this no beauty of the eye can be enjoyed…The only substitute I have been able to imagine is this. Let your ground be covered with trees of the loftiest stature. Trim up their bodies as high as the constitution & form of the tree will bear, but so as that their tops shall still unite & [yield] dense shade. A wood, so open below, will have nearly the appearance of open grounds. Then, when in the open ground you would plant a clump of trees, place a thicket of shrubs presenting a hemisphere the crown of which shall distinctly show itself under the branches of the trees. (Jefferson et al. 2008).

As early as 1771, Jefferson was already planning his vision for his version of an English landscape at Monticello including a waterfall from a "spring on the North side of the park," a temple and burying place "among antient [ancient] and venerable oaks" with instructions to "thin the trees. cut out stumps and undergrowth. remove old trees and other rubbish, except where they may look well" (Jefferson et al. 2008). Jefferson toured English estates with John Adams in 1786 along with Whately's influential text on English landscape gardens. Whately described contemporary English parks as typically grand, expanses of woods and lawns for walking or riding while gardens as more ornamental areas for pleasure walking (1777). Additionally, trees could be maintained singularly, in clumps, in groves, or as woods within a landscape. Woods maintained both their overstory and understory while groves contained only overstory trees (Whately 1777). Jefferson's modification for the Virginia climate was to maintain his English garden as a grove instead of isolated clumps. The garden grounds were still differentiated from his adjoining park further down the south slope by its greater distance from the house, the presence of deer, and a greater sense of picturesque wilderness within it.

Several of Jefferson's letters also mention an inclosure surrounding the house and grounds at the top of Monticello. This fenced area likely corresponded to the timber zone described on survey N129 in the 1790s (Jefferson 1778). On N211, Jefferson writes that a survey of 174 acres (70 ha) along the fourth roundabout should be enclosed by fencing for a “pleasure grounds” (Jefferson 1809). Fences during the Colonial period were often constructed to keep livestock out of fields (Silver 2001). At Monticello, Jefferson extolls Capt. Bacon to prevent an “animal of any kind” from entering the fencing and gates surrounding the top of Monticello (Pierson 1862) and depicts portions of this fencing on surveys titled “Monticello: mountaintop (plat), 1809” (Thomas Jefferson. N225; K169 [electronic edition]. Thomas Jefferson Papers: An Electronic Archive. Boston, MA: Massachusetts Historical Society, 2003. www.thomasjeffersonpapers.org) and a “Survey and Plat for Land Purchased from Richard Overton” (The Papers of Thomas Jefferson Digital Edition, ed. James P. McClure and J. Jefferson Looney. Charlottesville: University of Virginia Press, Rotunda, 2008–2017. rotunda.upress.virginia.edu/founders/TSJN-01-38-02-0291).

Capt. Bacon also recalled that a fence enclosed the upper portion of the mountain (approximately 300 acres or 120 ha) within which Jefferson would not allow trees to be cut nor animals to run loose within it (Pierson 1862). Jefferson also advised Capt. Bacon to use fallen wood prior over “cutting down a tree for fire-wood or any other purpose” and to use branches and hollow trees when possible (Jefferson et al. 2008).

While Jefferson’s plans for an English park and gardens at Monticello were among the earliest in North America, it is likely that these plans were not completed (Beiswanger 1984). During her 1809 visit, Margaret Smith was skeptical that Jefferson could finish these plans (Smith 1906). While Jefferson did carry through on design gardens and planting trees immediately around his house at this time (Druckenbrod and Chakowski 2014), four years later he wrote that he had “made no progress in the improvement of my grounds” (Jefferson et al. 2008).

Unable to meet his expenses with proceeds from agriculture, Jefferson died heavily in debt in 1826. Jefferson’s family sold Monticello in 1831 and, the house and surrounding grounds were eventually bought by a Naval Officer, Uriah Levy, in 1834 (Leepson 2002). Except for a period of contested ownership after Uriah’s death in 1862, during which the grounds and house fell into disrepair, Monticello was maintained as a tribute to Jefferson by Uriah, and then his nephew, Jefferson Levy who eventually assumed ownership in 1879 (Leepson 2002, Urofsky 2001). According to an 1899 magazine article, Jefferson Levy kept “the old house, the green terraces, the wide lawns, and the ancient trees as they were in the hands of the first owner” (Peterson 1899 cited in Urofsky 2001). By 1914, timber on the property was considered valuable in appraising the property (Leepson 2002). The property was then sold by Jefferson Levy to the Thomas Jefferson Foundation in 1923 (Urofsky 2001). In 1908, Jefferson Levy’s niece wrote for her school newspaper about the large size of the trees that grew along the sides of the steep ravine along the west slope of the timber zone (Urofsky 2001).

