EVALUATING INFLUENTIAL FACTORS OF FOREST GROWTH ACROSS CLIMATIC AND SILVICULTURAL GRADIENTS IN NORTHERN FORESTS OF THE UNITED STATES

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By Sarah Elizabeth Johnson

Thesis Co-Advisors: Drs. Aaron R. Weiskittel and Laura S. Kenefic

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
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Long-term silvicultural trials are used to study growth response at multiple temporal and spatial scales in forestry. Silvicultural trials provide unique opportunities to understand the growth and yield at multiple scales from intensively measured experiments. Differences in forest type, stand characteristics, site conditions, and silvicultural system implemented effect the growth and yield of these independent studies. Due to their varied implementation and methodologies it is difficult to extend results from one silvicultural trial to another. This study investigates the required effort and potential conclusions that can be garnered for previously collected independent long-term silvicultural studies across a subset of northern forest types.

Results from long-term studies are utilized for site specific conclusions, with results pertinent to similar forested areas. While site specific conclusions have furthered understanding of growth and yield, across site comparisons would provide a novel comparison across forest types. Large-scale comparisons across long-term silviculture trials could provide multiple of comparison metrics to further understanding of growth and yield with and between stand types. This project implements a start to finish description how to utilize historical forest growth

records to quantify regional variation in growth responses attributed to factors at multiple spatial scales.

The first chapter provides a rationale and methodology for data standardization necessary prior to a synthesis of silvicultural experimental results. Database construction was focused on maximizing flexibility for additional synthesis. Data used in initial construction of database were collected across the northern united states from 1927-2010. Multiple gradients of northern forest complexity are realized in these data, i.e. forest type, stand structure, and silvicultural system experimentation. Long-term stand trends across silvicultural treatments provide show standardization of raw tree records across sites could facilitate a variety of novel comparisons.

The second chapter presents a non-parametric technique, Boosted Regression Trees (BRTs), utilized in the across-site comparisons of the long-term forest growth records. The relative influence of site, stand, soil, and silvicultural variables were identified at a regional and site specific level. Difference in influential factors across sites provided snapshots of interacting factors affecting growth dynamics. Influential interactions of growth response are also identified and discussed. Diameter and density related factors were most influential across all sites. Within site influential factors varied with different dynamics driving growth responses (PAI). While rank and relative importance varied, climatic factors, in addition to density and diameter related variables were most common influential factors on site-level PAI. Periodic annual increment was relatively similar across all sites (0.48 ± 0.25 m^2 ha^{-1} yr^{-1}).

This initial effort to understand growth dynamics and influential factor variability proved possible opportunities are broad once initial data preparation is completed. To increase the strength and potential uses of standardized forest growth databases site specific data management support is required. Initial efforts should be focused on taking stock of available data with efforts to increase quality and robustness of records required at a site level. The compilation of metadata and standardized raw record formats would facilitate necessary data archival and increase potential future uses of these data.

DEDICATION

To Matt,

My future husband and best friend

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There are many people that contributed to this project that deserve acknowledgements, for without them this work would not have been possible. First I would like to thank my co-advisors Aaron Weiskittel and Laura Kenefic (USFS co-PI) for the guidance and support you provided me with the last two years. Aaron, the opportunities you have provided me with have undoubtedly made me more prepared for the next steps in my career. You were a model advisor and mentor. The year of independent study discussing a gamut of statistical topics was a treat not many burgeoning graduate students get to enjoy, thank you for that time. Laura, you are a strong female scientist whom has been an inspiration to myself and many other young women in forestry. I hope one day to be such an insightful and accomplished research scientist as you. Tony D’Amato and Jeremy Wilson, thank you for helping me keep this research in perspective with other long-term and large-scale forest management and ecology. I would also like to thank John Brissette for the continued interest and involvement in this project’s progression.

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Finally I would like to remember the men and women with the foresight to install, tend, remeasure, and believe in the USFS long-term research plots used in my thesis. Without these rare and illustrative living laboratories the field of forest science would be a much different, less enlightening, one.

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CHAPTER 1:
LINKING LONG-TERM U.S. FOREST SERVICE SILVICULTURAL EXPERIMENTS: HISTORICAL TRENDS AND POTENTIAL FUTURE USE OF A STANDARDIZED DATABASE

Introduction

Value of long-term forestry data

Long-term silvicultural experiments provide a unique opportunity to study forest attributes through time (Adams et al. 2010). To sufficiently study forest dynamics, long-term data are required; such data have been defined as data “monitored over many cutting cycles or an entire rotation, typically for many decades” (Seymour et al. 2006). However, the time, maintenance, and expense involved with long-term studies are quite substantial (Crawford 2006). Consequently, long-term studies of forests, including silvicultural experiments, are relatively rare (Adams et al. 2010) and usually operated through entities with relatively stable and constant funding such as governments or universities (Ostrom and Heibert 1954). Early long-term silviculture experiments by the U.S. Department of Agriculture, Forest Service (USFS), for example, have contributed substantially to growth and yield research, regeneration and management recommendations, and provided empirical findings on tree and stand response to various silvicultural systems (Westveld 1931, Eyre and Zillgitt 1953, Arbogast 1957, Harper 1950, Gingrich 1967, Gingrich 1970, Leak 1987, Buckman et al. 2006).

These long-term studies provide rare opportunities to understand historical forest conditions and trends with large amounts of empirical forest data and have provided many of the forest-type specific conclusions that form the scientific basis of forest (Lugo et al. 2006)

The relative rarity of these data in the field of forest science makes them very valuable in current and future applications, regardless of study implementation impetus.

USFS Experimental Forests and Rangelands (EFRs)

The USFS has the unique ability to perform research on a wide variety of land types throughout the United States. The USFS has been conducting research and development since the organization's inception in 1905 (Jain 2012, Stine 2012, Lugo et al. 2006). The USFS EFR network was initiated with the establishment of the first EFR: Fort Valley EF in Arizona, in 1908. The network is currently comprised of 80 EFRs in six USFS Research Stations: the Northern Research Station (NRS), Pacific Northwest Research Station, Pacific Southwest Research Station, Rocky Mountain Research Station, Southern Research Station, and International Institute of Tropical Forestry. Research Stations are subdivided into Programs and Research Work Units (RWU), with specific focused research areas. RWUs with responsibility for EFRs provide detailed hydrology, forest growth, composition, and other ecological data at long and short timeframes at regional and local scales (Stine 2012).

Silvicultural experiments within EFRs have very detailed measurements, usually on permanent sample plots, and are considered living laboratories that provide the ability to perpetuate experiments beyond the term on any individual's career (Stine 2012) . The intensity of measurements on EFRs provide large amounts of high-resolution data, but also present challenges regarding data maintenance, organization, and future outlook (Adams et al. 2010). A key challenge for EFRs is to maintain high-quality, well-documented, long-term data that were collected differently at each EFR, and in some cases, in individual experiments (Kenefic et al. 2011, Lugo et al. 2006). Another key challenge is maintaining the long-term stability of infrastructure and funding required facilitating collecting data and operating research sites (Stine 2012, Crawford 2006).

Scope of inference

The USFS EFRs have largely worked independently from one another in the past due to organizational structure and scope of research questions. Yet the EFR network and results have implications at multiple levels, and many sites have similar experiments. The care of data has been variable at the site or within site level.

Research is often focused within one forest type, species mix or silvicultural system. Research questions often vary by EFR, including questions of forest type, stand history, silvicultural system and other experimental factors of interest. Consequently, EFR studies have informed the adaptation and implementation and of site-specific or regional silvicultural guidelines based on some initial stand or forest type condition (Westveld 1928, Leak 1957, Seidel 1966, Roach and Gingrich 1968, Frank and Bjorkbom 1973,Tubbs 1977, Buckman et al. 2006) .

Experiments within EFRs are usually stand-alone, though they often have common themes or research objectives, such studying a specific range of cutting methods. This similarity in study design or treatment across some sites is the outcome of Station and Washington Office influence on local USFS research in the early to mid-1900s, when many EFRs were established (e.g. Harper 1950). Though stand-alone in their research questions, the USFS EFRs are part of a larger organization that imparted some consistency to experimentation across sites (Nowak et al. 1997). While region-specific work continues at EFRs, additional large-scale and long-term comparisons can be done if the scope of inference increases to across studies (Rustad et al. 2001, Adams 2010, Rustad 2008, D'Amato et al. 2011)

Current status of the field

While data collected from EFRs are immensely valuable, these sites are very expensive and operationally difficult to maintain constantly through time (Stine 2012 , Kenefic et al. 2011). These expenses and challenges are manifested through time by discontinuation of individual studies and disestablishment of EFRs (Stine 2012). Many EFRs have been placed in inactive status; some are ultimately disestablished (e.g., the Gale River, Finch-Pruyn and Paul Smith EFs in New Hampshire and New York) while others become more active when staffing and funding are made available (e.g. the Dukes EF in Michigan and Silas Little EF in NJ) or study design change (Adams et al. 2008, Adams et al. 2010, Berven 2011)

The North Central and Northeastern Research Stations (NCRS and NERS, respectively) merged into the NRS in 2006. Many historical documents refer to these separate Stations. Within this work, use of or reference to the NRS refers to the current infrastructure, which includes the twenty-two official EFRs and two cooperating EFRs formerly within the NCRS and NERS (Figure 1). The USFS implemented many long-term studies on EFRs and continues to use the historical experiments to explore changes over time. Long-term studies often have an abundance of plot re-measurement data and may also have large quantities of site-specific climate, soil, or atmospheric data of high quality that is filed away for the future; all in different formats depending on the research needs at the time of collection (Kenefic et al. 2011).

Although data collection continues to occur differently at most EFRs, the use and incorporation of standardized procedures within the USFS R&D system are increasing (Schweik et al 2005, Stine 2012). With current focus on the importance of long-term data, it is becoming evident that additional attention to data management (Lugo et al. 2006) and standardization of records is required (Adams et al. 2010, Curtis and Marshal 2005). Standardization is required to ensure data are in a usable and available form in the future (Stine 2012). While many EFRs store both electronic and hard copies of data, data loss or incompatibility occurs. In order to make data available to future users and reduce future loss of historical data, the USFS R&D has begun a remote research data archive (Kenefic et al. 2011). Currently, archival assistance is available to USFS data managers and research scientists, in hopes of initiating a continual archival quality data support system (Dave Rugg, pers. comm, 2011).

While some NRS EFRs receive funding for data management (Appendix D), the specific needs can vary greatly between EFRs. A key component of increasing data availability and quality for future users is to provide high-quality archival raw data with metadata, i.e., detailed information describing the data (Bluhm et al. 2010). Metadata allows users to familiarize themselves with data structure, content, and other archival information necessary to understand intricacies within the data files. The use of metadata with long-term studies allows for increased opportunities for collaboration and ensures data integrity (Bluhm et al 2010). Metadata provide a framework for cataloguing data records, without which users cannot adequately interpret long-term silvicultural experiments and study methodology. Some EFRs, such as the Penobscot Experimental Forest, have begun to compile metadata and provide online access to silvicultural data (Kenefic et al. 2011). In the age of electronic data storage, the care of data and importance of data management have been identified as areas for improvement by many organizations like the USFS (Lugo et al. 2006).

Future outlook

Catalogued, well-documented, long-term studies increase the ability of researchers to draw new, broad, and wide conclusions from data previously collected in silvicultural experiments. For example, D'Amato et al. (2011) recently used data from long term silvicultural experiments in the Lake States to compare carbon storage across silvicultural experiments in two forest types. The EFR system provides detailed re-measurements that allow individual researchers to develop snapshots of forest composition, structure, and response to a variety of cultural treatments. While these snapshots are invaluable, these studies also produce large quantities of site-specific information that is filed away following initial analysis, but could be used for future multi-scale assessments of forest growth, carbon sequestration or a myriad of other forest related goods and services.

Researchers today could use previously collected data to answer emerging questions about the influence of site and silviculture and other influential factors on forest growth. Utilizing historical silvicultural experiments, or retrofitting data from previous experiments to answer new research questions at multiple scales has been proposed (Lugo 2009, Adams et al. 2010) but only once been implemented within silvicultural studies (D'Amato et al 2011). Uncertainty of requirements or methodology to facilitate a large-scale synthesis utilizing data collected from silvicultural experiments across the region is one reason retrofitting silvicultural studies is rare. While the potential for large-scale comparison exists, data are not currently compatible across most long-term experiments within the EFR network. There is an opportunity to use these previously collected data in a novel application to understand temporal and geographic trends at the regional level by merging and synthesizing, or "retrofitting" different long-term silvicultural experiments to new research questions (Lugo 2009).

Study rationale

If a large-scale comparison of independent experiments using raw data is to be implemented, then substantial data configuration measures will be required. All of the USFS EFRs are viewed as independent experiments, which require some form of data management prior to any across-site comparisons (Lugo et al. 2006, Adams et al. 2010). But how can current USFS researchers most efficiently, or more importantly, flexibly, design a database for multiple future analysis and large-scale comparisons? Initial efforts to do such comparisons with subsets of EFR data are needed to better understand future data configurations necessary to perform across-site comparisons. Without data standardization, EFR silvicultural experiments with different study methodologies would not be possible perform across site comparison of growth variability at multiple scales (i.e the tree, stand, or landscape scale) would not be possible.

One key component of data configuration or inclusion is the compilation of metadata and some form of data record standardization (Curtis and Marshal 2005). As many of the studies on EFRs do not currently have metadata, equivalent data must be compiled for this initial effort. Efforts to document silvicultural experiments in an initial synthesis case study will likely produce guidelines for improved record keeping at EFRs, and reinforce the importance of metadata compilation for the continued use of long-term silvicultural data. The work outlined here will serve as example of a standardized database scheme necessary for the large-scale comparison of previously collected data within the context of the USFS EFR system.

The implementation of a relational, standardized database of raw tree records would allow for future research questions or other scopes of inference to be studied. Due to differences in study methodology and record documentation and storage some process of standardization of record type must be implemented previous to any statistical analysis.

Project goals and objectives

The impetus for this work was to increase collaboration among scientists at USFS EFRs in NRS through a silvicultural synthesis. Additional project goals were to: 1) increase data quality and accessibility by generating a standardized, relational database for a subset long-term silvicultural studies, and 2) reveal large-scale trends by comparing within- and between-site variability across forests types. Objectives of this work include: a) provide a methodology and rationale for standardizing long-term EFR forest growth data, b) contrast growth response within, between and across long-term silvicultural studies in USFS EFR system, c) provide simple guidelines for the future standardization or compilation of site-specific records, d) showcase the importance of thoughtful, long-term data management and metadata procedures when cataloguing EFR or other long-term forest growth records.

Data and methods

The first step in a synthesis of long-term silvicultural studies such as this is to generate a standardized, relational database that can accommodate the addition of new and existing studies, in order to reveal unrecognized trends across large scales. This database must allow for comparisons of within- and between-site variability across multiple forests types, which have historically not been analyzed together, particularly with regard to silvicultural treatment response. A key component in database planning is to be able to compare studies at multiple scales, while also allowing for response variables to be linked to multiple key determining factors. Here a framework to design a robust database of long-term silvicultural experiments is presented. This database was designed, not to answer one specific query, but to facilitate future comparisons across multiple forest types, silvicultural systems and climatic gradients.

This case study will provide a start-to-finish methodology for the standardization of data from a selected subset of NRS long-term silvicultural experiments; including the Argonne Experimental Forest (AEF), Birch Lake Study (BLS), Dukes Experimental Forest (DEF), Fernow Experimental Forest (FEF), Kane Experimental Forest (KEF), Penobscot Experimental Forest (PEF), Sinkin Experimental Forest (SEF), and Vinton-Furnace State Experimental Forest (VFSEF). Included sites have a range of forest types (Table 1), and study methodologies that will detailed in regards to the data compilation and standardization necessary to facilitate across-site comparisons of forest growth rates

To provide flexible or transferable methodologies, while allowing for potential future additions to the standardized data repository, we identified a subset of forest types and long-term experiments on a longitudinal gradient from the Midwest to the northeastern U.S., which should be sufficient for illustrative purposes and incorporating arability of record types to a preliminary standardized database of silvicultural experimental data.

Table 1. USFS Study Site Locations and General Descriptions. Site establishment denotes the initiation of research facilities on site, not forest establishment.

Site	Location Lat. (°)	Long (°).	Nearest City	Forest Type	Site Establishment	Record Length	Minimum Measured Diameter (cm)
AEF	45.750	-89.000	Three Lakes, WI	Northern Hardwoods	1947	1951-2006 (55)	11.43
BLS	47.716	-91.933	Babbitt, MN	Red Pine Plantation	1957	1957-2009 (52)	8.89
DEF	46.350	-87.166	Marquette, MI	Northern Hardwoods	1926	1927-2007 (79)	11.68
FEF	39.054	-79.680	Parsons, WV	Appalachian Hardwoods	1934	1979-2009 (30)	2.54
KEF	41.597	-78.766	Kane, PA	Allegheny Hardwoods	1932	1932-2004 (72)	1.27
PEF	44.866	-68.633	Bradley, ME	Mixed Northern Conifer	1950	1954-2009 (55)	2.54
SEF	37.500	-91.250	Bunker, MO	Central Hardwoods	1950	1978-2003 (25)	1.50
VFSEF	39.183	-82.366	McArthur, OH	Central Hardwoods	1954	1977-2012 (33)	8.89

Table 2. Treatment sample sizes and inventory descriptions for standardized tree list data within database. Record length denotes range of available tree measurements, while inventory period denotes the number of time unique plots were measured at the site level as included in the database.

Site	Study Name	Plots (n)	Sample Sizes *				Record Length**			Inventory Periods***		
			CNTL	*EA*	*UEA*	*Tot.*	*Mean (se)*	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*
AEF	Cutting Methods	90	7176	15751	13747	36674	53.83 (1.16)	48	55	21.15	6	24
BLS	Growing Stock/Cutting Methods	9	8298	-	-	8298	52	52	52	10	10	10
DEF	Cutting Methods	3	2557		1760	4317	57.16 (7.3)	35	79	4.01	4	5
DEF	Stocking and Cutting Cycle	121	-	-	20547	20547	50	50	50	4.01	4	5
FEF	Large Area Comparisons	24	18706	11626	11122	41454	28 (1.35)	24	30	7.12	6	9
KEF	R-Series Yield Overstory	15	14893	-	-	14893	72	72	72	10	10	10
PEF	Compartment Study	74	8579	17434	56553	82566	51.66 (2.84)	46	55	6.69	6	10
SEF	Spatial Distribution	11	21962	48570	-	70532	24.2 (0.8)	21	25	8.41	7	9
VFSEF	Cutting Practices	8	17856	-	11654	29510	27 (3.0)	24	33	23.37	10	29
Total		**355**	**100027**	**93381**	**115383**	**308791**						

*Tree level with site-level truncations **Plot level ***Site level

Study sites

Initially, sites within RWU-NRS-07 (the Center for Research on Ecosystem Change, http://nrs.fs.fed.us/units/crec/) were identified in fall 2009 as those potentially available and willing to contribute data to a collaborative silvicultural synthesis study. Following reevaluation in 2010, this project's initial calls for interested collaborators and available data were expanded to include all EFRs within NRS (Figure 1). Template requests for specific information concerning available datasets and preliminary sites were sent to key NRS scientists identified as potential collaborators. Some scientists declined to participate in data sharing. Following scientist responses, ten sites were initially identified at potential contributors.

While the ten EFRs had different studies, there were some similarities that would become the basis for more specific study inclusion criteria. After initial responses and subsequent reviews of study design and stand conditions, some sites willing to participate were deemed to not meet all criteria for inclusion to the case-study database. After further evaluation, the initial ten sites were reduced to eight sites across the NRS (Figure 2).

Inclusion criteria

To manage this project's focus, criteria were developed to identify a subset of EFRs to include in the case study database. The goal of study criteria was to establish a subsample of available sites based on similar stand structures or silvicultural methods across a wide geographic range. This study criterion allowed for experimental units that could be logically grouped together for comparisons, while still providing a robust sample of silvicultural trials within the northeastern United States. Criterion could be changed in the future to facilitate additional experiments' inclusion for a larger regional comparison.

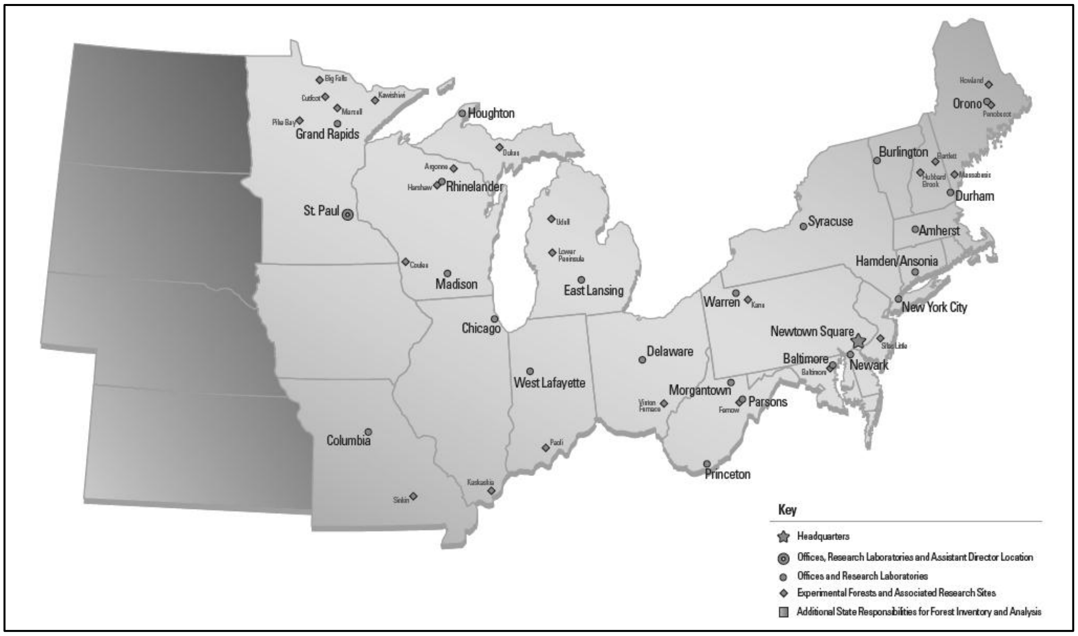

Figure 1. Northern Research Station (NRS) office and Experimental Forest and Range (EFR) and cooperating locations. Source: 2011 NRS Highlights. http://nrs.fs.fed.us/local-resources/downloads/2011_nrs_highlights.pdf

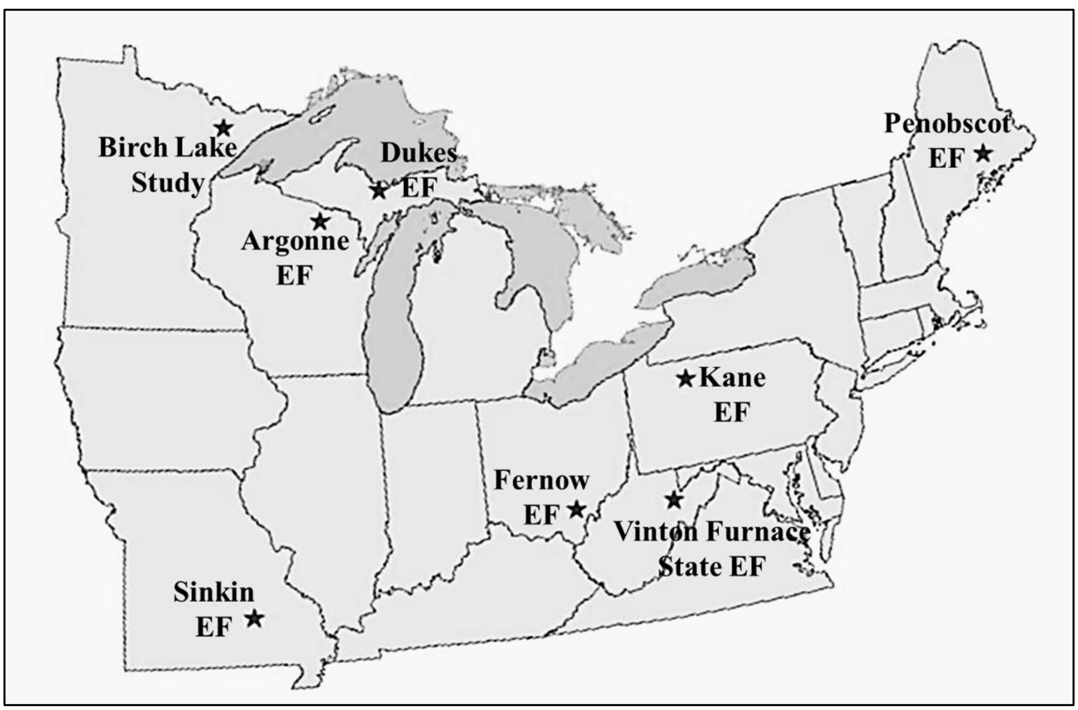

Figure 2. Included USFS silvicultural experiment locations, denoted by stars.

The primary criterion for study inclusion was longevity of records, which was arbitrarily set to 20 years. There was no minimum required number of inventory periods, as long as data records spanned 20 years of more (Table 3). In addition, studies included needed to have some combination of the following: a) an unharvested control or natural area, b) and even-age treatment with stand initiation around mid-20th century (1940- 1960), or an uneven-age system with an approximate ten-year entry cycle. A site needed to only have one type of silvicultural treatment category; although most submitted multiple silvicultural experiments if available (Table 4). After the lead scientist at a site indicated willingness to participate, a call for data was sent out. Some included silvicultural experiments included in this database have intermediate treatments, which were coded to show difference in stand histories. Some of the data we received did not meet all of the study requirements and were not included in this silvicultural synthesis case study.

Compiling data

A key component of this project was to compare previously collected information from different sites utilizing a non-traditional, raw-data approach to synthesize growth response and assess ranges of variability. Data compilation was a multi-stage process. All tree records to be compiled were previously collected (Table 1), i.e. no new growth measurements were taken in the field. Some additional spatial data requests were fulfilled by site technicians when necessary.

Table 3. Descriptions of unique treatment names used within database.

Site	TrtName	Description	Included in Summarization
AEF	CNTL	Control	Y
AEF	CC1951	Clearcut in 1951	Y
AEF	SW	Two-Stage Shelterwood	Y
AEF	13mRBA	10 yr selection interval (RBA 13.7 m² ha^{-1})	Y
AEF	17mRBA	10 yr selection interval (RBA 17.2 m² ha^{-1})	Y
AEF	20mRBA	10 yr selection interval (RBA 20.7 m² ha^{-1})	Y
BLS	CNTL	Control	Y
DEF	CNTL	Control	Y
DEF	27CC	Clearcut in 1927	N
DEF	Sing	Single Tree Selection	Y
DEF	11mRBA	10 yr selection interval (RBA* 11.5 m² ha^{-1})	Y
DEF	16mRBA	10 yr selection interval (RBA* 16.0 m² ha^{-1})	Y
DEF	20mRBA	10 yr selection interval (RBA*20.7 m² ha^{-1})	Y
FEF	CNTL	Control	Y
FEF	STNT	Seed Tree- No thinning	Y
FEF	STT	Seed Tree - Thinned	Y
FEF	SngT	Single Tree Selection	Y
KEF	CNTL	Control	Y
PEF	CNTL	Control	Y
PEF	2SW	Two-Stage Shelterwood	Y
PEF	10yS	Selection, 10 year interval	Y
SEF	CNTL	Control	Y
SEF	60RT	Rule Thin** to 60%	Y
SEF	80RT	Rule Thin **to 80%	Y
SEF	60TB	Thin from below (60%)	Y
SEF	80TB	Thin from below (80%)	Y
VFSEF	CNTL	Control	Y
VFSEF	Sel	Selection (~10 yr interval)	Y
VFSEF	SelwTSI	Selection with TSI*** (~10 yr interval)	Y

*Residual basal area
**Spatially explicit thinning experiment descried in Rogers 1978
***Timber stand improvements (removal of vines, etc.)

Table 4. Minimum metadata as deemed necessary at the tree level for inclusion in silvicultural synthesis project and the standardization of variables in the database.

Abbreviation	Name	Description
Site	Site	Site location name
Trt	Treatment Class	Treatment class: 0= control 1= even age 2=uneven age
TrtName	Treatment Name	Unique name of treatment, varies
Rep	Replicate	Standardized replicate number
Plot	Plot Number	Original plot number*
Tree	Tree Number	Original tree number
Year	Year	Year of measurement
SppFIA	Tree Species (FIA)	Standardized species codes, see APPENDIX D
DBHcm	Diameter at breast height (cm)	diameter measurements**
MetaStatus	Status Code	Standardized status code 0=Alive 1=natural mortality 2=harvested/salvaged 3=ingrowth* 4=(intentionally blank) 5= missing measurement
ExpFHa		Inverse of metric plot size

*all numeric plots original, if plots were non numeric those were converted into a numerical code
**significant digits remain un-standardized

Four types of data were compiled from each site. First, study information such as maps, study plans, site descriptions, and published results were collected. Second, raw tree lists were compiled for specific studies or subsets of studies depending on which met inclusion criteria at each EFR. Third, documents compiled from each EFR that were integral to discern formats of raw data, i.e. supplementary data or non-standardized metadata, were included. These documents were primarily coding keys for various site-specific codes such as species, unit of measure, status, and other noted numeric codes. Commonly, studies had site-specific species and status codes. Other site-specific numeric codes were also common, such as additional tree-list notes. Fourth, ancillary site data were compiled from other available sources for each site. Examples of these additional data were long-term climatic records such as annual temperature extremes, precipitation and soil classifications. Additional metrics at a stand (plot) level were calculated based on available data following database construction.

Soil information was extracted at the replicate level using the USDA Natural Resources Conservation Service (NRCS) web soil surveys (WSS) and official soil descriptions (OSD) (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx). Soil area of interest at the block level was input into WSS and most ubiquitous soil (by area) of the replicate was recorded into additional database tables. Soil type, drainage class, water holding capacity, depth to restrictive layer, depth to water table and a variety of parent material and landform classifications are available as future model covariates while increase record robustness (Table 6).

Climatic parameters were downloaded from the Oregon State University PRISM Data Explorer (http://www.prism.oregonstate.edu/products/) for single site-level grid-point data (Table 2). Climatic parameters downloaded were minimum and maximum January and July temperatures as well as annual precipitation. These annual climatic parameters were downloaded for the entire span of records at each site, regardless of measurement years collected or available at each site. In other words, if a site had a 25-year span of measurements as recorded through ten separate inventories, climate data were downloaded for the entire 25 years, not just the ten inventoried years.

Site history

Based on the inclusion criterion, eight sites were identified for this EFR standardization case-study (Table 1). Sites are under direction, or co-direction, of USFS NRS scientists. As described below, these experimental forests have many different types of silvicultural experiments occurring at multiple scales. Although most EFRs have multiple long- and short-term experiments occurring at any given time, only the silvicultural experiments included in the standardized database are discussed in detail (Table 2). All soil characteristics discussed within this work were extracted from NRCS soil surveys of the study blocks, available online.

<u>Argonne Experimental Forest (AEF)</u>

The Argonne Experimental Forest (AEF) is located within the Chequamegon-Nicolet National Forest in northern Wisconsin near the town of Three Rivers. Originally part of the NCRS, this EFR was established in 1947.

The AEF soils are of glacial origin with common landforms of drumlins, moraines, kames, terraces and outwash plains. Parent material on the AEF consists of loamy drift above glacial outwash and mud deposits. Slopes on the AEF range between one and thirty-five percent. In general, water holding capacity is low, while depth to water table ranges between 4.7-31.5 cm. Soil series representative of the included AEF studies are the Argonne-Sarwet sandy loams, Padus Sandy Loams, and Loaona-Sarona sandy loams. Soils range between moderately well to well drained soils with between zero and thirty-five percent coarse fragments by volume in soil. Other soils series exist in the area.

AEF forest composition is highly dependent on the soil attributes (Kern et al. 2006, Adams et al. 2008). Forest types on the AEF include northern hardwoods, mixed lowland conifers, and mixed pine. The mixed pine stands are located on sandy soils and dominated by jack (*Pinus banksiana* Lamb.) and red pine (*Pinus resinosa* Ait.) with a hardwood component of paper birch (*Betula papyrifera* Marsh.) and quaking aspen (*Populus tremuloides* Michx). The lowland mixed conifer stands occur on peat soils and are dominated by black spruce (*Picea mariana* Mill.) and tamarack (*Larix laricina (Du Roi)* K. Koch). The northern hardwoods stands are located on loamy soils dominated by sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula Alleghaniensis* Britton), American basswood (*Tilia americana* L.*)*, and eastern hemlock (*Tsuga canadensis* (L.) Carr.) with minor components of black cherry (*Prunus serotina* Ehrh.), quaking aspen, northern red oak (*Quercus rubra* L.), and American hornbeam (*Carpinus caroliniana* Walt.)

The cutting methods study (CMS) on the AEF was implemented in 1952 and is the only experiment from that EFR included in this database. The CMS includes a control, even-age (EA) and uneven-age (UEA) silvicultural experiments (Table 3). Primary goals of the AEF CMS were to study response of second-growth hardwoods to management alternatives (Erdmann and Oberg 1973). Study objectives were "(1) to obtain information on basal-area production and volume in terms of cubic feet, board feet, and cords, and (2) to obtain growth and mortality data under different cutting methods" (Erdmann and Oberg 1973) . Additional study information can be found in Erdmann and Oberg (1973), with results detailing regeneration and understory dynamics on AEF in other studies (Tubbs 1977, Kern et al. 2006).

The CMS consists of three, 18.19-hectare blocks all with similar site indices (base age 50 years), namely 19.8 m for sugar maple and yellow birch, and 21.3 m for American basswood and white ash (Erdmann and Oberg 1973) . Included in the database are five plots from each of three replicates of control, shelterwood and clearcut systems for a total of fifteen plots per treatment type. There are five plots per replicate of the variable residual basal area (RBA) selection treatments for a total of forty-five UEA plots included. All 90 included AEF plots are 0.047 hectares.

Birch Lake Study (BLS)

The Birch Lake Plantation Density/Thinning Methods Study (BLS) is located in the Superior National Forest near Babbitt, Minnesota at approximately 47.716° N, 91.933° W. Primary goals were to study the effect of release, stand density and thinning methods on red pine growth response (Buckman et al. 2006). The BLS study is not a NRS EFR, but under the direction of NRS scientists and provides the only plantation data included in this initial standardized database.

The BLS soils are of glacial origin with a parent material consisting of thick, sandy glacial outwash. Landforms within the BLS unit are outwash till plains and valley trains. Slopes range between one and nine percent. On the BLS, sandy soils water holding capacity is low, and a range of 60.96-203.20 (cm) depth to water table. Soils types representative on included BLS treatments include the Biwabik-Rollins complex and Eaglesnest stony loam with less than one percent of coarse fragments in soil. Soil drainage range between somewhat-excessively drained and moderately well drained. Other soil series are located nearby.

The study area primarily consists of mature red pine plantations established from seed in 1912/1913 (Buckman, 2006). Control plots were planted in 1915 and 1917. Other species present as ingrowth on site include; aspen spp., balsam fir (*Abies balsamea* (L.) Mill.), jack pine, eastern white pine (*Pinus strobus* L.), white spruce (*Picea glauca* (Moench) Voss), burr oak (*Quercus macrocarpa* Michx.), alder (*Alnus spp*.), red maple (*Acer rubrum* L.), and paper birch. Site index (base age 50) for red pine throughout the study ranged between 17.98-20.42 m (Buckmann et al. 2006).

Only the control plots from BLS are included in this project. These control plots, part of comparative thinning method study, are characterized by having very high standing basal area (37.4-73.0 m^2 ha^{-1}) with elevated levels of mortality. There are a total of nine, 0.08-hectare control plots from three replicates included from the BLS. Some plots in the controls have experienced significant blow-down as seen by significant drops in standing live basal area (Appendix A).

Dukes Experimental Forest (DEF)

In 1926, silvicultural experiments were established on the Upper Peninsula Experimental Forest near Dukes, Michigan at approximately 46.350° N, 87.166° W. The name of this area was later changed to the Dukes Experimental Forest (DEF) and was originally part of the NCRS. Most of the forested area in the DEF was donated by a large landholder in the 1920s: the Cleveland-Cliffs Iron Company. A portion of these lands had previously been cutover, and a portion was old- growth northern hardwoods. Partial cutting and comparative clearcutting studies were established to research growth potential and subsequent requirements of sugar maple selection stands in the northern hardwood region. Primary goals on the DEF through time have been to study regeneration and growth dynamics of old and second-growth northern hardwoods. Results from the DEF have been integral in the development of regional silvicultural guidelines (Arbogast, 1957, Tubbs 1977, Crow et al. 1981, Eyre and Zillgitt 1953). Stocking and structure guides for maximizing growth in sugar maple with the use of selection have been of summarized in Crow et al. (1981).

The soils on the DEF are of glacial origin, with common landforms being ground and end moraines. Parent material consists of loam or sandy loamy till. The area is relatively flat with slopes of zero to six percent. Water holding capacity ranges from very low to very high, depending on soil series. Depth to water table is usually greater than 200 cm, although in some areas only 69 cm. Depth to restrictive layer on the DEF ranges between 38 and more than 203 cm. Soil series representative of included treatments include Reade silt loam, Shoepac-Trenary silt loams, and Munising fine sandy loam. All the soils series discussed are moderately well drained. Coarse fragments by volume in soil range between zero and fifteen percent. Other soils series are present in the area.

Species composition in the old-growth portion of the DEF include: sugar maple, yellow birch, red maple, and eastern hemlock with minor components of American basswood, American elm (*Ulmus americana* L.), northern red oak (*Quercus rubra* L.), and ironwood (*Ostrya virginiana* (Mill.) K. Koch) (Eyre and Zillgitt 1953, Crow et al. 1981) .

Two studies from the DEF were included in this project: the Cutting Methods Study (CMS) and the Stocking and Cutting Cycle Study (SCCS), initiated in 1927 and 1951/1952, respectively (Table 3). The CMS is an incompletely replicated permanent sample plot study with relatively large plot areas (0.40- 0.81 ha) with 100% inventory. Included CMS PSPs in the database include two 1927 clearcut plots; two single-tree selection plots, and one research natural area (RNA). The RNA was an uncut control until a 1953 tornado and salvage, with an additional harvest in 1962 (Appendix A). While 1927 clearcut plots are available in the database, plot summaries are not included in the case-study summarizations.

The SCCS include UEA treatments of varying cutting cycles (5-20 years) and RBA treatments (6.88, 11.48, 16.07, 20.66 m^2 ha^{-1}). Marking was done following regional stocking guidelines (Eyre and Zillgitt 1953, Arbogast 1957) .Within SCCS, the 10-year cutting cycle replicates with 11.48, 16.07, 20.66 m^2 ha^{-1} RBA treatments are included in the database. A significant windstorm/tornado was also documented as affecting some SCCS plots not included in the database (Crow et al. 1981). The DEF SCCS contains three replications of completely randomized block design for 121 UEA and 126 total plots within database.

Fernow Experimental Forest (FEF)

The Fernow Experimental Forest (FEF) was established in 1934 near Parsons, West Virginia located approximately 39.054 ° N, 79.680 ° W. During World War II, it was temporarily closed. New research programs on the FEF were initiated in 1948 with consistent measurements collected since 1951. Two main types of research occur on the FEF: silvicultural and watershed research, as well as overlapped studies (Adams, 2008). Primary goals on the FEF are to quantify long-term stand dynamics affected by different treatments. FEF silvicultural research focuses on silvicultural systems of mixed hardwood stands typical in the area. Other multi-disciplinary studies and fire-related research are also occurring on the FEF (Adams et al. 2008).

The FEF is located on the un-glaciated portion of the Allegheny Plateau. Parent material consists of a reddish-brown loamy residuum consisting of non-calcareous shale, siltstone, limestone and sandstone. Landforms in the area consist of mountain slopes, ridges, and structural benches. Slopes range between three and sixty-five percent. Water holding capacity ranges between very low and moderate. Depth to water table ranges between 50.8 and 152.4 cm, with depth to restrictive layer greater than 203 cm (80+ inches). Soils series as representative by area of the plots include Calvin channery silt loam, Dekalb very cobbly loam, and Belmont silt loam. All representative soils are well drained with coarse fragments ranging between zero and eighty percent by volume.

Site index (base age 50) for oak is between 18.28 and 24.38 m (Trimbel 1974, Perket et al. 1999). The FEF history includes heavy, but variable cutting between 1905-1911 based on slope and accessibility (Trimbel 1974), and is characterized today as second-growth mixed hardwoods. Species composition includes northern red oak, sugar maple, yellow poplar (*Liriodendron tulipifera* L.), and red maple. There are twenty-two documented commercial species on the FEF. Control sites had dead American chestnuts (*Castanea dentata*) removed around the time of World War II (Wiemann et al. 2004).

Both even-age and uneven-age silvicultural systems are studied on the FEF. While the FEF has control watershed areas, diameter-limit cutting, crop tree management, commercial clearcuts, single-tree selection, and studies that mimic acid deposition, only a subset of these studies were included in the database. Studies included in the database were the replicated seed tree harvests with and without thinning, 10-year selection stands, as well as a control watershed. Plot sizes within included treatments on the FEF range between 0.1 and 0.2 ha. Included in the database are watershed and compartment studies from the FEF with a total of 24 plots (Table 2).

Kane Experimental Forest (KEF)

The Kane Experimental Forest (KEF) was established in 1932 and is located near Kane, Pennsylvania at approximately 41.597° N, 78.766° W. Initial research focused on the second-growth mixed hardwoods following heavy regional logging between 1890-1930 (Stout and Ristau 2005).

Soils on the KEF are not of glacial origin with a parent material consisting of residuum weathered from sandstone or shale, with hills as the primary landform. Slopes range between twenty-five and sixty percent. Water holding capacity is low with a depth to water table between 101.6-152.4 cm. Soils associated with studies included in this database are comprised of well drained, Hartleton channery silt loams. Coarse fragments in this soil ranges between fifteen and ninety percent by volume.

The KEF study area is within the Allegheny hardwoods forest type with characteristic species including black cherry (*Prunus serotina* Ehrh.), sugar maple, red maple, American beech (*Fagus grandifolia* Ehrh.), eastern hemlock, sweet birch (*Betula lenta* L.), yellow birch, white ash (*Fraxinus americana* L.). Common understory species are striped maple (*Acer pensylvanicum* L.) and American beech. Regeneration composition is variable between sites with different management histories (Stout and Nyland 1986). Most areas of the KEF are second-growth forests stands between sixty and one-hundred years old that were originally hemlock-beech-maple stands in the 1800s. On other areas of the KEF there are some third-growth stands, with one area considered remnant old growth.