The earliest aerial photograph of Monticello shows sections of the timber zone remaining on the north and south sides (Fig 2).

Fig. 2. ca. 1927-1928 oblique aerial of Monticello oriented eastward showing early successional evergreen forests recruiting on the upper southeast slope (a) and portions of the timber zone as a partial band around the house (b). [Credit: Thomas Jefferson Foundation, Inc. at Monticello].

Considering Jefferson's writings and those of his contemporaries, it is possible to reconstruct a documentary model of forest cover circa 1826 at Monticello (Fig. 3). Returning to the opening quote in the Introduction from the draft letter to William Hamilton, Jefferson notes that the lower two-thirds of the northern quadrant of his mountain is forested and then the upper third is forested across the entire mountain. The upper third (200 m) occurs at the approximate elevation of the fourth roundabout above the Rivanna River on the north slope. This interpretation suggests that Jefferson was referring to the timber zone spreading around the crown of Monticello. Jefferson also referred to his Grove and Upper Park as forested. In an agreement with the Directors of the Rivanna River Company in 1810, Jefferson allows the harvesting of timber and non-timber quality trees from the lower north slope (Jefferson 1810). Thus, Jefferson's use of this forested area varied from ornamental near the summit to a source of wood resources near the base.

Visitors to Monticello during Jefferson's lifetime and later in the nineteenth century record a similar extent of forest cover. When Lt. Francis Hall visited in 1817, he wrote that the "whole of the sides and base are covered with forest, through which roads have been cut circularly … the summit is an open lawn" (Jefferson et al. 2008). Other contemporary references between 1815 and 1822 portray a similar appearance with forested slopes . containing "a noble forest of oaks in all stages of growth and of decay, Their trunks straight and tall put forth no branches till they reach a height almost equal to the summits of our loftiest trees in New England (Gray 1824 cited in Rosenberger 1953).