Most stands on the KEF are considered EA, yet are actually comprised of many age-classes due to cultural augmentations in the last hundred years. Four main long-term studies have been implemented on the KEF since establishment (Stout and Ristau 2005). These studies include a "weeding study" established by Ash Hough (1936), a long-term thinning study established by Ben Roach and others (1971), management strategies study established by John Bjorkbom (1979-1981), and a cutting practice level study from the 1950s (Stout and Ristau 2005). Based on study inclusion criteria, only KEF controls were included in the current database (Table 2).There are fifteen, 0.04-ha control plots included in the database.

Penobscot Experimental Forest (PEF)

The Penobscot Experimental Forest (PEF) is a collaborative effort between the USFS NRS and the University of Maine's School of Forest Resources. Though owned by the University of Maine Foundation since 1994, the PEF was originally purchased by nine industrial land holding companies for USFS experimentation in 1950. This 1618 ha experimental forest, located in Bradley and Eddington, Maine at approximately 44.866 ° N, 68.633° W, is one of few in the NRS that is not on federal land.

Soils on the PEF are of glacial origin and quite variable. Parent materials include glacio-lacustrine or glacio-marine deposits, coarse-loamy lodgment till derived from quartzite, loamy melt-out till, lodgment till, and silty marine deposits. Landforms include drumlins, ridges, till and coastal plains. Slopes range from zero to fifteen percent. Water holding capacity ranges between very low to high with depth to water table ranging between zero and greater than 203 cm. Soil series in the area of the included treatments are Buxton silt loam, Plaisted very stony loam, Monarda and Burnham very stony silt, Thorndike very stony silt loam, and Biddeford silt loam. Soil series drainage ranges from very poorly drained to well drained. Coarse fragments in soil range between zero and eighty percent by volume. There are many other soil series in this area.

Species composition on the PEF includes red spruce (*Picea rubens* Sarg.), balsam fir, eastern hemlock, eastern white pine, red maple, paper birch, American beech, and aspen spp. There are both conifer-dominated and conifer–hardwood stands on the PEF. Historical studies have focused on the management of mixed-conifer stands for timber, but more recent studies incorporate more broad ecological questions such as wildlife dynamics and browse intensity Semlitsch et al. 2009, Larouche et al. 2009, Berven 2011).

The PEF was established for silvicultural studies in 1950. A compartment study initiated between 1952 and 1957 is the main study on the PEF (Table 2). It is a replicated study with ten silvicultural prescriptions including: two- and three-stage shelterwood, selection cutting on a five, ten, and twenty year cycle, fixed and modified diameter-limit cutting, unregulated harvest, and control (Sendak et al. 2003) . These types of harvest regimes are common through the Northeast and Appalachian areas of the United State (Schuler 2004) . Many of the results from the PEF discuss and compare the influences of different harvest methods to multiple stand characteristics (Sendak et al. 2003, Sokol et al. 2004, Kenefic et al. 2005. Inventories of research areas on the PEF occur on a rotational 5- or 10-year interval. Given the lack of site index measurements in this region, an equivalent measure was estimated by the use of 100 dominant and co-dominant trees, which is generally 18.4 m on the PEF (Sendak et al. 2003).

Included in the database are paired replicates of EA, UEA, and control (Table 3). Management units or blocks included in the database include: two-stage shelterwood, ten-year selection cutting, and control (Table 3). Other types of cutting methods on the PEF were not included in the database. There are other types of experimental UEA harvest methods on non-USFS land in the PEF (Arseneault et al. 2011) these have a less-than 20 year record and were not included. Selection removals are based on the BDq method (Gingrich 1967). The control was not replicated from the initiation of the compartment study, but was split in 1993 when it was recognized two different stand structures were evident (Sendak et al. 2003). Nested circular plots of different sized plots are inventoried on the PEF compartment study.

Plot sizes measured on the all PEF studies range between 0.008 and 0.40 hectares. Only the 0.08-ha overstory plots are summarized (Appendix A-C), but all plot sizes for the included treatment types are within the database. Previous to 1977, overstory trees were not individually numbered; trees were measured and tallied to the closest one-inch diameter class. Trees without individual numbers are not included in summarization, but included in the database for select treatments. Any tree that was recorded by diameter class instead with a unique diameter was also excluded in the present summarizations. Two management units (replicates) of included treatments are included in the database, for a total of 74 plots.

Sinkin Experimental Forest (SEF)

The Sinkin Experimental Forest (SEF) was established in 1950 within the Mark Twain National Forest in Dent County, Missouri. The included study from the SEF is located at approximately 37.500° N, 91.250° W. Initial research focused on management and reproduction of shortleaf pine (*Pinus echinata* Mill.), while later research focused on the oak-dominated stands' management and natural or artificial regeneration issues. Oak regeneration is a subject of interest in this area, thus savanna and fire science projects have also been implemented 9Adams et al. 2008) . Regeneration guidelines for oak in oak-pine forest types have been developed through long-term studies on the SEF (Johnson et al. 2009).

Soils on the included portions of the SEF are of non-glaciated history. Parent materials consist of slope alluvium over residuum or pedisediment over residuum weathered from dolomite or cherty limestone on upland sites. Landforms are consistently hill slopes, with slopes ranging from eight to fifty percent. Water holding capacity is very low with depth to water table ranging from 40.6 to greater than 203 cm. Soils series from included treatments are Scholten-Bendavis-Poynor complex and Coulstone-Bender very stony complex. Coarse fragments in soils range from fifteen to seventy-five percent by volume. Soil drainage ranges between moderately well drained and somewhat excessively drained.

The majority of the SEF is dominated by oaks. Main components include white oak (*Quercus alba* L.), post oak (*Quercus stella*), black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), and northern red oak. The SEF's oak cover type associates include hickory (*Carya spp*.), black tupelo (*Nyssa sylvatica* Marsh.), sassafras (*Sassafras albidum* (Nutt.) Nees), shortleaf pine, black cherry, maple (*Acer spp*.), dogwood (*Cornus* spp.), and black walnut (*Juglans nigra* L.). Hardwood species dominate the understory. There is a relatively small amount of oak-shortleaf pine forest type where the predominant oak stands do not cover (Adams et al. 2008) .

Within the database are data from the SEF spatial distribution study (Table 2). The spatial distribution study was initiated in 1977 as a PhD dissertation project (Rogers 1978) . This study was established on a 16.18 ha stand clearcut in 1963, with all plots an evaluation of even-age oak stand development. Included within the spatial distribution, and the preliminary database, study are two iterations of intermediate treatments. Two iterations of rule thinning (RT), which is based on two factors: trees-area ratios and spatial pattern characterization (Rogers and Johnson 1985). RT is an algorithm which defines alternative methods of selecting "remove trees" in a thinning prescription are included in the database. The RT algorithm tries to efficiently and consistently select leave/remove trees where thinning is based on stocking goals (Rogers and Johnson 1985). There are also two iterations of thinning from below in the spatial distribution study (SDS) included in the database. Additional plots were added in 2002 to the SDS, but are not included within this database or additional summarizations. A total of eleven, square 0.25 ha plots were included from the SEF (Table 3).

Vinton-Furnace State Experimental Forest (VFSEF)

The Vinton-Furnace State Experimental Forest (VFSEF) is located near McArthur, Ohio at approximately 39.183° N, 82.366 ° W. The VFSEF was established in 1952 following a donation from the Baker Wood Preserving Company. Originally designated as the Vinton-Furnace Experimental Forest in 1963, it has since been renamed. Presently the land is owned by the Ohio Division of Forestry and co-managed by the USFS NRS.

Soils on the VFSEF are of non-glacial origin with parent material consisting of different classifications of residuum. Residuum structure consists of weakly cemented, fine to coarse grained fractured sandstone and nearly horizontal interbedded shale and siltstone. Primary landforms in the area are hills, with slopes on included plots ranging from six to forty percent with nearby slopes up to seventy percent. Water holding capacity is low with depth to water table ranging from 50.8-101.6 cm. The Germano-Gilpin complex and Gilpin Rarden complex are well drained silt loams, which are indicative of the included VFSEF treatments. Coarse fragments in soil by volume range between zero and eighty percent.

The study area is dominated by central hardwoods, as characterized by mixed-oak stands. There are more than fifty tree species growing in the VFSEF. Species composition is stratified by slope position. From ridgetop to mesic forests main tree species include; chestnut oak (*Quercus prinus* L.), scarlet oak, black oak, white oak, red maple, hickories (*Carya spp*.), and Ohio buckeye (*Aesculus glabra* Willd.) and yellow poplar, respectively. Control plots have a black oak site index (base age 50 years) of 19.8-21.6 m . Control plots have no record of any management activities since before 1952.

The VFSEF Cutting Practices Demonstration (CPD) studies different types of timber management systems in the mixed oak-hickory (*Carya spp*.) forest of southeastern Ohio. The CPD plots were initially inventoried in 1952 with initial cutting on plots occurring between

1955-1957, with other fire and thinning studies developed in 1994 and 2001 (Adams et al. 2008) The CPD plots were one of the earliest clearcutting studies in the area, and data collected were used to produce regional growth and yield simulators; GROAK and OAKSIM (Adams et al. 2008) and regional stocking guides (Gingrich 1970) .

While data were collected from 1952, early raw data were lost. Only CPD stand summary information is available previous to 1976, and for this study, only tree lists were used in the summarization of stand structure (Table 2). Included treatments from the CPD include the selection with and without intermediate timber stand improvement and the control plots of VFSEF Study 27 and 25 (Table 3). Other CPD cutting methods not incorporated into the database were the commercial clearcuts and diameter-limit cuttings. Eight plots from control and partial CPD selection plots are included in the database and range from 0.20 to 0.40 ha.

Database construction

The standardization process detailed within this project was a multi-level approach. First, data from sites were collected in an unaltered state. These unaltered data were in a variety of electronic formats, programs, and organization structures. A simplified, conceptual framework for data standardization delineates progression from raw, unaltered data to standardized plot summaries utilized in cross-site comparisons (Figure 3).

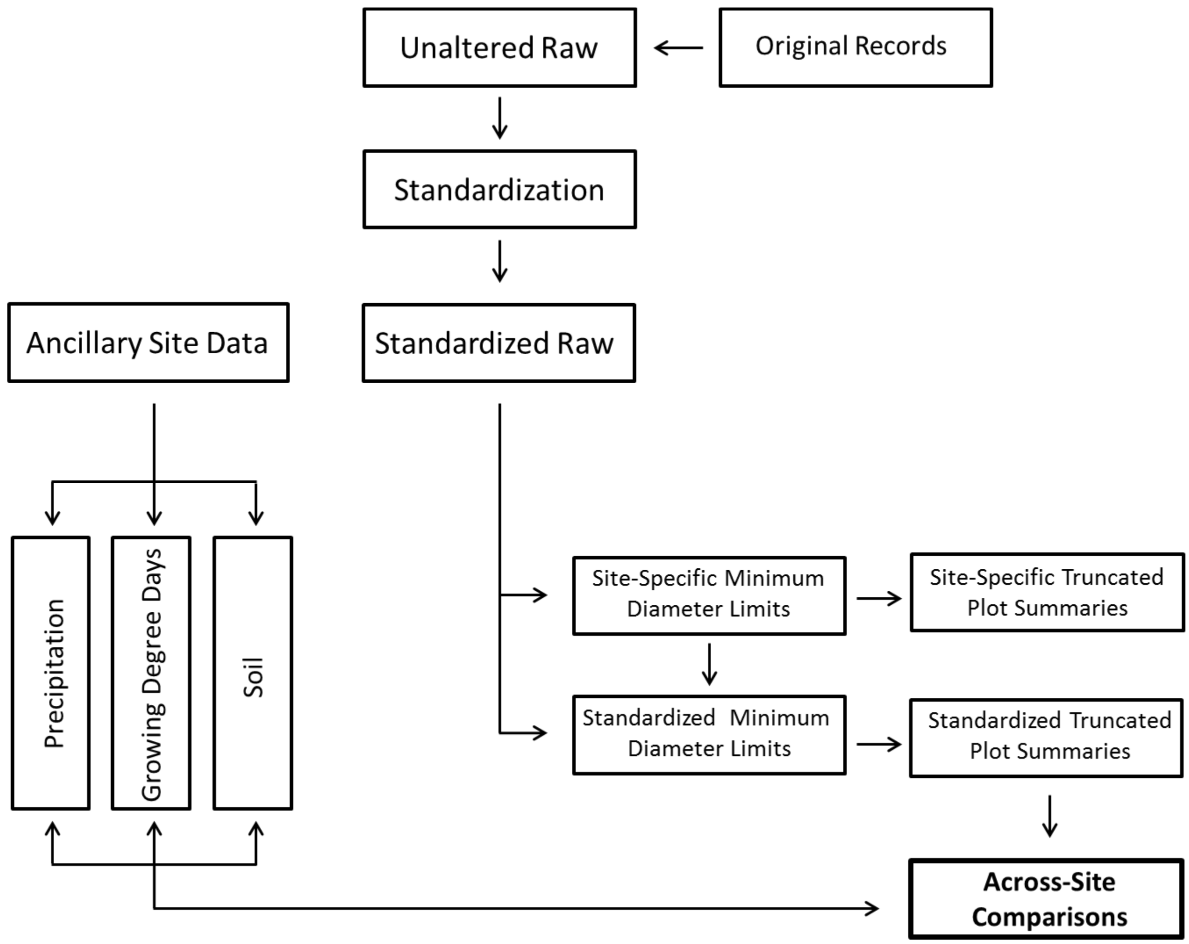

Figure 3. Conceptual framework of standardization process with U.S. Forest Service (USFS) raw site data utilizing multiple file input types to prepare data across sites for silvicultural synthesis project.

Once data were compiled from all sites, a standardization of record format and content occurred. A few ancillary tree-level data descriptions were deemed necessary to identify, separate, and classify these silvicultural data in a robust, transparent format. This initial standardization of raw unaltered data produced an altered data format that was associated to each tree (Table 4).

Following initial data and study site recognition, minimum data requirements for tree-lists at each site or study were outlined. There were twelve minimum pieces of information identified as necessary to store data in an archival quality (Table 4). If additional information at a site was available, it was retained following the standardized minimal data methods. Some unique treatments within the database were not included in cross-site comparisons (Table 3). Two standardized files were made for each site: one with only the standardized meta-database records and a site-specific standardized file containing additional site specific standardized data.

Standardization of original data followed simple procedures for data management such as consistent formatting and naming (Borer et al. 2009). Initial standardization was needed to varying degrees at each site. Even these universally "standardized raw" data had issues that were subsequently edited/mitigated through statistical software.

Standardization

Different file formats were transposed and reorganized as needed previous to universal standardization of raw data. Truncation of raw tree records occurred at two different scales. First, site-level truncation of the largest minimum diameter measured through time was performed (Table 1). Site level truncation was necessary to mitigate changed in minimum diameter limit levels through some long-term silvicultural experiments. For example, a subset of years at the DEF were excluded because the minimum diameter sampled from 1942 to 1960 was 25.4 cm, while all included years if the database were measured to a minimum of 11.68 cm. Second, a truncation of standardized raw tree across sites was performed across sites to exclude all trees less than 11.68 cm. All presented summaries utilize this standardized truncation level, (Table 2). The effect of site and standardized truncation level at sites were evaluated at the plot level (Appendix B).

Treatment classification was standardized and unique treatment names were developed (Table 3). Standardization of species codes was done using the USFS FIA species codes

(Appendix D), while tree-level status codes were edited into new standard format (Table 4) . Diameter records were standardized to metric units (cm), while site, treatment, and replication information was added to the tree lists. Metric tree expansion factors were included for each individual record to facilitate identification of plot sizes, particularly when nested plot designs were used. Additional notes as necessary were included following the standardized information.

Once site-level data were in the same format, they were reimported into the Microsoft Access database with additional site-specific notes retained. Another meta-file was created with only the minimal meta-data records (Table 4) utilized in statistical summarizations.

Post-processing

After initial data were standardized, a webinar of preliminary site-level results was presented to collaborators and data managers. A key concern following the webinar was initial data quality. Resulting discussions provided a framework for post-processing including the QAQC of included site data records (Appendices A-C).

Quality assurance and quality control (QAQC)

Quality control of raw and standardized records occurred through data compilation and summarization stages of this case study. While data preparation and other standardization measures occurred, continual cross reference of samples sizes was done to confirm no loss of data. Raw data were flagged if above a critical diameter to ensure these records were indeed large trees and not a keystroke error. Summarized data at the plot level were sent to scientists or data managers at each site to confirm observed trends.

Standardization and QAQC were implemented separately for each experiment and then combined at the site level. Each site was standardized separately to keep a consistent and clear order of operations. The second step of the QAQC during post processing of standardized data was to summarize individual plots through time, and identify anomalies in conjunction with unexpected temporal trends. These plot summaries were sent to scientists or data managers at each site to confirm observed trends over time within and between replicates, with overview of included data files. Plot summaries also assisted with identifying undocumented changes in inventory methods, as evidenced by changes in stand structures without documented harvesting. Changing minimum diameters for measurement were the most common issue identified on these plots. Many studies did not have metadata showing changing sampling protocol over time. The largest minimum diameter measured was identified by site (Table 1) and used in all site-level summaries. All available data (i.e. some data not used in summarization) were included in the database of standardized raw diameter growth measurements with additional information available.

Results

Resulting database can highlight the temporal and spatial trends evident in the standardized forest and ancillary site data across study areas, and are presented as an illustration of potential comparisons. The goal of the database was to provide a flexible format to perform multiple future comparisons, so presented figures are small portion of available comparison metrics using standardized data. The presentation of common stand attributes will increase the readers understanding of database flexibility towards storing multiple silvicultural experiments of varying methodologies and stand structures.

Database

A standardized database of 361,775 diameter records were compiled from the eight included long-term silvicultural sites (Appendix D). Database measurements range from 1927 to 2010 (Table 5). Following additional standardization to mitigate differences of inter-study design there were 245357 total records usable for across site comparisons. Standardized truncation to tree >11.68 cm resulted in 184144 records used in across-site comparisons detail within this work. Multiple relationships are present in database (Figure 4). The raw database has all included records form silvicultural experiments. Summarizations of this database do not utilize all records, i.e. diameter truncation and other methodologies excluded some data from this comparison. Additional ancillary site data including soil and climatic data are also included in the database.

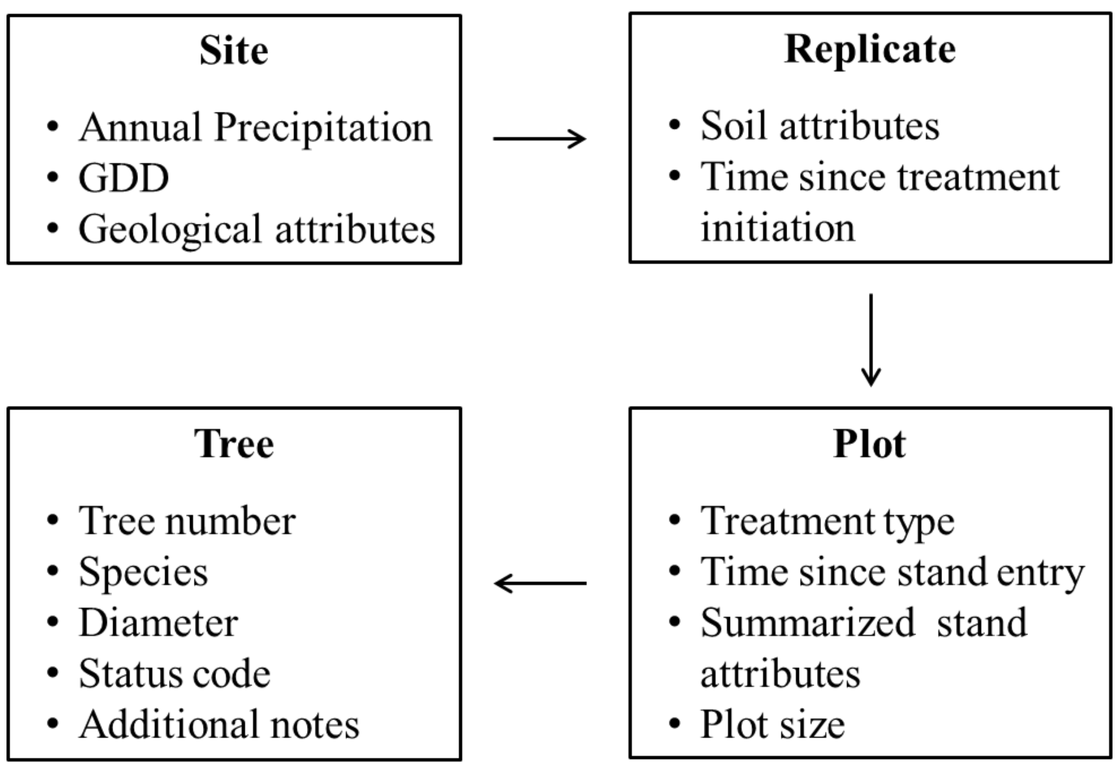

Figure 4. Spatially related characteristics of resulting database relationships following universal standardization in preparation for a silvicultural synthesis using data from 8 long-term U.S. Forest Service Experimental Forests.

Table 5. Inventory years by site and treatment. Bolded years denote active harvesting on at least one plot within treatment type with at least six trees removed; additional plot-level detail can be found in original study descriptions or included database.

Site	TrtName	Inventory Year
AEF	CNTL	1951, 1957, 1961, 1966, 1971, 1974, 1976, 1981, 1986, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2006
AEF	51CC	1951, **1957**, **1958**, **1961**, 1966, 1977, 1990, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2006
AEF	SW	1958, **1965**, **1966**, 1974, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2006
AEF	13.7 M RBA	1951, **1957**, 1961, **1966**, 1971, **1974**, **1976**, 1981, **1986**, 1990, 1991, **1992**, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, **2002**, 2003, 2006
AEF	17.2 M RBA	1951, **1957**, 1961, **1966**, 1971, **1974**, **1976**, 1981, **1986**, 1990, **1991**, **1992**, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, **2002**, 2003, 2006
AEF	20.6 M RBA	1951,**1957**, 1961, **1966**, 1971, **1974**, **1976**, 1981, **1986**, 1990, 1991, **1992**, 1993, 1994, 1995, 1996, 1997, 1998, 1999, **2000**, 2001, 2002, 2003, 2006
BLS	CNTL	1957, 1962, 1967, 1972, 1976, 1982, 1987, 1992, 2003, 2009
DEF	CNTL	1927, 1932, 1936, 1941, 1946*,1952*,1956*,1962
DEF	Sing	1928, 1932, 1933, 1937*, 1942*, 1947*,1952*, 1953*, **1956***, **1958***, 1961, 1 **1966**, 2007
DEF	11.4 M RBA	1952*,**1957*** ,1962, **1967**, 1973, **2002**
DEF	16.0 M RBA	1952*,**1957***, 1962, **1967**, 1973, **2002**
DEF	20.6 M RBA	1952*,**1957***, **1962**, **1967**, **1973**, **2002**
FEF	CNTL	1979,1983, 1989, 1994, 1999, 2009
FEF	SDNT**	1980, 1982, 1984, 1990, 1995, 1999, 2005, 2009
FEF	STT**	1980, **1982**, 1984, 1985, 1990, 1995, 1999, 2005, 2009
FEF	SngT***	1983, 1987, **1988**, 1992, 1997, **1998**, 2002, 2006, **2007**
KEF	CNTL	1932, 1937, 1942, 1952, 1957, 1977, 1984, 1989, 1993, 2004
PEF	CNTL	1980, 1984, 1989, 1993, 1999, 2009
PEF	2SW	1976, **1982**, **1986**, 1987, 1991, 1992, **1997**, 1998, **2002**
PEF	10yS	1976, 1977, **1980**, 1981, **1984**, 1986, **1987**, 1989, 1991, 1994, **1995**, 1997, **1998, 1999**, **2003**, **2004**, **2008**
SEF	CNTL****	1978, 1982, 1985, 1986, 1988, 1993, 1999
SEF	60RT	1978, 1982, **1985**, 1986, 1988, 1993, 1999, **2001**, 2003
SEF	80RT	1978, 1982, **1985**, 1986, 1988, 1993, 1999, **2001**, 2003
SEF	60TB	1978, 1982, **1985**, 1986, 1988, 1993, 1999, **2001**, 2003
SEF	80TB	1978, 1982, **1985**, 1986, 1988, 1993, 1999, **2001**, 2003
VFSEF	CNTL	1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1986, 1987, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007 2008, 2009, 2010
VFSEF	Sel	1976, 1978, 1979, 1980, 1981, 1982, **1984**, **1985**, 1989, 2000
VFSEF	SelW	1976, 1978, 1979, 1980, 1981, 1982, **1984**, **1985**, 1989, 2000

*Years excluded from analysis, but available in database

**Seed tree harvest occurred in 1960 with overstory removal in 1962/63 winter

***Harvests also occurred in 1958, 1968, 1978 previous to available records

***Thinning of non-commercial species occurred in 1983

Site characteristics

Climate

Precipitation

Mean precipitation across all sites was 97.6 ± 24.36 cm (Figure 5). Temporal variation exhibits oscillating trends with variable magnitudes between sites (Figure 5). The FEF has the highest mean annual precipitation of 139.95 ±3.32 cm followed by the KEF at 114.25 ±1.67 cm. The AEF, BLS, and DEF have the lowest temporal variability through included years with standard deviations of ± 1.53, 1.51, and 1.25 cm, respectively. Sites within sub-regions, e.g. the upper Midwest: AEF, BLS and DEF, exhibit similar mean precipitation (79.63, 71.57, and 85.07 cm, respectively). Overall, relatively low variability of annual precipitation was seen within site. The SEF exhibits a large magnitude of temporal oscillation shown with a bimodal distribution of precipitation (Figure 5) and also had the highest deviation within site at total annual precipitation standard deviation ± 4.78 cm. The PEF and VFSEF have similar mean precipitation at 103.31 and 104.70 cm, respectively.

Growing degree days (GDD)

Mean GDD across all years of included site measurements was 2527.5 ± 293.7 °C. The SEF had the highest and most variable GDD with 3205.5 ±49.12°C. GDD also exhibited oscillating trends similar to precipitation. The PEF, FEF and KEF had similar GDD at 2499.7, 2559.24, and 2464.9, respectively. Temporal trends of mean GDD varied across sites. Some sites had increasing (i.e. PEF) and decreasing (i.e. KEF, FEF) trends over the last few decades, while others seem to fluctuate with no clear directional trends (DEF and VFSEF). The VFSEF and the FEF show a similar peaking, decreasing and peaking GDD trend between 1980 and 2005. The upper Midwest sites (AEF, BLS, and DEF) exhibit overall similar variability (Figure 6), but show different trends through time (Figure 6 panel A) such as short-term directional changes (i.e. ~1980). The eastern and northeastern sites (KEF, PEF, and FEF) exhibit similar mean and variability ±19-36.25°C, but show different trends through time such as short-term directional changes (i.e. ~1990) (Figure 6). Both the PEF and KEF exhibited similar temporal trends with general increasing and decreasing GDD periods, which generally coincided through study inclusion periods.

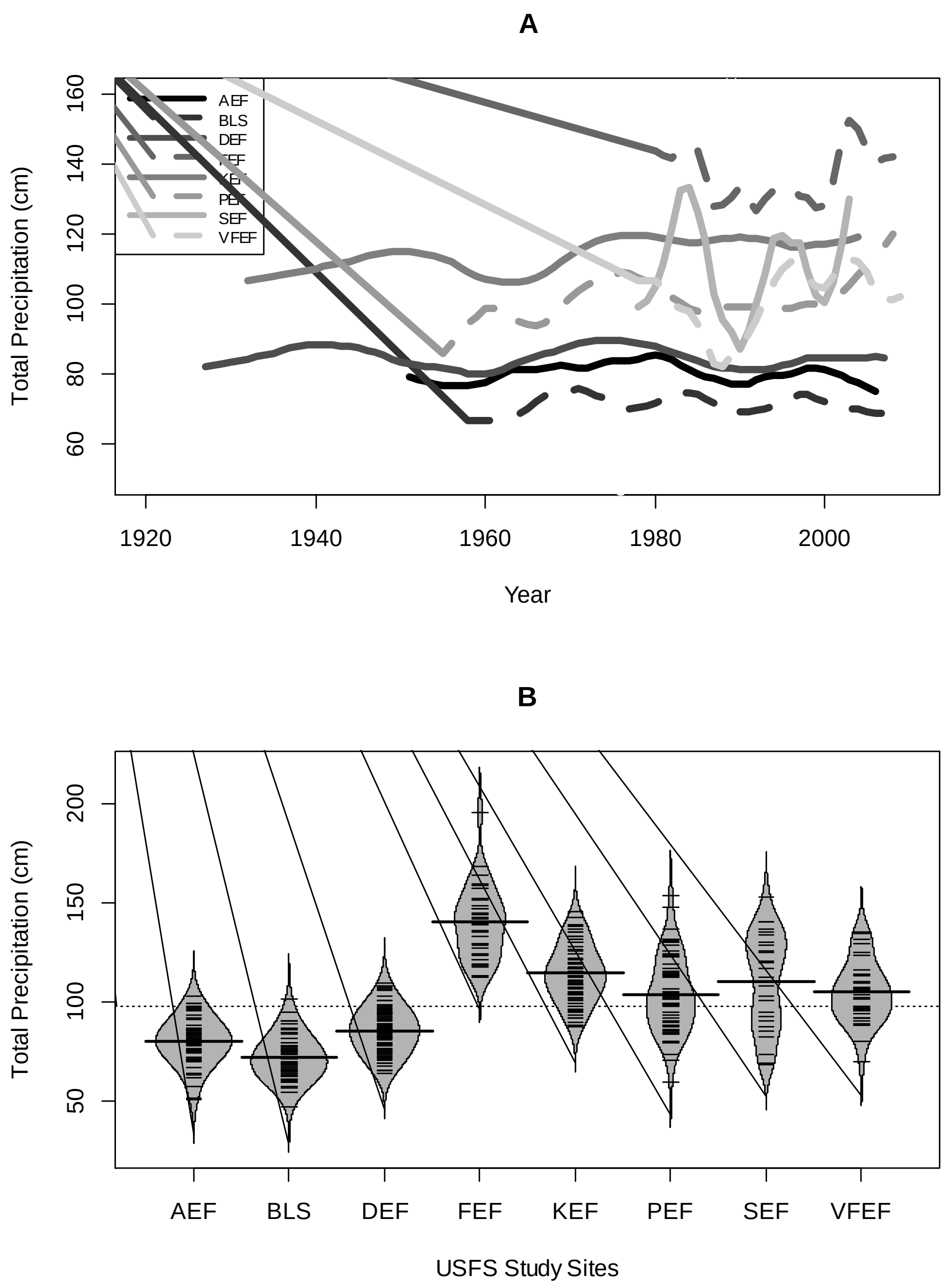

Figure 5. Total annual precipitation variability, shown by lowess smoother *(f=.25)* of all years within available range of measurement period at each USFS study site (Panel A). Beanplot (Kampstra 2008) of total annual precipitation for all years within available range of measurements at USFS study sites (Panel B). The dotted horizontal line is the overall mean, while the black solid lines are the site means. Climate data were extracted from PRISM Climate Group's Data Explorer (Oregon State University).

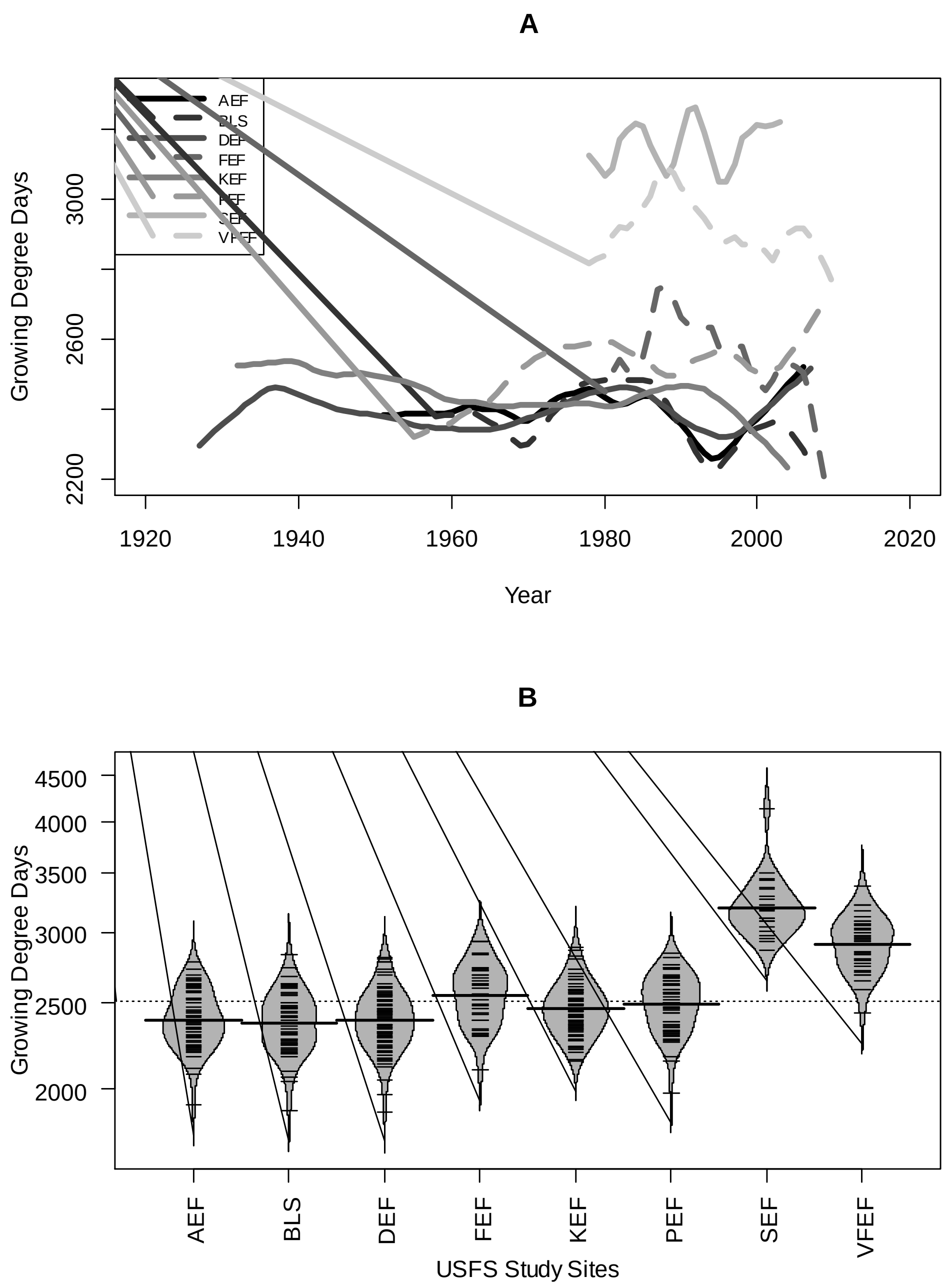

Figure 6. Mean annual growing degree day (5˚C) variability, shown by lowess smoother *(f=.25)* of all years within available range of measurement period at each USFS study site (Panel A). Beanplot (Kampstra 2008) of mean growing degree day (5˚C) for all years within available range of measurements at USFS study sites (Panel B). The dotted horizontal line is the overall mean, while the black solid lines are the site means. Climate data were extracted from PRISM Climate Group's Data Explorer (Oregon State University).

Stand Structure

Live basal area (trees ≥ 11.68. cm dbh) across sites and treatments ranged between 1.99 and 65.97 m^2 ha^{-1} during all included study period. The AEF controls reached a plateau of mean standing BA at approximately 35 m^2 ha^{-1} from 1997 to 2006. The first AEF clearcut measurements were taken prior to overstory removal in 1951 at 20.72 ± 1.21 m^2 ha^{-1}, which was reduced to 3.33 ± 0.856 m^2 ha^{-1} after the removal in 1957. Mean standing live basal area has been increasing since final overstory removal (1968) on the AEF shelterwood, while the selection harvests have a fluctuating BA through time. Plot-level variability is most apparent in the 1951 clearcut and control plots, with less inter-plot variability in the shelterwood and selection treatments (Appendix A).

The BLS control data show increasing mean basal area at decreasing rates with no replicates showing growth and mortality stabilization, i.e. plateau of live BA. Some isolated mortality has occurred in control plots from a known blow-down event (Appendix A). The BLS control plots have the highest standing live basal area per hectare of any of the included sites at 65.97m^2 ha^{-1}.

The DEF control area has experienced reductions in standing live basal area from study initiation (Figure 7). However, temporal trends are difficult to discern at the DEF control area because of changes in the smallest tree size measured (which led to data exclusions) and lack of replication (Appendix A). The BA trends of the DEF single-tree selection are also simplified because of inventory exclusions based on changes in the minimum diameter measured over time. Plot variability within RBA selection treatments is evident in initial relative BA and changes through time (Appendix A).The selection treatment prescriptions of 13.7, 17.2, and 20.6 m^2 ha^{-1} were slightly lower than actual mean live basal area in 2006 on those treatments with 15.9 ± 0.43, 19.2 ± 0.73, and 22.7 ± 0.55 m^2 ha^{-1} respectively.

The FEF control area had reductions in mean standing BA between 1990 and 2000 (Appendix A). The trend in control plots during that time period is of relatively stable BA at approximately 34 m^2 ha^{-1} (Figure 7). The seed tree treatments, both thinned and un-thinned, exhibit increasing live BA through time. Initially, both treatment types had similar standing live BA and standard errors, at 11.48 and 11.37 m^2 ha^{-1} ± 2.49 and 0.59 m^2 ha^{-1}, respectively. Seed tree (with thinning) stands reduced to approximately 7.86 m^2 ha^{-1} in 1982, and by 2009, the un-thinned plots had had 4 m^2 ha^{-1} more standing BA on unthinned plots. There is low inter-plot variability in the thinned seed tree and unthinned treatments (Appendix A). The single-tree selection plots have decreased in standing live BA through time from 24.18 ± 0.58 m^2 ha^{-1} in 1983 to 19.19 ± 0.97 m^2 ha^{-1} in 2007.

Table 6. Soil characteristics by USFS Study Site. All measurements are shown in metric (cm). Data were extracted at the USFS replicate level from NRCS web soil surveys.

Site	Parent Material	Landform	Slope Class*	Drainage Range**	Depth to Water Table (cm)	Depth to Restrictive Layer (cm)	Water Holding Capacity (cm)	% Coarse Fragments
AEF	Glacial	Drumlins & moraines	B-D	MWD-WD	30-203+	203 +	12.1-14.7	0-35
BLS	Glacial	Plain	A-B	MWD-SWED	61-203+	40-203 +	8.4-10.1	0-1
DEF	Glacial	Moraine	B	PD-MWD	203+	38-203 +	6.1-32.4	0-15
FEF	Residuum	Mountain & ridges	C-F	WD	51-152	203 +	6.6-20.3	0-80
KEF	Residuum	Hills	F	WD	102-152	203 +	9.9	15-90
PEF	Glacial	Drumlin & plains	A-C	VPD-WD	0-203+	31-203 +	7.1-29.2	0-80
SEF	Residuum	Hills	C-F	MWD-SWED	41-203+	46-203 +	6.1-7.4	15-75
VFSEF	Residuum	Hills	C-E	WD	251-102	203 +	8.6-10.6	0-80

* Slope classes 1=A class (0-1%), 2=B class (1-6%), C class (6-15%), D Class (15-25%), E Class (25-40%), F class (25-60%)
**VPD=very poorly drained, PD=poorly drained, MWD=moderately well drained, WD=well drained, SWED=somewhat excessively drained

Table 7. Mean plot-level species-related measures by USFS study site across all included treatment types.

Site	Sample Size (n=plots)	Hardwood Composition* (SE)		Species Richness (n)		Mean Shannon Diversity Index (se)	
		Min	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*
AEF	90	0.86 (0.04)	1.00 (0.00)	1	10	0.36 (0.10)	1.14 (0.12)
BLS	9	0.00 (0.00)	0.01 (0.01)	1	4	0.00 (0.00)	0.11 (0.02)
DEF	124	0.98 (0.01)	1.00 (0.00)	1	9	0.07 (0.00)**	0.74 (0.00)**
FEF	24	1.00 (0.00)	1.00 (0.00)	6	19	1.48 (0.00)**	2.08 (0.08)
KEF	15	0.86 (0.05)	0.95 (0.03)	2	7	1.03 (0.08)	1.19 (0.05)
PE	74	0.12 (0.02)	0.30 (0.08)	1	10	1.11 (0.08)	1.51 (0.08)
SEF	11	0.78 (0.07)	1.00 (0.00)	1	16	0.47 (0.24)	1.97 (0.13)
VFSEF	8	1.00 (0.00)**	1.00 (0.00)**	2	19	0.85 (0.46)	2.16 (0.00)**

*percentage of total standing basal area ($m^2 ha^{-1}$) by plot calculated from standardized truncated dataset
**no standard error of the mean due to some non-replicated plots

The KEF control area exhibits a peaking mean standing live mean BA in the late 1980s with a decreasing trend from 1989 to 2004. There is considerable plot variability regarding initial stand BA and temporal trends within the KEF control plots (Appendix A).

The PEF control areas were more variable than the two-stage shelterwood or ten-year selection treatments (Figure 7). The nine control plots included from the PEF had variable temporal and directional trends across plots (Appendix A). Some control plots increased in standing live BA from 1978 to 2010, while others generally decreased or plateaued. The two-stage shelterwood standing basal area was generally increasing through time at similar rates within and across treatment replicate's (Figure 7; Appendix A). The ten-year selection treatments have periods of increasing standing live BA followed by lower standing basal area as result of periodic harvesting.

Standing live BA at the SEF are similar across treatments (Figure 7). The SEF control plots show increasing standing live BA from 1978 to 1999 (Appendix A). Noted variability within control plots occur from a TSI thinning of noncommercial species in 1983. Site managers preformed this thinning due to concern of non-commercial species competition and study longevity. The removal primarily focused on *Cornus* spp. individuals in the mid- and over-story. All thinned plots, both the rule thinned and thinned from below, have low variability across iterations of treatments (Appendix A). All thinning experiment plots were thinned in the winter of 1983/84, and winter 2001.