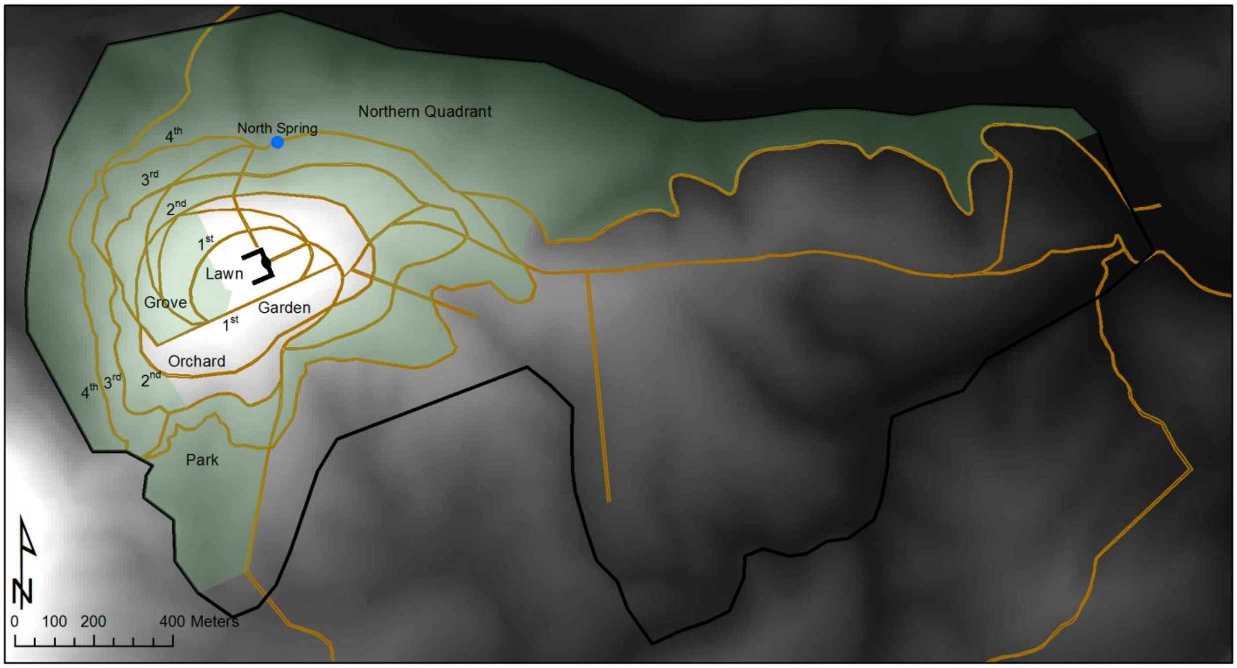

Fig. 3. Document-Based Reconstruction of Forest Cover at Monticello circa 1826

While Jefferson doesn't write directly of the composition of his forests, he occasionally referred to trees by location and species in surveys, deeds, and writings of Monticello. The trees within or bordering forest cover during Jefferson's lifetime are generally more characteristic of later successional forests than those in agricultural cover (Table 1).

Table 1: Trees listed in surveys, deeds, and also instructions to an overseer (dated December 8, 1806) at Monticello by Jefferson and grouped by whether the document refers to trees within forest or agricultural land use as reconstructed in Appendix S3. Common names of trees are those used by Jefferson.

Common name	Scientific name	Agriculture	Forest
Apple	*Malus pumila*	X	
Ash	*Fraxinus americana* or *pennsylvanica*		X
Cherry	*Prunus* spp.	X	
Chestnut	*Castanea dentata*		X
Blackgum	*Nyssa sylvatica*		X
Locust	*Robinia pseudoacacia*	X	
Maple	*Acer* spp.		X
Oak	*Quercus* spp.	X	X
Oak, White	*Quercus alba*		X
Pawpaw	*Asimina triloba*		X
Peach	*Prunus persica*	X	
Persimmon	*Diospyros virginiana*	X	
Pine	*Pinus* spp.	X	X
Poplar	*Liriodendron tulipifera* or *Populus* spp.	X	
Walnut	*Juglans nigra*	X	

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Appendix S2: Example Time Series Analyses of Tree-Ring Series

Iterative growth-curve detrending using a negative exponential growth curve was used to reconstruct canopy conditions at recruitment. Removing growth curves within tree-ring series in closed canopy forests typically proceeds by fitting a negative exponential curve to the entire series; if that fails, then a linear regression. Trees that began growing in a canopy gap, but were unable to reach the canopy prior to lateral gap closure record an initial negative exponential growth decline, requiring a subsequent release event to attain canopy status. That release event causes poor fit with a monotonic, negative exponential curve or linear regression.

Additionally, intervention detection using a Hugershoff curve was used to reconstruct disturbance growth indices. Figures 1-3 show an example of this method applied to a yellow poplar tree on the north slope, where much of the 1967 logging occurred. The initial negative exponential fit of this series up to the logging year (indicated with red triangle at lowest value of error term variance) indicates that it recruited under open canopy conditions with a greater initial growth rate.