The VFSEF control plots are the most frequently measured plots in the database (Figure 7). Overall, trends show increasing standing live BA until the mid-late 1990s with plateauing mean live BA from the late 1990s to 2010 (Figure 7). Some plots show faster accretion than others (Appendix A). Standard error of the mean decreased throughout the included study period

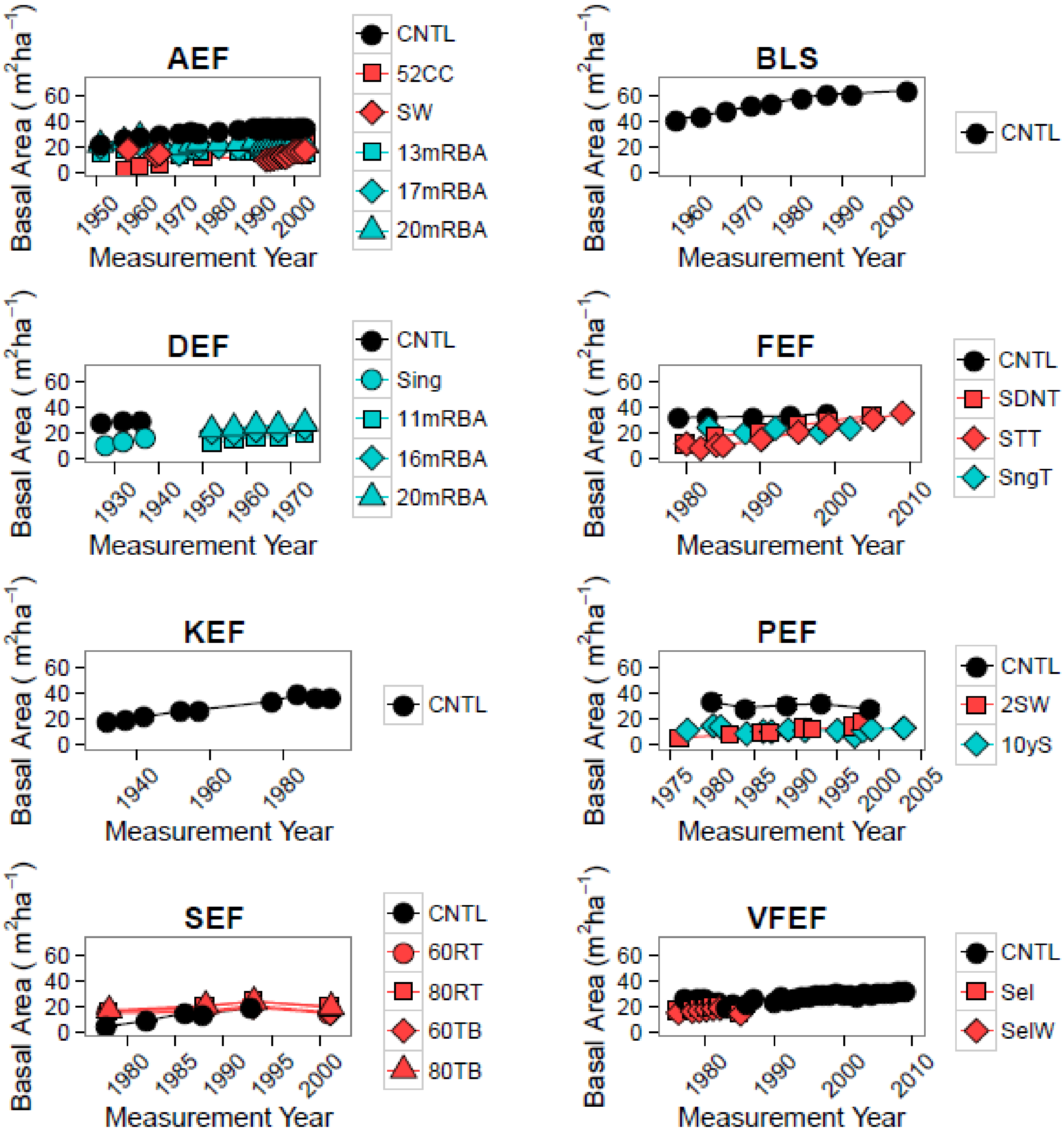

Figure 7. Mean standing live basal area (m^2 ha^{-1}) and standard errors by treatment types between USFS Study Sites.

at the controls from 2.97 m^2 ha^{-1} in 1977 to 0.44 m^2 ha^{-1} in 2010. Selection plots (with and without TSI show similarly increasing then sharply decreasing plot level standing live BA (Figure 7).

Across site comparisons of mean standing live BA show AEF, BLS, FEF, SEF and VFSEF control plots increasing in standing live BA through the included time periods (Figure 7). Control plots at AEF, BLS, and VFSEF may have reached plateau of live BA, but additional measurements are required to be certain. The control plots at DEF, KEF, and PEF have all had plateaued or exhibited mean decreasing BA in the last 15 years. DEF control plots have less standing live BA at the last measurement than the first included measurements.

EA treatments across plots are more variable, with directional trends similar to other site level treatments (Figure 7). UEA trends exhibit relatively stable standing BA (AEF, FEF and PEF), while others (DEF) increase in mean standing BA through study inclusion period (Table 5).

All density values were calculated from data that had been truncated to exclude all diameter measurements less than 11.68 cm (Table 3). Effect of truncation across sites varied based on initial stand conditions, study methodology, and changes in stand structure through silvicultural experiment at each EFR (Appendix B). Truncation affected standing basal area values to the greatest degree at the SEF, with a mean reduction of 4.71 ± 0.64 m^2 ha^{-1}. The FEF and KEF had a mean reduction in standing basal area of approximately 3 m^2 ha^{-1}; with all other sites experienced less than 1.0 m^2 ha^{-1} change. Reductions in calculated TPHa following truncation were most apparent at the FEF, KEF and SEF (Table 7).

Tree density across sites was quite variable, ranging from 0 to 590 TPHa when calculating across sites at the standardized minimum diameter (11.68 cm.). Tree density on control areas across sites was more stable through time than any silvicultural treatment across sites.

Composition

Composition trends through time were calculated as percentage of live basal area (m^2 ha^{-1}) across unique treatment types (Figure 8). All composition figures are derived from standardized truncated tree and plot values (Table 2). Hardwood composition is separated from softwood and non-commercial species composition. Dominant composition at the BLS and PEF are softwoods, with all other sites dominated by hardwoods (Figure 8). The SEF is the only site with noticeable components of non-commercial species within the overstory (Table 7).

Directional trends in compositional change are evident at some sites. The AEF became more hardwood dominated through time (Figure 8). The DEF silvicultural experiments were still very heavily dominated by hardwoods but between 1960 and 2000 showed increasing softwood components (Figure 8). The VFSEF and FEF never had any softwood BA during the available measurement period (Figure 8). The KEF controls decreased in hardwood components, though they were highly variable (Figure 8). The PEF silvicultural treatments had fluctuating compositional trends, while the control also had notable variability (Appendix C). The SEF became almost exclusively hardwood dominated by the last available measurement (Figure 8). Across sites, there were no clear geographic trends concerning changes relative composition.

Diversity measures

The most southern and eastern sites (VFSEF, FEF, and SEF) generally had higher overall measures of diversity related to species richness. Maximum plot-level species richness at

VFSEF, FEF, and SEF was 19, 19, and 16, respectively. The red pine plantations at BLS ranked lowest in overall species diversity through time with mostly a monoculture overstory (Figure 9).

Relative diversity between treatments became more similar through time at the DEF, FEF, PEF, SEF and VFSEF (Figure 9). There were no apparent geographic trends across site relating to changing diversity. Using included re-measurements, diversity values in general are more uniform across treatments within sites. Standard errors of mean diversity were highest at the VFSEF, but generally low across sites and at times unavailable due to lack of replication in some larger (1.0-2.0 ha) plots (Table 7).

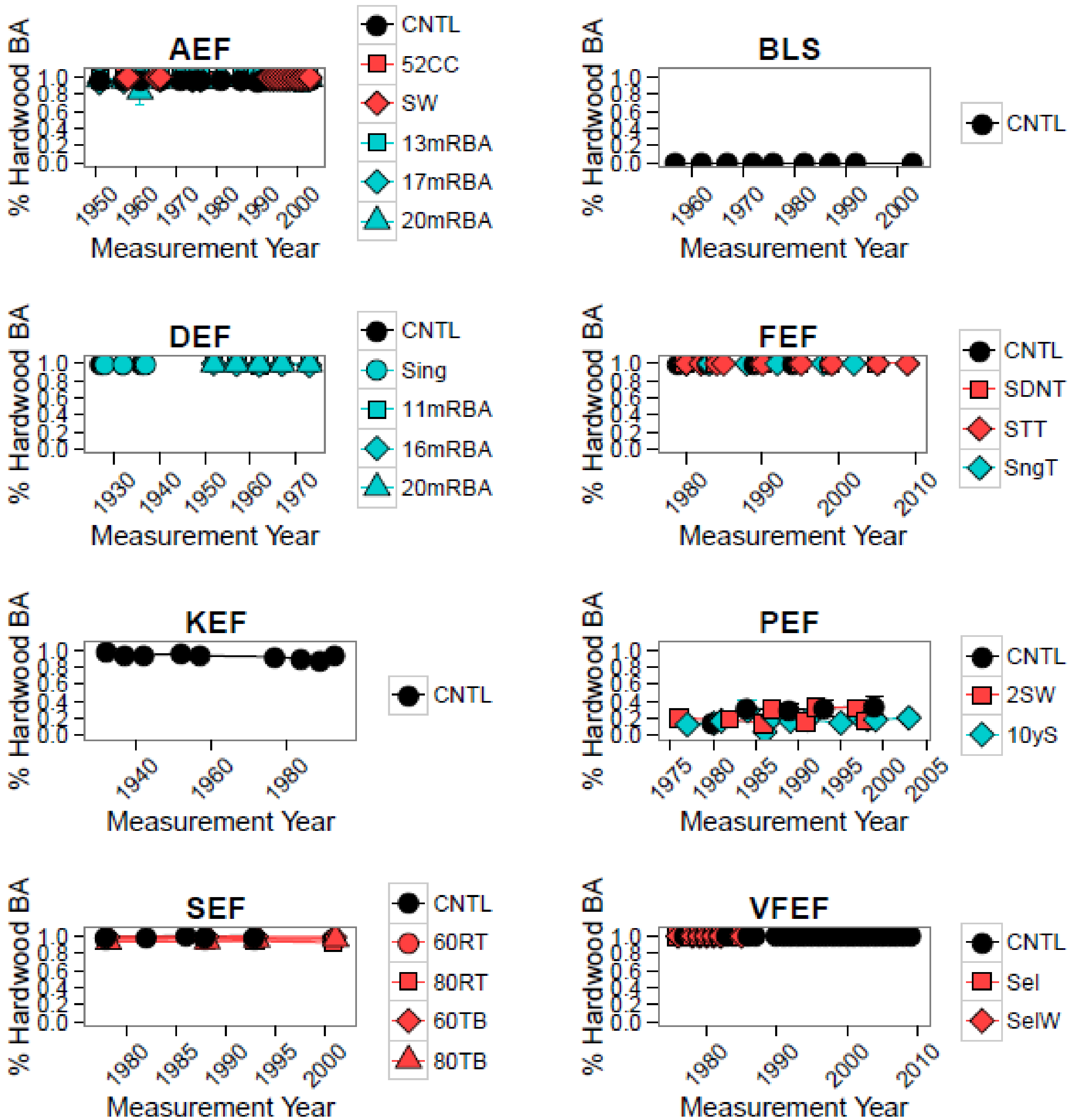

Figure 8. Relative mean composition (percentage of basal area) by treatment types between USFS Study Sites. Note BLS has nonstandard vertical axis range. BLS and PEF show percentage of softwood, while all other treatments are showing percentage of hardwood.

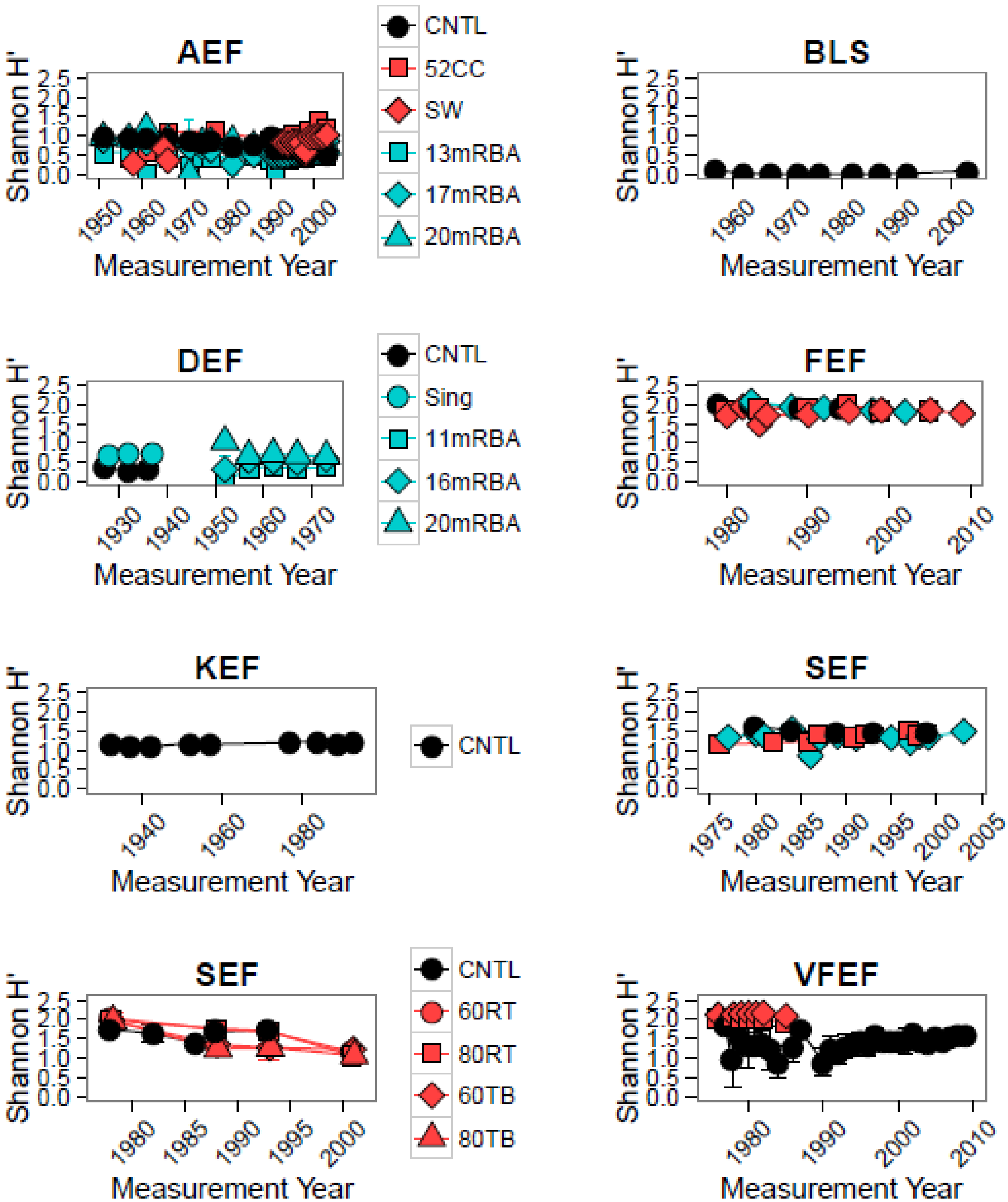

Figure 9. Mean Shannon Diversity Index and standard errors by treatment types between USFS Study Sites.

Discussion

Initially, this project was designed to increase collaboration among scientists and staff of the USFS NRS, but evolved into a preliminary effort to utilize historical silvicultural studies retrofitted together to provide future opportunities for large-scale comparisons of multiple long-term silvicultural studies. This work provides a simple approach to understanding and quantifying large-scale, long-term trends across a subset of historical silvicultural experiments on EFRs. This work attempts to provide a framework and rationale on how to utilize the extensive and fine-scale data previously collected in USFS silvicultural experiments to better understand historical and regional trends in forest growth.

Scientists are now interested in better understanding forest response and system variability across regional scales and new metrics (Stine 2012). Utilizing a standardization scheme, multiple forest attributes can be compared across silvicultural systems and forest types (e.g. Figures 6-8). While included examples of across site comparisons are simple, the opportunities for use of across-site comparisons are quite large. Once data are available, documented and standardized there relatively no limit to the comparisons possible using long-term silvicultural data in the EFR system.

Many of the long-term USFS silvicultural data are not readily accessible to scientists outside of the immediate study staff. While data sets may have been stored in association with silvicultural studies, these data may not be readily available to scientists interested in utilizing them. To facilitate collaboration and large scale synthesis using independent data common record formats are required. Standardized records formats are not required for metadata (Rugg 2004) but common formats could facilitate future silvicultural comparisons by reducing data preparation requirements. While this project did not create explicit and standardized metadata records for the silvicultural studies, increasing record robustness and data quality are supplementary activities to metadata creation, and could facilitate future metadata compilation. Efforts to increase data record quality and accessibility are currently being undertaken at some EFRs, but not all (Dave Rugg, pers. comm. 2011).

A link between historical, locally oriented studies and future large-scale comparisons needs to be made to better facilitate future large-scale synthesis projects. This linkage is made by standardization in how we collect, store, and archive long-term data records. This project focused on increasing data quality and record robustness as a way to standardize data formats, while increasing future potential synthesis across unique silvicultural studies.

Historical silvicultural studies, as found within the USFS EFR network, provide extremely rare and valuable data for a synthesis effort, but require substantial able management on previous records prior to any across-site synthesis. Increasing data quality and record robustness by compiling multiple long-term experiments into a standard format provide many opportunities to compare large-scale trends across multiple forest types and silvicultural systems. While standardization or metadata compilation may be tedious, any effort to better store and catalogue these historical and rare silvicultural studies, such as those found in EFRs and few other places, will be helpful to future scientists interested in utilizing these data (Curtis and Marshal 2005, Whitlock et al. 2010). In order to make this complex task less tedious, we provide some simple recommendations to increase current and future record quality:

1. Know what types of data are available at your site
    a. Take inventory of all current inventory files
    b. Note any missing or associated data located in other areas.

   c. Identify clarity or other known data weakness or study plans and try to mitigate weakness in future

2. Identify missing information or unclear records that can be immediately fixed
   a. Never leave species undefined in records if possible
   b. Append notes to the files as necessary
   c. Clearly denote changes in study methodology if they exist
3. Document all known changes to studies not shown in current documents.
   a. Document all codes and abbreviations and note the existence of these files
   b. Append notes to the files as necessary
4. Prepare bundle of documents that are associated with silvicultural experiment
   a. Prepare study information such as official plans, notes to the file, and study maps for future collaborative projects
   b. Provide these records and contact information in response to a data request
   c. Prepare list of available data at site for future collaboration
   d. Include documented QAQC procedures completed or required
5. Increase record robustness
   a. Include plot locations and sizes to raw data
   b. Document all codes and abbreviations and note the existence of these files in central location
   c. Utilize common species codes such as the FIA codes
   d. Condense and standardize record type within a site
   e. When in doubt, record everything you do to your data, or at your site

6. Increase the strength of data storage
    a. Store raw and study data in multiple formats and locations
    b. Store data in long format, with clear keys of site specific codes and only data type per column
    c. Do not store individual plots or years in separate files
    d. Treat these data as valuable and highly regarded documents
    e. Get them out of your file cabinet and in a backed-up secure location
7. Begin metadata compilation
    a. Designate a data manager for site
    b. Regularly assess and need of the data manager in relation to the storage of long-term data
    c. Investigate archiving data with USFS data archival representatives
    d. Initiate metadata on all future studies
    e. Draft metadata for existing studies
8. Design data use policies
    a. Draft data agreement policies if unavailable
    b. Encourage data users and requests to implement some sort of QAQC of data they are not familiar with
    c. Implement logs of which data is shared with and intended purpose
    d. Reward opportunities to collaborate with other EFRs and their silvicultural experiment data

Implementing some of these simple recommendations could better prepare any USFS site for the increasing use and need for metadata or increase the potential for future large scale collaborations while strengthening the archival quality of existing data (Kenefic et al. 2011).

Following a flexible and robust standardization of raw data, comparisons of variability within, between, and across silvicultural experiments could be possible. These multi-site and treatment comparisons can provide increased understanding of complex interactions between climate, silviculture, and ranges of variability seen in historical studies (D'Amato et al. 2011, Adams et al. 2010). Becoming aware and implementing record management recommendations (Kenefic and Palik 2011, Kenefic et al. 2011) may begin preparing managers for future collaboration or data sharing.

This database was designed to be flexible, and will allow additional studies and data formats to be added. Initial sites incorporated into this standardized database of raw tree records were variable in forest type, silviculture, and study methodology. Additional metadata of current and future data records could be incorporated, as well as historical study plans. These files are integral in properly documenting and storing raw data as collected from study sites and may be difficult to access by collaborating scientists not directly affiliated with a specific silvicultural study (Crawford 2006).

Future managers can better understand local and regional trends using historical forest data when data standardization or record augmentation has occurred. While the focus of data collection needs to be rather explicit in the future, how do we address current or historical data previously collected? How can we use these data to increase our understanding of forest growth and interactions of climate and silvicultural treatments moving forward? A focus on current as well as future uses of data needs to be documented and implemented. A standardized database of forest records provide additional opportunities to collaborate across sites with reduced data preparation following initial standardizing and inclusion of database. High quality data presented in a concise and standard format, such as in standardized repositories will allow future users, unfamiliar with initial stand conditions or regional variation of growth rate, to reduce error associated with lack of expectations of growth and variability. Most importantly, large-scale synthesis and collaboration projects require accessible data with scientists willing to participate (Curtis and Marshall 2005, Stine 2012, Bluhm et al. 2010, Crawford 2006, National Science and Technology Counsel 2009). Some scientists contacted as potential collaborators in this work declined to share data or participate. Data sharing may be a concern due to importance of publication rates of scientists (Witt 2009, NRS 2012). Data sharing policies are also a useful tool for defining expectations and protocols in future collaborative efforts (Palik and Kenefic 2012, Porter 2010, Kenefic et al. 2010, National Science Foundation 2002). Embargos on data following initial publications may mitigate concerns over publishable results (Whitlock et al. 2005, Witt 2005). Additional resources, requirements, or incentive programs (Scheik et al. 2005) may be necessary to facilitate data management and archival record and data sharing for collaborative uses (Scheik et al. 2005, National Science and Technology Council 2009).