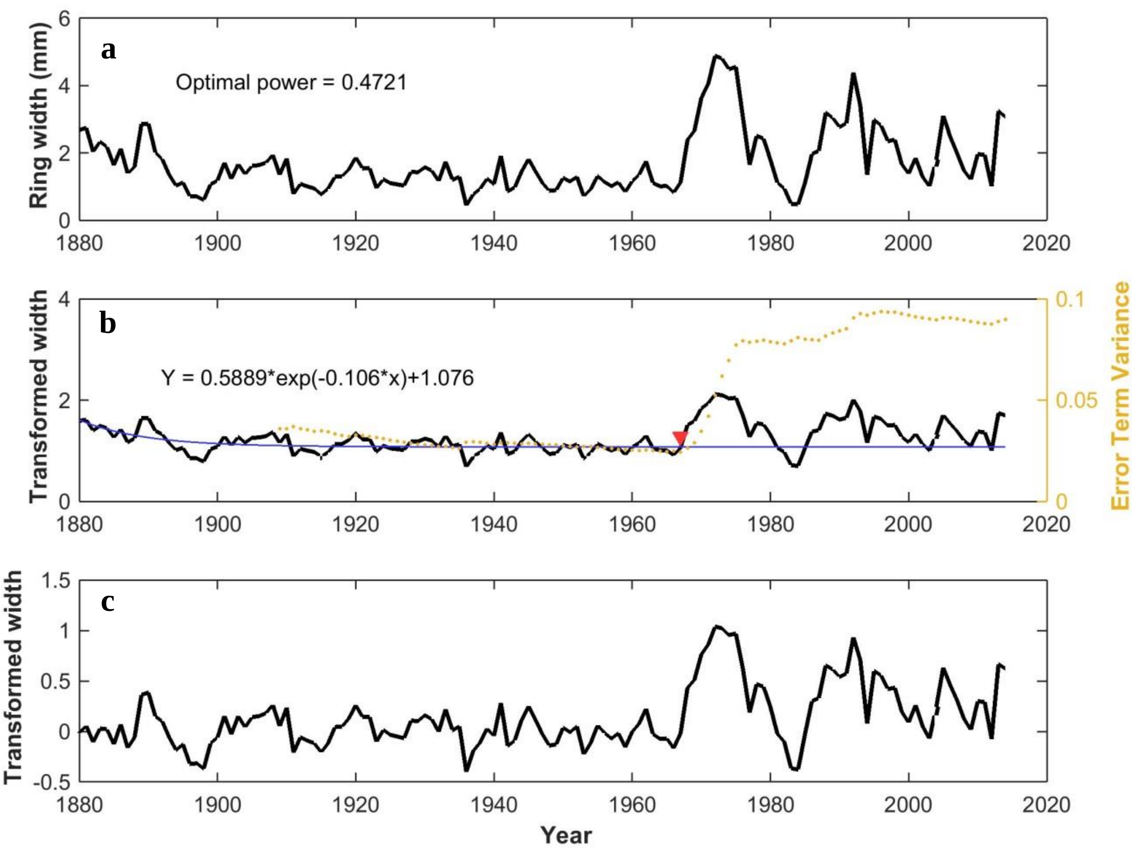

Fig. 1: Iterative growth-curve detrending of a yellow poplar on Monticello's north slope. Ring width measurements (a). Power transformed ring widths that are best fit to a negative exponential curve extending to 1967 (blue line), when the logging occurred (b). Growth-curve detrended ring-width series showing greater stationarity for autoregressive analysis (c).

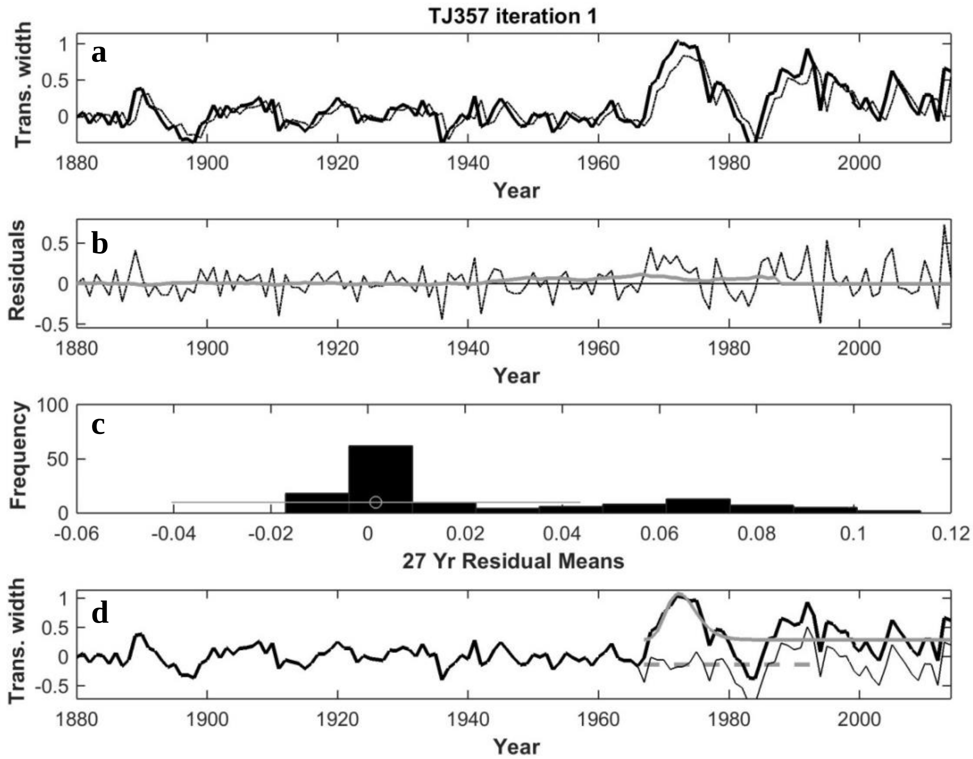

Fig. 2: Curve intervention detection of a yellow poplar on Monticello's north slope. Detrended series (bold line) best fit by a first order autoregressive model with a 0.81 coefficient (thin line) (a). Residuals from AR1 model fit show a period of poor fit beginning in 1967 and extending for 27 years as shown by the increase in the 27-year running mean (gray line) (b). The 27-year mean at 1967 is greater than 99.95% of 27-year residual means across this series, identifying it as an outlier (c). Hugershoff curve fit to series (bold line) beginning in 1967 (gray line). Subtracting the Hugershoff curve fit disturbance detrends this series in transformed units (d).

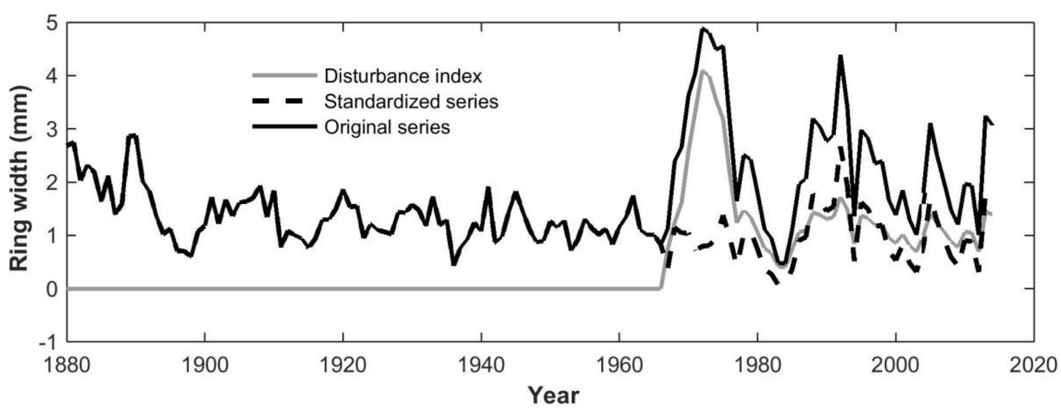

Fig. 3: Re-expressing intervention detection to original units of ring widths (with growth-curve trend included). The difference between the original series and the disturbance-standardized series enables a reconstruction of a disturbance growth index (gray line) quantifying the timing, duration, and magnitude of the 1967 logging event on this tree.

Appendix S3: Historical Land Use and Estimates of Forest Cover at Monticello through Time