Within this initial case study of NRS silvicultural studies, we utilize the finest scale data available. This type of data will be the most difficult and time consuming to standardize and will provide a template into which less complex or detailed data can be incorporated. Here raw data utilized were individually numbered trees, with different tree size thresholds for sampling at each site. Additional site data of any scale can be incorporated, although the most flexible data for future comparisons are individually tagged, tree-level records. Future additions to the database may necessitate different truncation or standardization, which can be achieved by utilizing the finest scale of data. By utilizing such fine scale data, the effect of diameter truncation across sites could be quantified. This work also does not recommend specific methodological changes within the collection of forest data, but reinforces the necessity of well documented, organized, and multiple forms of record care.

The incorporation of additional information about study designs and changes to methodology (i.e. metadata) into this relational database will strengthen and increase opportunities for synthesis. Standardizing and using raw data, as opposed to stand summaries, increases transparency of summarizations. Standardizing data hierarchically allows future users to quickly understand a study's characteristics without paging through historical study plans only available from one person's file cabinet, and reduces errors associated with unclear study methodology communicated through unofficial documents such as phone calls and emails.

In any project for which substantial data management or standardization of data is required, improved data quality and completeness are major concerns (Curtis and Marshall 2005). Those concerns for data quality and record retention are compounded when using rare and potentially valuable data such as collected throughout the USFS EFR network. QAQC concerns were mitigated with multiple procedures within this project. In any standardized database construction effort, multifaceted QAQC mechanisms should be in place. Any additional data incorporated into a standardized database not provided by in-house data managers should also be checked for QAQC if possible (Palik and Kenefic 2012).

Utilizing historical data has equal parts opportunities and challenges (Lugo et al. 2006, Adams et al. 2010, Stine 2012). Most of the challenges remain constant regardless of dataset size, while opportunities for future analysis increase as more data are available. This initial effort to retrofit silvicultural studies to draw new conclusion provided identification of possible future improvements. The standardizations were relatively simple, but adequate to compare sites at a larger scale than previously utilized within the USFS. While across site comparisons using this data standardization procedure are possible, this methodology does not address all aspects of silvicultural data collected at sites. Standardizations did not allow for regeneration comparison across sites. Tree height information for some studies was not available or did not meet data inclusion criterion for this project, therefore was not included in this initial effort. Consequently, it is important to recognize that only a subset of available measurements were included in the current database; if utilizing these data in future large-scale comparison efforts, a longer record period may be available given a different criteria for site selection or inclusion.

This database was designed to be flexible, and will allow additional studies and data formats such as metadata and historical study plans to be added. These files are integral in properly documenting and storing raw data as collected from study sites and may be difficult to access by collaborating scientists not directly affiliated with a specific silvicultural study. Efforts to include all raw and supplementary data of silvicultural studies at the PEF are in testing phases with the USFS Research & Development Archive (Laura Kenefic, pers. comm. 2012). Current focus on storing, tending, and caring for these historical records could also increase the completeness and quality of long-tem, archival data these experiments produce (Kenefic et al. 2011).

Summary

Long-term forestry experiments are rare and illustrative datasets that have provided empirically driven management decisions at local and national levels for the past 100 years. The USFS EFR network maintains many unique long-term silvicultural studies through the U.S. and affiliated territories with a large variety of forest types and silvicultural experiments. These long-term studies have provided many of the forest-type specific conclusions that form the scientific basis of forest management to meet specific stand objectives.

While long-term silvicultural experiments have had an illustrative past, they also have a bright future. While long-term silvicultural studies are rare and illustrative in their individuality and specificity, they present unique challenges for retrofitting, or reutilizing, long-term data across multiple gradients to draw large or multi-scale conclusions. Initial efforts to access the feasibility of utilizing raw records from historical silvicultural experiments are implemented here. This work attempted to provide initial rational and discussion of how data standardization at long-term silvicultural trails will allow for larger scale comparisons of data, while increasing data quality and robustness. A case study of eight long-term silvicultural sites provides a rationale and methodology for data standardization necessary prior to a synthesis across sites. A flexible standardized database was a simple, but appropriate method for data preparation. Data standardization and additional spatial data were required at all sites. Data truncation and standardization allowed for a multi-site synthesis utilizing previously recorded tree-level data.

Small steps, as recommended within this work, could be taken to incrementally increase long-record quality prior to implantation of metadata. Metadata is the standard of data archiving to uphold, but additional resources are required at many sites prior to synthesis of metadata. Future work is necessary at EFR sites to increase the archival quality of long-term silvicultural experimental data. Producing metadata for all long-term silvicultural experiments records and supplementary information is the best way to increase the data quality, record robustness, and study methodology transparency for sustained accessibility to historical tree growth records. Future efforts to increase data quality, and robustness of included records could reduce future initial efforts necessary for multi-site syntheses from non-congruent data structures. Incorporating additional site characteristics to long-term forest growth records can allow for better understanding silvicultural outcome variability across large-scales. Additional efforts are planned to prepare metadata and provide access to the standardized database designed in this work pending additional resources.

From this initial effort at synthesizing EFR forest growth data; it is clear that any effort to increase data quality, record robustness, or compile metadata will increase future opportunities and relative ease of collaboration across sites. Based on the methodology utilized, additional large-scale synthesis could be implemented using data that has been previously collected for up to 80 years. This type of opportunity to understand the variability of large-scale and long-term trends of forest dynamics would not be possible without the continued maintenance and measurement of the USFS studies. This synthesis effort was the first systematic study to evaluate EFR silvicultural data by building a standardized data repository of tree records for multiple future analysis across a subset of NRS long-term silvicultural experiments.

CHAPTER 2

VARIABILITY ACROSS MANAGED NORTHERN FORESTS: QUANTIFYING EFFECTS OF REGIONAL AND LOCAL FACTORS ON LONG-TERM STAND-LEVEL GROWTH

Introduction

Growth rates of individual trees and forest stands are influenced by a variety of factors at multiple spatial and temporal scales. The effect of various influential factors on forest growth and yield is highly interactive and dynamic, especially in complex forests. While growth and yield research is a foundation of forest science, the differences in influential factors and their relative importance on forest growth are not well defined in the literature. The relative importance and influence of multi-scale factors and their interactions on growth response across forest types can be difficult to discern due to confounding effect of site, climatic and past management differences (Orwig 1997, Park 2010, Savva 2008, Legendre 1993, Powers et al. 2010, Bradford et al. 2011).

Due to competition and other microsite features, the influential factors affecting tree-level growth may be different than the influential factors of growth at a stand or landscape scale (Pinno 2011, Lõhmus 2011). Regional factors that influence forest growth and regeneration include climatic and geologic factors such as growing season (Heineman et al. 2010), precipitation or drought (Wilmking & Juday 2005, Wishnie et al. 2007), climatic variability (Mäkinen et al. 2002, Savva et al. 2008), and species composition (Valencia 2004). Understanding the influential factors at multiple scales could allow prediction and quantification of complex forest growth dynamics in a comprehensive approach. One way to address complex interactions within influential factors of growth is to fit multiple preliminary models (Yue et al.

2012, Powers et al. 2010) using integrated response functions (Burkhart and Tomé 2012), which are also called “systems formulation” (Weiskittel et al. 2011).

Complex interactions between anthropogenic and inherent site characteristics have been studied to some degree in provenance and restoration trials, where survival depends on an array of local and regional factors (Park 2010, Savva 2008). However, in managed forests, the effect of silvicultural treatment is usually constrained to one forest type (Peracca & O’Hara 2008). The relative influence of different factors may also vary within or between stand types, i.e. even age, uneven age, mono- or mixed species stands. For example, previous research has suggested that relative importance of influential factors varies across different silvicultural treatments (Lõhmus 2011, Pineaar 1995) and forest types (Larocque et al. 2011). In addition to varying silvicultural systems, the relative influence of climatic factors on forest growth is currently of great interest to forest managers (Latta et al. 2009, LeBlanc et al. 2009, Miyamoto et al. 2010, Yang and Huang 2011, Bradford 2011). Climatic influences on forest may have increasing importance due to the opportunity to utilize forest management within local or sub-regional areas as a mitigation aide in the face of recent changing climatic trends (Weng et al.2007, Lapointe-Garant et al. 2010, D’Amato et. al 2011).

While the study of northern forests span more than 100 years (Cary 1896, Westveld 1931, Whitney 1987) current intensive research efforts continue to provide novel conclusions across this diverse landscape. Current research focuses on effect and mitigation of changing climates (Zhu et al. 2012, Iverson et al. 2010 , Hanson et al. 2012), forest ecological attributes (Kenefic and Nyland 2000, Batzer et al. 2005, Scheller and Mladenoff 2008) and long-term results of silvicultural experiments (Leak and Yamasaki 2012, Larouche et al. 2010, Buckman 2006).

The northern forest; an area bounded by Maine, Minnesota, Missouri and Maryland, is the most forested area of any US region (Shifley et al. 2012). Not only is it a large part of the landscape, but it is also a complex mosaic of varied cover types, structural diversity, and ecological characteristics (Shifley et al. 2012). Forest cover type across the region is variable, with 10 cover type groups and 17 forest type mapping zones (Ruefenacht et al. 2008). Complexity of managed stands in NE range from simple, even-age monocultures (Bradford and Kastendick 2010, Buckman 2006) to complex uneven-aged mixed stands (Erye and Zillgitt 1953, Leak 1987, Seymour and Kenefic 2002) with a continuum of conditions between on the landscape. Forest complexity, within and between northern stands, is due in part to the wide range of site conditions and anthropogenic influences. A longitudinal climatic gradient spans from oceanic to continental. Growing season length and seasonal fluctuation follow a latitudinal gradient

Forest complexity and the rich tradition of long-term studies in the northeastern US provide future opportunities to compare long-term results across gradients of site and stand characteristics. Differences in stand and site conditions undoubtedly influence forest growth, but it is not well understood the relative influence, or importance, of multiple factors and their interactions on growth response within the northern forests. Studies evaluating differences across multiple gradients present in the northern forest are rare (D'Amato et al. 2011). Multiple gradient comparisons have unique challenges based on data availability, similarity of manipulative experiment, and variability of climatic and site characteristics that are difficult to comprehensively address.

The evaluations of influential factors on forest growth rates across a multiple gradients are complex and require comprehensive datasets and additional study (Rehfeldt et al. 2006, McLane et al. 2010, Melles et al. 2011). A unique analytical approach to assess the relative influence of various factors is required due to the array of complex interactions and confounding features. Long-term trends and implications based on interactions of local, regional, and anthropogenic factors influencing forest growth require data collected repeatedly and at a high frequency with extensively documented records collected at multiple scales. Quantifying the interactions of key forest growth drivers in natural and artificially regenerated, managed stands across a large-scale would require a comprehensive dataset of many factors not usually collected in unison to be compiled.

Within this work, the identification of several key influential factors across multiple forest types spanning wide spatial and temporal measurement periods was attempted. This was done by combining various influential forest growth factors at multiple scales including site characteristics, silvicultural history, and climatic variation. In short, this work attempts to identify whether the influence of local and regional factors vary across forest type, silvicultural system, or climatic gradients for long-term silvicultural experiments across the Northeastern US. Specific objectives were to 1) identify general trends and variability of stand-level basal area periodic annual increment across multiple forest types, 2) identify the relative ranking of factors influencing growth across a subset of Northern forest study sites, and 3) explore the influence of specific factors on stand growth response.

Methods

All forest growth data utilized in this project were previously collected by the United States Forest Service (USFS). Nine silvicultural experiments from eight long-term experimental areas, a subset of twenty-two active sites within the Northern Research Stations' (NRS) Experimental Forest and Range (EFRs) Network, were utilized within this synthesis (Figure 1). Seven of the eight study areas are part of the NRS EFR Network, with one experimental area located on the Superior National Forest. All experimental areas were included in this study based on wiliness to participate, and contributed raw forest growth data to this effort from stands meeting general study inclusion criteria (Ch. 1).

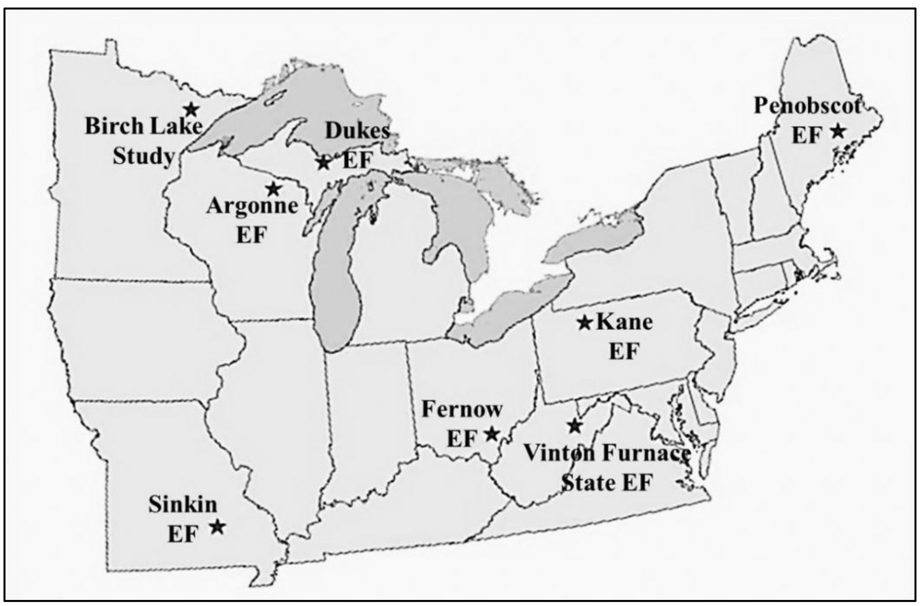

Figure 1. Included USFS silvicultural trial locations, denoted by stars.

These experimental locations were identified to have a variety of similar independent study designs that were located on a variety of forest types with multiple silvicultural systems in place (Table 1). Included in this synthesis are NRS long-term silvicultural trial locations with a range of stand types from monoculture even-age to uneven age mixed stands (Table 2). Ranges of plot-level diversity, composition, and structural attributes are summarized in Ch. 1 Appendices A-C. Included studies were initiated in the early to mid-twentieth century across a gradient of forest types (Table 1) to study effect of silvicultural treatments or cutting methods within a specific forest type.

Table 1. USFS silvicultural experiment locations and descriptions of summarized data used in this analysis.

USFS Site	**Location**		**Forest Type**	**Record Length**		**Sample Sizes**		**PAI** (m^2 ha^{-1} yr^{-1})	
	Lat.	*Long.*				*Records*	*Trees*	*Mean*	*SD*
Argonne EF, WI	45.750	-89.000	Northern Hardwoods	1951-2006	55	30054	4335	0.51	0.25
Birch Lake Study, MN	47.716	-91.933	Red Pine	1957-2009	52	7769	898	0.56	0.22
Dukes EF, MI	46.350	-87.166	Northern Hardwoods	1927-2007	80	18442	5669	0.39	0.18
Fernow EF, WV	39.054	-79.680	Appalachian Hardwoods	1979-2009	30	12800	5918	0.53	0.27
Kane EF, PA	41.597	-78.766	Allegheny Hardwoods	1932-2004	72	3202	2720	0.41	0.19
Penobscot EF, ME	44.866	-68.633	Mixed N. Conifer	1954-2009	55	19368	4725	0.43	0.26
Sinkin EF, MO	37.500	-91.250	Central Hardwoods	1978-2003	25	40410	2207	0.74	0.23
Vinton-Furnace State EF, OH	39.183	-82.366	Central Hardwoods	1977-2010	33	23944	2433	0.5	0.26
Total						**184144**	**30905**	**0.48**	**0.25**

Table 2. Description of included silvicultural trials used in this analysis. Plot measurements denote the maximum sample (n) of plot-level measurement intervals within a treatment included in this analysis. Additional measurement periods may be available at study site but were excluded from this analysis based on study inclusion criteria. Thinning regime (TR) denotes the presence of intermediate thinning in some studies where 0= un-even age stands, 1= even-age stands, and 2= stands with intermediate treatments previously applied.

USFS Site	**Study Name**	**Included Treatments**	**TR**	**Plots**	**Size (ha^{-1})**		**Plot Measurement Periods**			
				(n)	*Min.*	*Max*	*Mean*	*SD*	*Min.*	*Max.*
AEF	Cutting Methods	Control	0	15	0.04	-	22.7	0.5	22	23
AEF	Cutting Methods	1952 Clearcut	1	15	0.04	-	14.3	4.9	5	18
AEF	Cutting Methods	Shelterwood (1958/1975)	1	15	0.04	-	14.3	1.0	13	15
AEF	Cutting Methods	Selection (13.7 RBA)	0	15	0.04	-	23	-	-	-
AEF	Cutting Methods	Selection (17.2 RBA)	0	15	0.04	-	23	-	-	-
AEF	Cutting Methods	Selection (20.7 RBA)	0	15	0.04	-	23	-	-	-
BLS	Growing Stock	Control	0	9	0.08	-	9	-	-	-
DEF	Cutting Methods	Control	0	1	0.80	-	4	-	-	-
DEF	Cutting Methods	Single Tree Selection	0	1	0.80	-	4	-	-	-
DEF	Stocking & Cutting Cycle	Selection (11.5 RBA)	0	39	0.08	-	4	-	-	-
DEF	Stocking & Cutting Cycle	Selection (16.0 RBA)	0	42	0.08	-	3.9	0.2	3	4
DEF	Stocking & Cutting Cycle	Selection (20.7 RBA)	0	40	0.08	-	3.9	0.2	3	4
FEF	Large Area Comparisons	Control	0	13	0.2	-	5	-	-	-
FEF	Large Area Comparisons	Seed Tree	1	2	0.02	0.10	7	-	-	-
FEF	Large Area Comparisons	Seed Tree (thinned)	1 / 2	4	0.05	0.2	4	-	-	-
FEF	Large Area Comparisons	Single Tree Selection	0	5	0.20	-	7	-	-	-
KEF	R-Series Yeild Overstory	Control	0	15	0.04	-	7.9	1.2	5	9
PEF	Compartment Study	Control	0	9	0.08	-	4.5	0.7	3	5
PEF	Compartment Study	Shelterwood (1957/1968)	1	30	0.08	-	4.9	0.2	4	5
PEF	Compartment Study	Selection (10 yr.)	0	35	0.08	-	6.9	1.1	3	8
SEF	Spatial Distribution	Control	1 / 2	3	0.25	-	6	-	-	-
SEF	Spatial Distribution	Rule Thin (60%)	1 / 2	2	0.25	-	8	-	-	-
SEF	Spatial Distribution	Rule Thin (80%)	1 / 2	2	0.25	-	8	-	-	-

SEF	Spatial Distribution	Thin From Below (60%)	1 / 2	2	0.25	-	7	1.4	6	8
SEF	Spatial Distribution	Thin From Below (80%)	1 / 2	2	0.25	-	8	-	-	-
VFSEF	Cutting Practices	Control	0	6	0.04	0.40	26	1.3	25	28
VFSEF	Cutting Practices	Selection	0	1	2.02	-	8	-	-	-
VFSEF	Cutting Practices	Selection w/TSI	0 / 2	1	2.02	-	8	-	-	-
Total				**354**	**0.04**	**2.02**	**9.3**	**7.3**	**3**	**5**

Study Areas

The Argonne Experimental Forest (AEF) is dominated by northern hardwoods including by sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula Alleghaniensis* Britton), American basswood (*Tilia americana* L.), and eastern hemlock (*Tsuga canadensis* (L.) Carr.) with minor components of black cherry (*Prunus serotina* Ehrh.), quaking aspen (*Populus tremuloides* Michx.), northern red oak (*Quercus rubra* L.), and American hornbeam (*Carpinus caroliniana* Walt.). Treatments included from the AEF include even- and uneven-age silvicultural experiments. Even-age treatments include a shelterwood initiated in 1958 with an overstory removal in different replicates in 1966 and 1975, and clearcuts initiated in 1952. Included uneven-age treatments are from a selection study: with variable (13.7-20.7 m^2 ha^{-1}) residual basal area (RBA) criteria at a 10 year selection interval. Included and additional silvicultural experiments on the AEF are summarized in Erdmann and Oberg (1973), Tubbs (1977), Niese and Strong (1992) , Kern et al. (2006), and Adams et al. (2008).

The Birch Lake Plantation/Thinning Methods Study (BLS) is a long-term thinning trial located on the Superior National Forest in northern Minnesota. The BLS is not an NRS EFR site. The BLS plantation was planted in 1915 and 1917 with red pine (*Pinus resinosa* Ait.) growing stock originating from a 1912/1913 local seed source. Ingrowth on the BLS include aspen spp. (*Populus spp.*), balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), eastern white pine (*Pinus strobus* L.), white spruce (*Picea glauca* (Moench) Voss), burr oak (*Quercus macrocarpa* Michx.), alder (*Alnus spp*.), red maple (*Acer rubrum* L.), and paper birch (*Betula papyrifera* Marsh.). Multiple types of thinning regimes are studied with the BLS, but only control plots were used in this analysis. Additional descriptions of the BLS cutting methods are detailed in Buckman et al. (2006) and Powers et al. (2010).