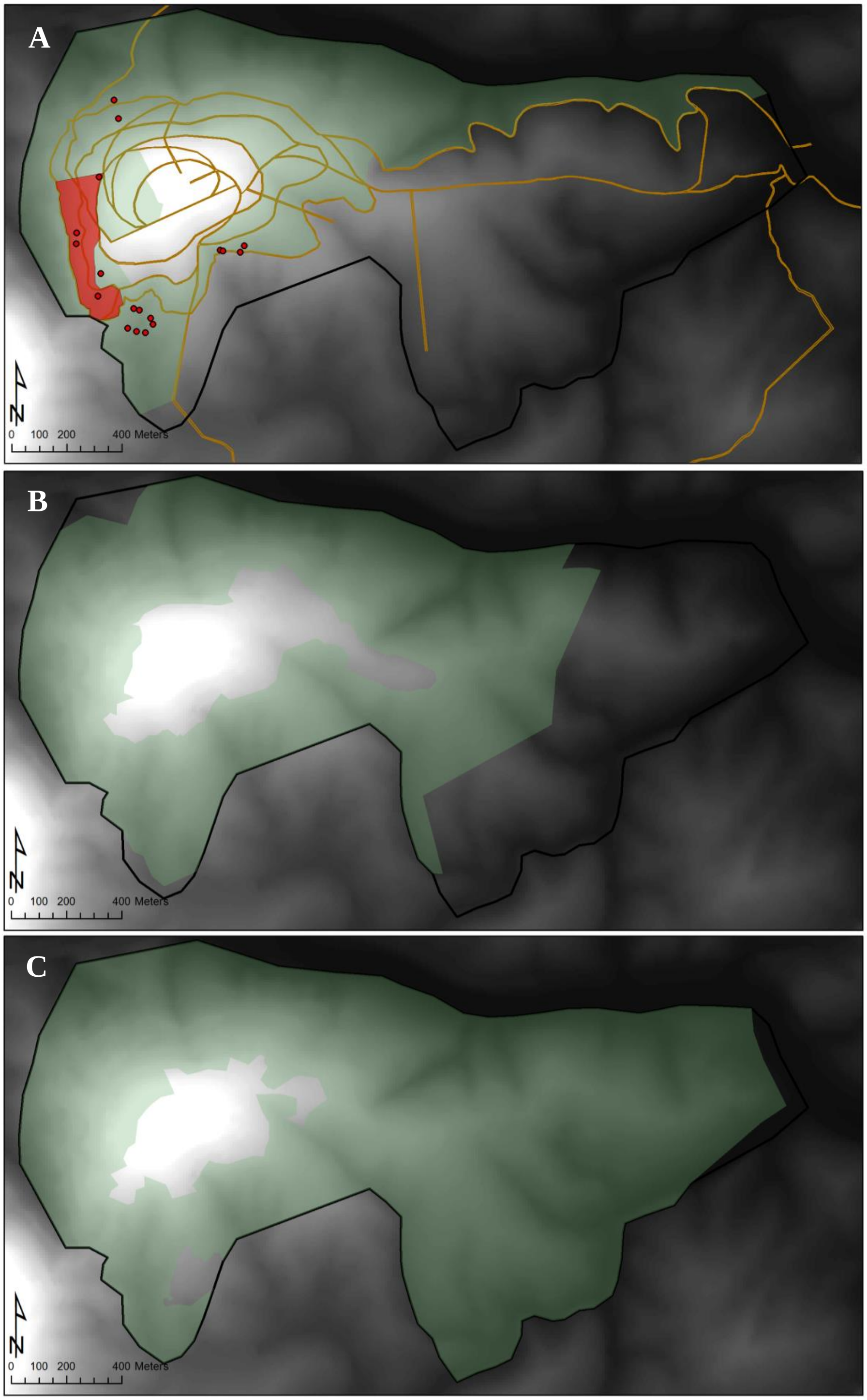

Fig. 1: Reconstructed forest cover (in light green) at Monticello circa 1826 from documentary evidence along with roads and trees dating to Jefferson's lifetime (a). Red dots indicate location of individual trees while red polygon encompasses an additional 17 trees found in an initial sampling without marking individual locations. Estimated forest cover in 1937 (b) and 1994 (c) from aerial photographs. Forest cover is overlain on a 30m DEM.

Appendix S4: Species Names in NMDS Ordination.

Abbrev.	*Genus*	*Species*
ACNE	*Acer*	*negundo*
ACRU	*Acer*	*rubrum*
AIAL	*Ailanthus*	*altissima*
ALIN	*Alnus*	*incana*
ASTR	*Asimina*	*triloba*
CACA	*Carpinus*	*caroliniana*
CAAL	*Carya*	*alba*
CACO	*Carya*	*cordiformis*
CAGL	*Carya*	*glabra*
CAOV3	*Carya*	*ovalis*
CAOV2	*Carya*	*ovata*
COOC	*Celtis*	*occidentalis*
CECA	*Cercis*	*canadensis*
CHVI	*Chionanthus*	*virginicus*
COFL	*Cornus*	*florida*
CR	*Crataegus*	*spp*
DIVI	*Diospyros*	*virginiana*
FAGR	*Fagus*	*grandifolia*
FRAM	*Fraxinus*	*americana*
FRPE	*Fraxinus*	*pennsylvanica*
GLTR	*Gleditsia*	*triacanthos*
HAVI	*Hamamelis*	*virginiana*
ILOP	*Ilex*	*opaca*
JUNI	*Juglans*	*nigra*
JUVI	*Juniperus*	*virginiana*
LISI	*Ligustrum*	*sinense*
LIBE	*Lindera*	*benzoin var. benzoin*
LITU	*Liriodendron*	*tulipifera*
MORU	*Morus*	*rubra*
NYSY	*Nyssa*	*sylvatica*
OSVI	*Ostrya*	*virginiana*
PATO	*Paulownia*	*tomentosa*
PIEC	*Pinus*	*echinata*
PIVI	*Pinus*	*virginiana*
PRAV	*Prunus*	*avium*
PRSE	*Prunus*	*serotina*
QU	*Quercus*	*spp*
QUAL	*Quercus*	*alba*
QUCO	*Quercus*	*coccinea*
QUPR	*Quercus*	*prinus*
QURU	*Quercus*	*rubra*
QUVE	*Quercus*	*velutina*
RHPE	*Rhododendron*	*periclymenoides*
ROPS	*Robinia*	*pseudoacacia*
SAAL	*Sassafras*	*albidum*
TIAM	*Tilia*	*americana*
TSCA	*Tsuga*	*canadensis*
ULRU	*Ulmus*	*rubra*
VIAC	*Viburnum*	*acerifolium*
VIPR	*Viburnum*	*prunifolium*