The Dukes Experimental Forest (DEF) is dominated by northern hardwood components including sugar maple, yellow birch, red maple, and eastern hemlock with minor components of American basswood, American elm (*Ulmus americana* L.), northern red oak (*Quercus rubra* L.), and ironwood (*Ostrya virginiana* (Mill.) K. Koch). Old growth and second growth northern hardwoods stands have allowed unique comparisons of long-term effect of silvicultural treatments in these stand structures. Included in this analysis are single tree selection (org. termed "Over Mature and Defective" by Eyre & Zillgitt) and variable RBA ("improvement") selection plots. Descriptions of study areas on the DEF and a subset of results drawn from DEF studies include Eyre & Zillgitt (1953), Arbogast (1957), Tubbs (1977), Crow et al. (1981), and Gronewold et al. (2012).

The Fernow Experimental Forest (FEF) is located in the Appalachian hardwood region and has twenty documented commercial species with main components of northern red oak, sugar maple, yellow poplar (*Liriodendron tulipifera* L.), and red maple. Both even- and uneven-age management studies were established on the FEF. Included even-age plots were from a seed tree experiment initiated in 1960 with overstory removal in 1963. One third (n=2) plots received a commercial thinning in 1980 which removed 38% of standing basal area. Uneven age plots included in this analysis were from a single-tree selection with removals of 14-21 % basal area at ~ 10 year intervals between 1958 and 2007. Additional FEF silvicultural trials descriptions can be found in Trimbel (1977), Perkey et al. (1999), Wiemann et al. (2004), Schuler (2004), and Schuler et al. (2006).

The Kane Experimental Forest (KEF) is located on the un-glaciated portion of the Alleghany plateau with overstory composition including black cherry (*Prunus serotina* Ehrh.), sugar maple, red maple, American beech (*Fagus grandifolia* Ehrh.), eastern hemlock, sweet birch (*Betula lenta* L.), yellow birch, and white ash (*Fraxinus americana* L.). Only control plots were included in this analysis, but other treatments on the KEF include both even- and un-even-age experiments. Publications detailing results and silvicultural studies on the KEF include USDA NRS (1999), and Stout & Ristau (2005).

The Penobscot Experimental Forest (PEF) is located within the Acadian forest, a mixed northern forest type where red spruce (*Picea rubens* Sarg.) and balsam fir are the signature species with components of eastern hemlock, eastern white pine, red maple, paper birch, American beech, and aspen spp. present. Treatments in used in this analysis include even- and uneven- age silvicultural experiments. The even-age treatment is a two-stage shelterwood with implementation in 1957 and a final overstory removal in 1968. The uneven-age treatment included ten year selection plots with a RBA and BDq structural goal. Descriptions of included and additional PEF study designs and highlighted results can be found within Sendak et al. (2003), Sendak et al. (2004), and Kenefic et al. (2006).

The Sinkin Experimental Forest (SEF) is located in the oak-dominated central hardwood forest type. Species composition on the SEF include white oak (*Quercus alba* L.), post oak (*Quercus stella*), black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), northern red oak, hickory (*Carya spp*.), black tupelo (*Nyssa sylvatica* Marsh.), sassafras (*Sassafras albidum* (Nutt.) Nees), shortleaf pine (*Pinus echinata* Mill.), black cherry, maple (*Acer spp*.), dogwood (*Cornus* spp.), and black walnut (*Juglans nigra* L.). All data from SEF included in this study are from even-age stands established following a 1963 clearcut. Even-age stands with some intermediate treatments were included in this analysis. Additional descriptions of included silvicultural trials include Rogers (1978) and Rogers (1983), with general results from the SEF in Shifley et al. (2000).

The Vinton-Furnace State Experimental Forest (VFSEF) is dominated by central hardwoods. Species are stratified by slope position (Adams 2008) and include chestnut oak (*Quercus prinus* L.), scarlet oak, black oak, white oak, red maple, hickory spp. (*Carya spp*.), Ohio buckeye (*Aesculus glabra* Willd.) and yellow poplar. Both even- and uneven-age treatments are studied at the VFSEF. Only uneven-age treatments were included from the VFSEF. Two large (2.02 ha) selection plots were used in this analysis, selection treatments both initiated in 1952. Selections were focused on mature and damaged trees with a minimum RBA of 11.5 m^2 ha^{-1} with a target harvest interval of ten years. One plot also received intermediate timber stand improvements in 1955 and 1984 with a commercial thinning occurring 1955. Highlighted results include Brown et al. (2004) and Yaussy et al. (2003).

Data Collection

Data were collected by multiple organizations in a variety of formats, with detailed descriptions in Chapter 1. Data utilized fall into three categories; forest growth, soil, and climatic data. These data were each summarized separately at different scales and then merged together prior to comprehensive statistical analysis.

Raw forest data needed to be significantly altered to provide consistent record types across study areas (Chapter 1). All tree diameter at breast height (DBH) measurements were truncated to 11.68 cm within this analysis prior to stand summarizations due to differences in the minimum DBH measured. Quality control (QAQC) of standardization and database construction occurred at a site-specific level. Additional USFS data collected and incorporated included study descriptions, drawn and digitized maps, pertinent file memorandums, and other miscellaneous qualitative data. Original study descriptions are available through individual USFS NRS study sites.

Soil data were extracted from the USDA Natural Resources Conservation Service (NRCS) web soil survey (http://websoilsurvey.nrcs.usda.gov) at the replicate (block) level. The most prevalent soil type within replicate area was extracted from soil survey reports and the official soil descriptions. If soil data were not available for area online, regional soil scientists were contacted, and equivalent data were obtained.

Site-level climatic data, precipitation and temperature measures, were extracted from the PRISM Climate Group Data Explorer (http://www.prism.oregonstate.edu/ , PRISM Climate Group, Oregon State University). Climatic variables were summarized at the plot-level for each unique plot-level re-measurement period (Table 3).

Statistical Methods

The independent variables used for evaluating growth across sites were compiled from multiple sources and were depicted in nominal, ordinal, and interval data formats (Table 3). Tree-level diameter measurements were collected from the eight sites and summarized at the plot-level using SAS 9.2 (SAS Institute Inc. 2010) and R (R Development Core Team 2012). Specific standardization methodology varied within sites based on initial data structure and content (Ch. 1). Stand attributes were summarized and plot-level net periodic annual increment of basal area (PAI) were calculated across all plot measurement periods (n=3225 plot re-measures). Plots with intermediate harvest and disturbances with significant mortality, i.e. plots with negative PAIs, were excluded from further analysis (n=2613 periodic plot observations) to reduce the influence of intermediate treatments on overall stand results (Figure 2).

Attempts to increase descriptive data of stand and site characteristics were fulfilled with additional plot-level variables (Table 3). Classification of even and un-even age silvicultural treatment factor (*Treatment*) was documented based on study descriptions, with additional descriptive factors for stands with intermediate treatments (*TR*). Control plots were included in even age (*Treatment*) classifications regardless of structure as an effort to mitigate residual structures present prior to study initiations. Time since study initiation (*TSSI*) was calculated using the year of re-measure and the documented time of study initiation. Time since treatment (*TST*) was calculated at a plot-level using documented tree removal as found in raw–tree list status codes. Tree removals documented in control plots were cross referenced with sites, and following QAQC were excluded. If no data were available documenting last known treatment (prevalent in most controls), the study initiation date was used for calculations of TST to account for unknown prior harvesting. Stand density indices were summarized at the plot-level using additive (*SDIadd*) and estimated maximum stand density (*SDI_99*) calculated to determine a mixed- species estimation of relative density (*WD05_RD*) (Woodall et al. 2005, Miles and Smith 2009). Plot-level diversity was calculated using the Shannon's diversity index H′ (*sdi_H*) (Hill 1973). Soil data were standardized and categorized into classes (Table 3). Climatic summarizations were calculated within a measurement interval at the plot-level from extracted site-level locations (Table 3). Influential factors were grouped into seven broad attribute classifications; density, diameter, diversity, climate, composition, silviculture, and soil.

Boosted regression trees (BRTs), a non-parametric approach which incorporates two machine learning techniques, classification/regression trees and boosting (Elith et al. 2008), were used to identify relative ranking and interactions of model covariates. BRTs are a flexible, adaptive machine learning technique which can simply present complex relationships found in non-congruent ecological data structures (De'ath & Fabricius 2000, Elith et al. 2008, Buston & Elith 2011, Aertsen et al. 2012).

Table 3. Independent variables as used in fitting boosted regression trees within this analysis.

Class	Name	Sample Attributes *Mean*	*(SD)*	*Min.*	*Max.*	Variable Description
Silviculture*	Treatment	0.53	(0.5)	0	1	Treatment factor, 0=EA/CNTL, 1=UEA
	TR	0.3	0.5	0	2	Thinning regime, 0=UEA (none), 1=EA (none), 2=structure following any intermediate treatment
	TsinTrt	18.4	(18.7)	0	65	Years since treatment occurred
	TsinSdyIn	36.5	(16.5)	0	71	Years since study initiation
Density*	allba1	21.8	(10.6)	0.27	69.6	Standing live basal area (m^2 ha^{-1}, Interval)
	WD05_RD+	0.2	(0.1)	0.0	0.5	Mixed uneven age species relative density
	SDIadd+	161.4	(77.0)	2.9	507.1	Additive stand density index (SDI)
	SDI_99+	877.4	(167.9)	630.3	1396.4	Estimated maximum SDI for mixed stands
	alltpha1	406.2	(242.7)	24.7	1457.9	Live trees hectare^{-1} of all trees (Interval)
Diameter*	allqmd1	27.7	(7.9)	11.8	49.3	Quadratic mean diameter of stand (cm, Interval)
	m_d	26.1	(6.9)	11.8	58.2	Mean diameter at plot (cm)
	sd_d	37.3	(13.0)	1.5	87.2	Standard deviation of mean diameter (cm) at plot
	cv_d	36.6	(13.1)	1.52	72.0	Diameter coefficient of variation
	kurt_d	0.36	(2.1)	-5.2	18.1	Diameter kurtosis
	skew_d	0.6	(0.8)	-1.8	3.8	Diameter skewedness
Diversity*	sdiH	2.44	(1.63)	0	6.78	Shannon Diversity Index H value (ha^{-1})
	plotSG	0.22	(0.2)	0.03	0.63	Plot specific gravity
	SEsg	0.09	(0.1)	0.00	0.33	Standard error of mean specific gravity at plot
	SDsg	0.17	(0.1)	0.01	0.47	Standard deviation of specific gravity at plot
Composition*	HWBAc	0.8	(0.3)	0	1	Percentage of hardwood by basal area
	HWTPHAc	0.9	(0.3)	0	1	Percentage of hardwood by trees per hectare
Climate**	mat[a]	5.5	(2.2)	2.7	13.5	Mean annual temperature
	map[a]	89.6	(17.8)	63.0	153.0	Mean annual precipitation
	gsp[a]	55.6	(9.3)	36.2	89.4	Growing season precipitation, May-September
	mtcm[a]	-10.3	(3.8)	-17.7	3.3	Mean temperature in the coldest month
	mmin[a]	-16.3	(4.1)	-23.6	-2.6	Minimum temperature in the coldest month
	mtwm[a]	19.3	(1.7)	15.1	25.8	Mean temperature in the warmest month
	mmax[a]	26.1	(1.6)	22.3	32.6	Maximum temperature in the warmest month
	sday[a]	132.7	(12.4)	87.0	161.0	Julian day of the last freezing date of spring
	fday[a]	272.3	(9.4)	252.0	308.0	Julian day of the first freezing date of autumn
	ffp[a]	139.7	(18.7)	107.0	217.0	Length of frost free period
	dd5[a]	1863.3	(375.8)	1433.0	3454.5	Degree days $>5^{\circ C}$
	dd0[a]	1023.1	(355.4)	58.3	1652.2	Degree days $<0^{\circ C}$
	gsdd5[a]	1568.6	(351.2)	1125.0	3065.0	Degree days $>5^{\circ C}$ within the frost free period
	mmindd0[a]	1917.7	(504.8)	477.2	2749.9	Minimum degree days $<0^{\circ C}$
	d100[a]	124.3	(12.9)	69.1	143.4	Julian date of the sum of degree-days $>5^{\circ C}$=100
Soil***	WHC	2.18	(0.97)	1	5	Water holding capacity class
	DTWT_CL	2.76	(1.8)	1	5	Depth to water table class
	DTRL_CL	4.5	(1.24)	1	5	Depth to restrictive layer class
	DRN_CLS_n	4.3	(0.8)	1	6	Drainage class
	SLP_CL[b]	2.72	(1.14)	1	6	Slope classes
	CRSFRGmid	20.8	(14.4)	0	57.5	Midpoint of coarse fragments in soil by volume
	CRSFRGmin	3.43	(8.8)	0	35	Minimum coarse fragments in soil by volume
	CRSFRGmax	38.1	(22.4)	0	90	Maximum coarse fragments in soil by volume
	PM_Type	0.83	(0.37	0	1	Parent material type, glacial (1) or non (0)
	PL_CL	-	-	-	-	Sub-glacial parent material class
	PM	-	-	-	-	Parent material name
	LF_CL	-	-	-	-	Landform class
	LNDFM	-	-	-	-	Landform name

*Summarized at the plot level from raw tree records **Collected as site level single grid point, summarized at a plot measurement interval ***Summarized by dominant area within replicate (block)

+ Calculated using the estimated maximum SD, specific gravity at 12% MC, and calculated additive SDI for plots, see Woodall et al. 2005 and Miles & Smith 2009 for detail

[a] Includes calculated mean (2), minimum (3), maximum (4), standard error of mean (5), and standard deviation (6) of covariate within a plot-level measurement interval, attributes shown for mean value

[b] Slope classes 1= A class (0-1%), 2= B class (1-6%), C class (6-15%), D Class (15-25%), E Class (25-40%), F class (25-60%)

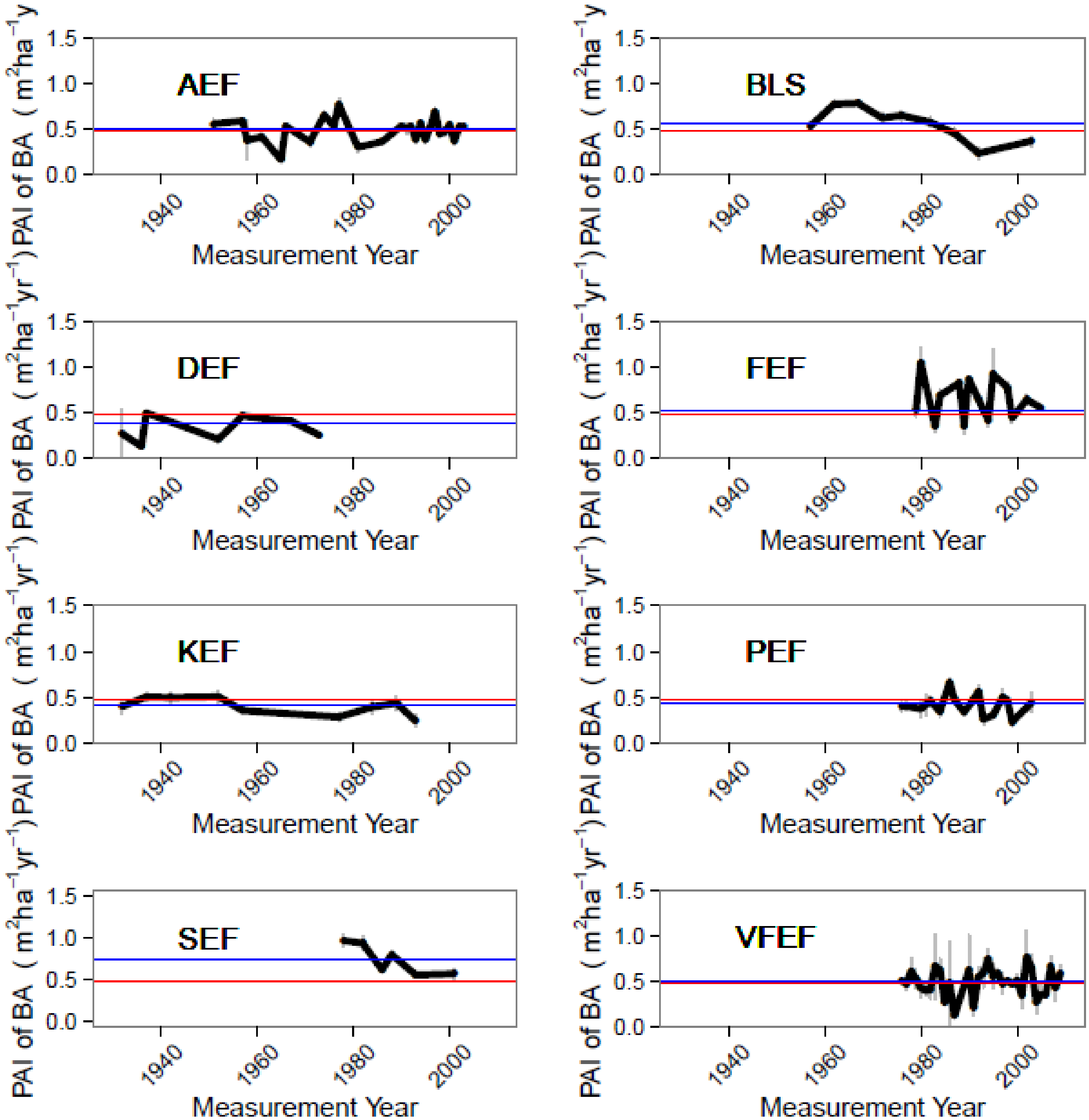

Figure 2. Site-level basal area PAI (m^{2} ha^{-1-1}) through included measurement years of USFS silvicultural experimental studies used in this analysis. Grey bars show standard error of the mean.

Both classification and regression trees partition predictor space rectangular regions; classes for classification trees and means for regression trees (Elith et al. 2008). When boosting is applied to tree structures, multiple (weaker) classification or regression trees are used to classify partitions of data to produce a stronger, final predication (Hastie et al. 2001). Optimal tree selection in BRTs is based on reducing the minimum predictive error (Elith et al. 2008). Optimization of trees in model (Figure 3) occurs when holdout deviance across cross-validated folds is minimized (Elith et al. 2008). Once optimal number of trees is estimated, models are run using global settings and the optimal number of trees. Global settings tested included tree complexity (indicative of interactions), learning rate (amount of data used in each step for initial model cross-validation), and bagging fraction (amount of data used in iterative cross-validation steps). Relatively slow ($lr \leq 0.0001$) and complex ($tc>4$) were tested in addition to presented models (Table 4). The slower models had lower performance and therefor excluded from results.

BRTs were used to quantify the relative influence of all model covariates at regional and local scales with a variety of global settings in the 'dismo' package (Hijmans et al. 2012) in R (R Development Core Team 2012). Following comprehensive BRT model fitting with all site data (n=2613), data were subset and BRT were fit at the site-level (n= 45-1417). Differences in data variability and sample size required a variety of global settings across models (Table 4). Using the 'dismo' package (Hijmans et al. 2012), BRT's influential factors can be simplistically plotted as a relative influence on predictor variables (Figure 4) or can be plotted showing the overall influence with centered values of the fitted factor functions on the response variable in partial dependency plots (Figure 5). The relative influence of interactions can be interrogated from BRT, but are most useful when plotted in 3D perspective. Interactions of climatic variability stand structures, and soil attributes were quantified and visualized using BRT. Default calculations extracted from ‘dismo’ are two-way interactions holding all other factors at their mean by default (Hijmans et al. 2012). Plots showing three-way interactions of a comprehensive model’s influential factors can be plotted showing effect on predicted (fitted) values by calling explicit values of a third variable.

Table 4. Boosted regression trees as evaluated within this project. Model [9] and [11] were fit with a bag fraction of 0.9. All other models were fit using the Gaussian family and bag fraction of 0.5.Tree complexity, TC, is the number of terminal tree nodes (TC-1= interaction levels). Learning rate, LR, is a shrinkage parameter applied to trees within overall BRT model.

Model	Data	TC	LR	Optimal trees	No. Obs.	Validation Statistics*			
						R^2	*RMSE*	*Mean Abs. Bias*	*Mean % Bias*
[1]	All	4	0.10	2650	2613	0.98	0.04	0.03	6.65
[2]	All	4	0.05	5200	2613	0.97	0.05	0.04	7.70
[3]	All	3	0.10	3900	2613	0.96	0.05	0.04	8.16
[4]	All	3	0.05	5800	2613	0.95	0.06	0.05	9.76
[5]	AEF	4	0.01	3750	1417	0.79	0.12	0.09	18.25
[6]	BLS	4	0.01	350	80	0.79	0.11	0.08	18.11
[7]	DEF	4	0.01	3650	424	0.97	0.03	0.03	6.47
[8]	FEF	4	0.01	500	107	0.78	0.12	0.09	17.43
[9]	KEF	4	0.001	1450	105	0.65	0.14	0.11	29.03
[10]	PEF	4	0.01	5500	334	0.99	0.02	0.02	3.14
[11]	SEF	4	0.0001	3100	45	0.53	0.17	0.13	32.62
[12]	VFSEF	4	0.001	3450	101	0.74	0.15	0.11	19.60

*based on predicting PAI from models fitted with same data

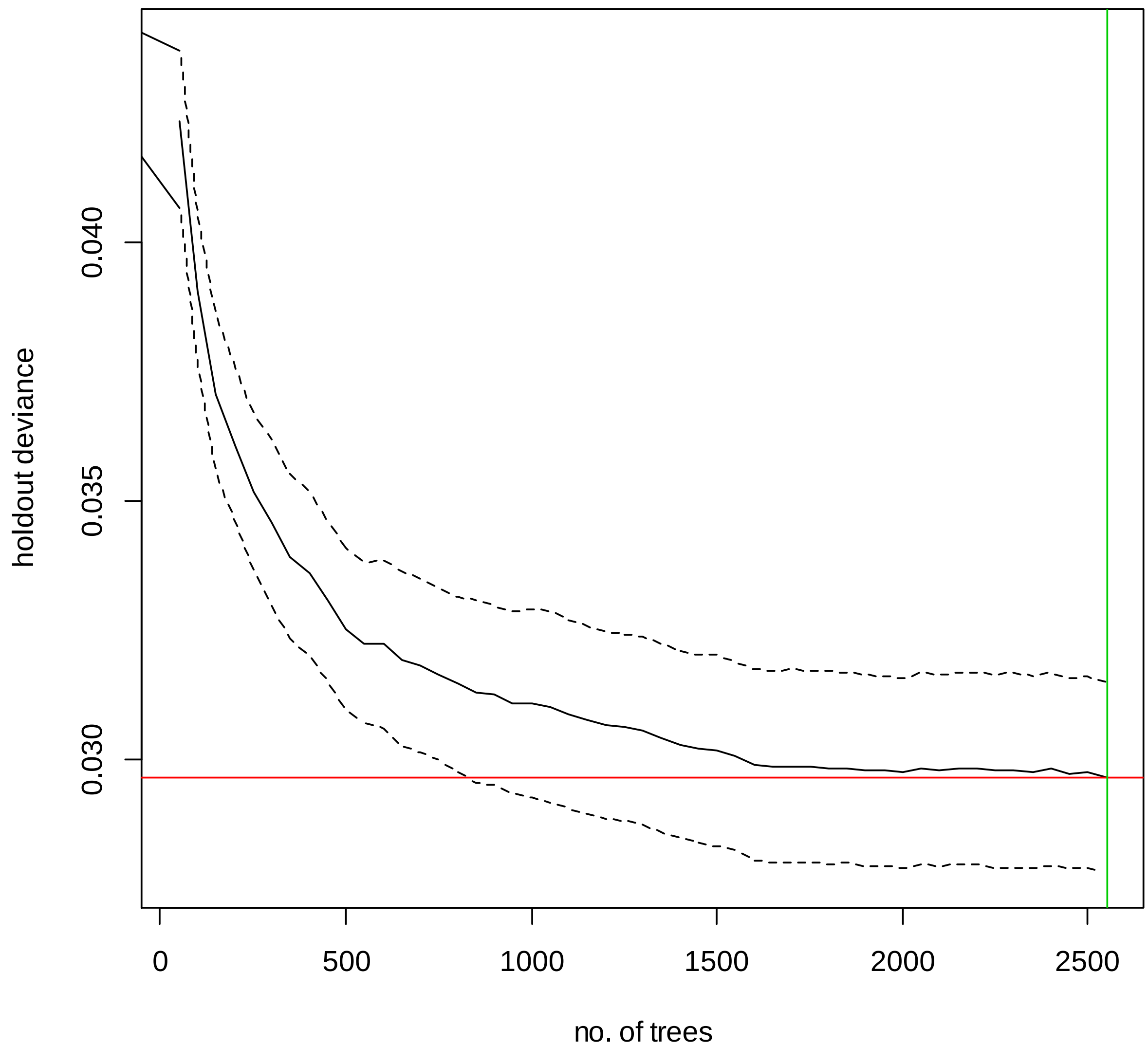

Figure 3. Example of boosted regression optimization within the comprensive model fitting to reduce holdout deviance during optimal tree calculation using ‘dismo’ package in R. Solid black line show the mean, dotted lines show approximately one standard error of the mean changes in preicivtive deviance by adding an additional tree. The red line shows the minimum mean holdout deviance, with the green line showing were the mean and minimum holdout deviance intersect.

Results

Growth trends

Annualized net PAI of basal across all sites was 0.48 ± 0.25 (m^2 ha^{-1} yr^{-1}). Treatment level PAI was calculated only for included treatments and measurement periods in this analysis (Table 5). Even age stands (BLS) and (SEF) exhibited the highest mean site PAI (Table 1). Across sites variability of PAI ranged between 33 and 60 % of the mean PAI (Table 1). Within sites, control area PAIs were usually lower than experimental areas with exceptions the SEF and VFEF (Table 5).

Model fits

All models had 109 independent variables of stand, site, and climatic factors (Table 3). The final comprehensive boosted regression tree (BRT) model [1] had three-way interactions (tree complexity=4), bag fraction of 0.5, learning rate (lr) of 0.1, fit with a Gaussian distribution. The most complex model [1] converged with approximately 2,700 trees. The comprehensive model contained 2,613 observations of unique plot and year measurements across all included covariates. Slow and complex models (tc >5) were computationally expensive, with evaluation statistics not significantly better than the less complex models presented within (Table 4). Indicators of model performance presented here should not be used as measures of independent predictive performance, as no predictions and validation with independent test data were performed.

Table 5. Treatment level net periodic annual increment (PAI) of basal area

USFS Site	Treatment Names	Observations (n)	PAI (m^2 ha^{-1} yr^{-1}) Mean	SD	Min	Max
AEF	CNTL	277	0.45	0.24	0.02	1.36
AEF	51CC	168	0.6	0.28	0.00	1.32
AEF	SW	163	0.68	0.32	0.02	1.32
AEF	13mRBA	268	0.46	0.22	0.05	1.24
AEF	17mRBA	263	0.49	0.22	0.03	1.17
AEF	20mRBA	256	0.46	0.21	0.00	1.15
BLS	CNTL	80	0.56	0.21	0.03	0.95
DEF	CNTL	3	0.12	0.11	0.00	0.23
DEF	SngTSel	3	0.51	0.03	0.49	0.54
DEF	11mRBA	133	0.41	0.17	0.01	0.84
DEF	16mRBA	145	0.42	0.19	0.01	0.81
DEF	20mRBA	140	0.33	0.16	0.01	0.73
FEF	CNTL	56	0.38	0.21	0.02	0.87
FEF	SDNT	12	0.81	0.22	0.54	1.22
FEF	SngTSel	25	0.72	0.15	0.26	0.91
KEF	CNTL	105	0.41	0.19	0.01	0.9
PEF	CNTL	36	0.31	0.19	0.00	0.66
PEF	2SW	148	0.53	0.26	0.01	1.18
PEF	10yS	149	0.36	0.25	0.01	1.33
SEF	CNTL	13	0.88	0.22	0.61	1.29
SEF	60RT	8	0.71	0.19	0.35	0.92
SEF	80RT	8	0.75	0.19	0.46	0.99
SEF	60TB	7	0.65	0.13	0.44	0.81
SEF	80TB	8	0.64	0.29	0.39	1.29
VFE	CNTL	125	0.5	0.27	0.03	1.35
VFE	Sel	7	0.46	0.15	0.25	0.69
VFE	Sel (w/ TSI)	7	0.51	0.2	0.28	0.8
Total		**2613**	**0.48**	**0.25**	**0.00**	**1.36**

Model fits across sites (model [5]-[12]) show variable, yet generally adequate, performance with semi-standardized global settings (Table 4). Models fit in 'dismo' provide a variety of cross-validated fold statistics (Elith et al. 2008, Hijmans et al. 2012). To maximize evaluation of included BRT models common parametric fit statistics of were calculated from predicted values (Figure 4) using BRT models for regional and site levels (Table 4). Final comprehensive model [1] maximized the R^2 and reduced the root mean square error (RMSE), mean absolute bias, and mean percent bias. Most site models had lower R^2 and higher error and bias, likely due to sample sizes (45< n>1417). Some site model fits [7], [10] were comparable or better than the final comprehensive model [1] (Table 4). Sites were initially fit with standard global settings. Some sites had small sample sizes with notable variability of observations that could not be optimized with the standard global settings. The KEF and SEF were fit with increased bag fraction (0.9), and reduced learning rate with variable results in fit statistics at individual sites.

Influential factors

BRT results may be mildly stochastic (Elith et al. 2008), and this was evident between closely ranked influential factors between iterations of the comprehensive model [1] runs (Figure 5). For example, in the comprehensive model the first two most influential factors (*allba1* and *WDRD_05*) relative importance were so similar, different runs of the model would show the relative ranking differently. To reduce stochasticity of conclusions and increase to ease of evaluation, influential factors were grouped into categories for general trend evaluation (Table 3). The final comprehensive and site-level models exhibit a variety of grouped site and regional trends when summarizing the ten-most influential factors on PAI (Figure 5). The comprehensive PAI model was driven mostly by density and diameter attributes. It is notable that the AEF, which provided approximately half of the observation for the final model, were also density and diameter driven. Other sites were also highly influenced by density and diameter levels, with multiple influential groups present at each site. Individual trends were more variable with climatic factors playing roles in six of the eight sites.

Some influential factors were influential across all sites, with little influence at individual sites, such and landform class (Table 6). In other cases, while the influential factor was common across sites, such as *allba1* the relative rank (1-36) varied between sites (Table 6). Trends of influential factor groups varied across sites. Some sites were driven by many factors within one group, such as the climate at the SEF or the density at the PEF (Figure 5). Other sites had one influential factor (BLS, KEF) that were of a different group than most other site influences (Figure 5).

Within an influential factor, BRTs allow for additional evaluation of the effect of one variable on the fitted function holding all others at their mean (Elith et al. 2008). Within the partial dependency plot of the ten most influential factors on PAI can be visualized across the range of included data. As expected, PAI is shown to increase with increasing relative density, increasing (additive) stand density index and, decreasing trees per hectare (Figure 6).

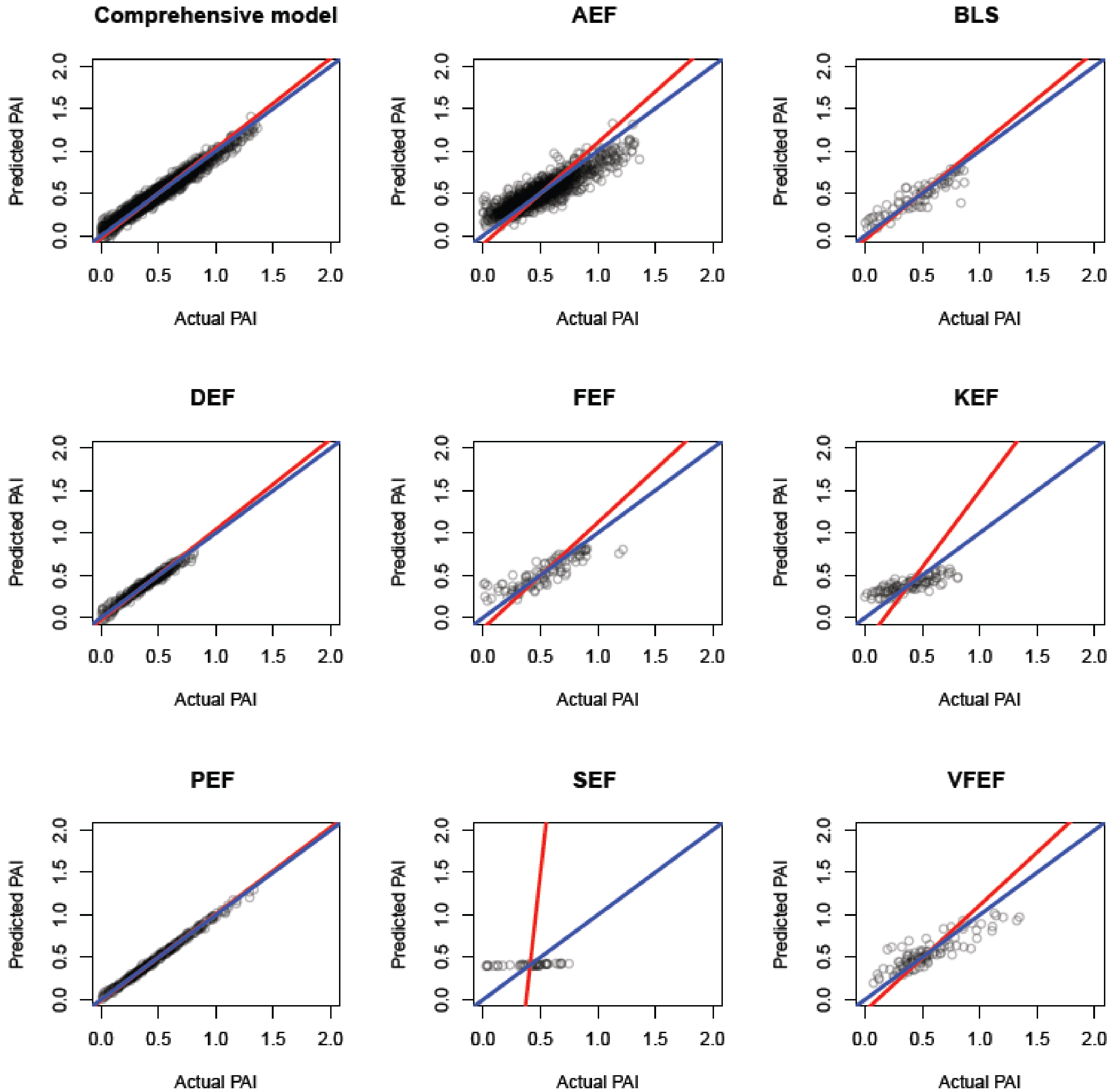

Figure 4. Predicted and observed periodic annual increment ($m^2ha^{-1}yr^{-1}$) for Comprehensive and all site specific models. Red line show least squares fit of the data, the blue line shows a 1:1 line with a 0 intercept for reference.

Table 6. Twenty most influential factors of final model [1] cross referenced with individual site [9]: [16] model's relative rankings of 50 most influential factors. Model characteristics are described in Table 3, variable descriptions are described in Table 4; note for the any climatic variable the last number in the name donates a statistic described in table footnotes.

Comprehensive Model			Site-Level Relative Influence (Rank)							
Rank	Relative Influence	Variable Name	AEF	BLS	DEF	FEF	KEF	PEF	SEF	VFSEF
1	8.46	WD05_RD*	6.07 (4)	-	9.73 (3)	1.57 (15)	3.14 (10)	16.96 (1)	18.11 (1)	0.50 (39)
2	7.84	allba1	6.4 (2)	0.74 (29)	17.74 (1)	4.41 (5)	1.53 (23)	12.17 (2)	0.10 (36)	6.33 (5)
3	7.27	sumsdi	6.53 (1)	0.75 (28)	12.77 (2)	1.01 (24)	2.19 (14)	10.78 (3)	6.98 (2)	2.72 (10)
4	4.31	m_d	4.92 (7)	3.68 (8)	2.77 (12)	1.62 (14)	2.92 (11)	1.75 (17)	0.30 (28)	0.51 (38)
5	4	sd_d	5.86 (5)	0.91 (22)	2.92 (8)	3.21 (7)	3.22 (9)	2.93 (5)	2.69 (6)	13.44 (2)
6	4	alltpha1	5.18 (6)	-	4.32 (5)	4.75 (4)	2.79 (12)	3.96 (4)	0.23 (31)	13.50 (1)
7	3.58	allqmd1	6.21 (3)	2.59 (12)	2.88 (9)	2.06 (10)	3.75 (8)	2.20 (10)	0.68 (24)	6.57 (4)
8	3.39	kurt_d	3.57 (9)	14.79 (1)	2.80 (10)	7.1 (3)	1.97 (15)	2.17 (11)	0.03 (45)	7.89 (3)
9	3.13	TsinTrt	3.44 (10)	1.08 (21)	2.29 (15)	18.15 (1)	4.94 (3)	2.06 (12)	0.05 (41)	-
10	2.81	skew_d	3.41 (12)	5.46 (5)	3.37 (7)	2.75 (8)	2.67 (13)	1.89 (14)	1.03 (17)	3.16 (8)
11	2.64	cv_d	3.43 (11)	1.17 (20)	3.96 (6)	1.94 (12)	15.62 (1)	2.66 (7)	0.27 (29)	3.99 (7)
12	2.58	LNDFM**	1.01 (20)	-	-	-	-	-	-	-
13	2.45	sdsg	4.15 (8)	3.42 (9)	2.36 (14)	2.01 (11)	4.00 (6)	1.66 (18)	2.69 (6)	13.44 (2)
14	2.22	shi_h	3.31 (13)	2.14 (16)	2.62 (13)	1.13 (21)	0.85 (30)	2.29 (9)	2.17 (9)	2.30 (11)
15	1.92	sesg	2.66 (14)	-	1.90 (19)	1.44 (16)	1.79 (17)	1.87 (15)	0.39 (27)	2.89 (9)
16	1.87	TsinSdyIn	0.65 (31)	4.65 (7)	2.79 (11)	4.22 (6)	-	2.00 (13)	-	-
17	1.8	plotsg	2.13 (15)	-	2.13 (16)	1.75 (13)	1.61 (22)	1.6 (19)	0.86 (19)	1.59 (13)
18	1.62	sdi_99	1.87 (16)	-	1.78 (20)	1.27 (19)	1.69 (19)	1.47 (20)	0.60 (25)	0.86 (23)
19	1.5	gsp3	-	0.62 (33)	-	-	0.40 (41)	-	-	0.46 (43)
20	1.22	d1002	069 (30)	-	0.13 (46)	-	0.29 (47)	0.73 (26)	3.33 (5)	0.66 (30)

*Calculated using the estimated maximum SD, specific gravity at 12% MC, and calculated additive SDI for plots, see Woodall et al. 2005 and Miles & Smith 2009 for detail
**Factor levels: Depression, Drumlin, Hill, Sill slope, Kame, Moraine, Mountain, Plain, Ridge, Terrace, from NRCS soil surveys

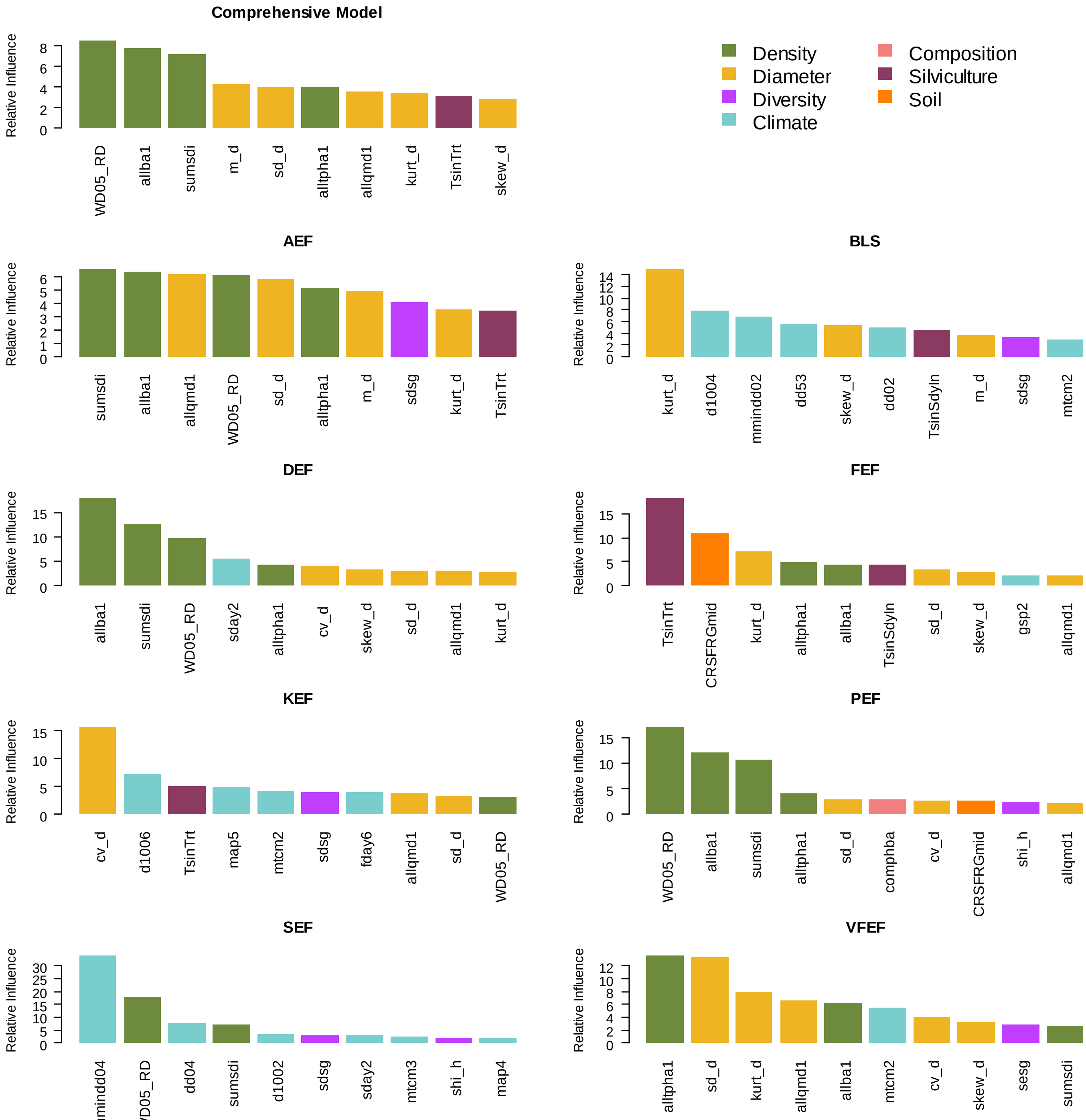

Figure 5. Relative Influences of comprehrenesive and site BRT models' top ten influential factors. Descriptions of covariate names are located in Table 3. Note different y-axis ranges.

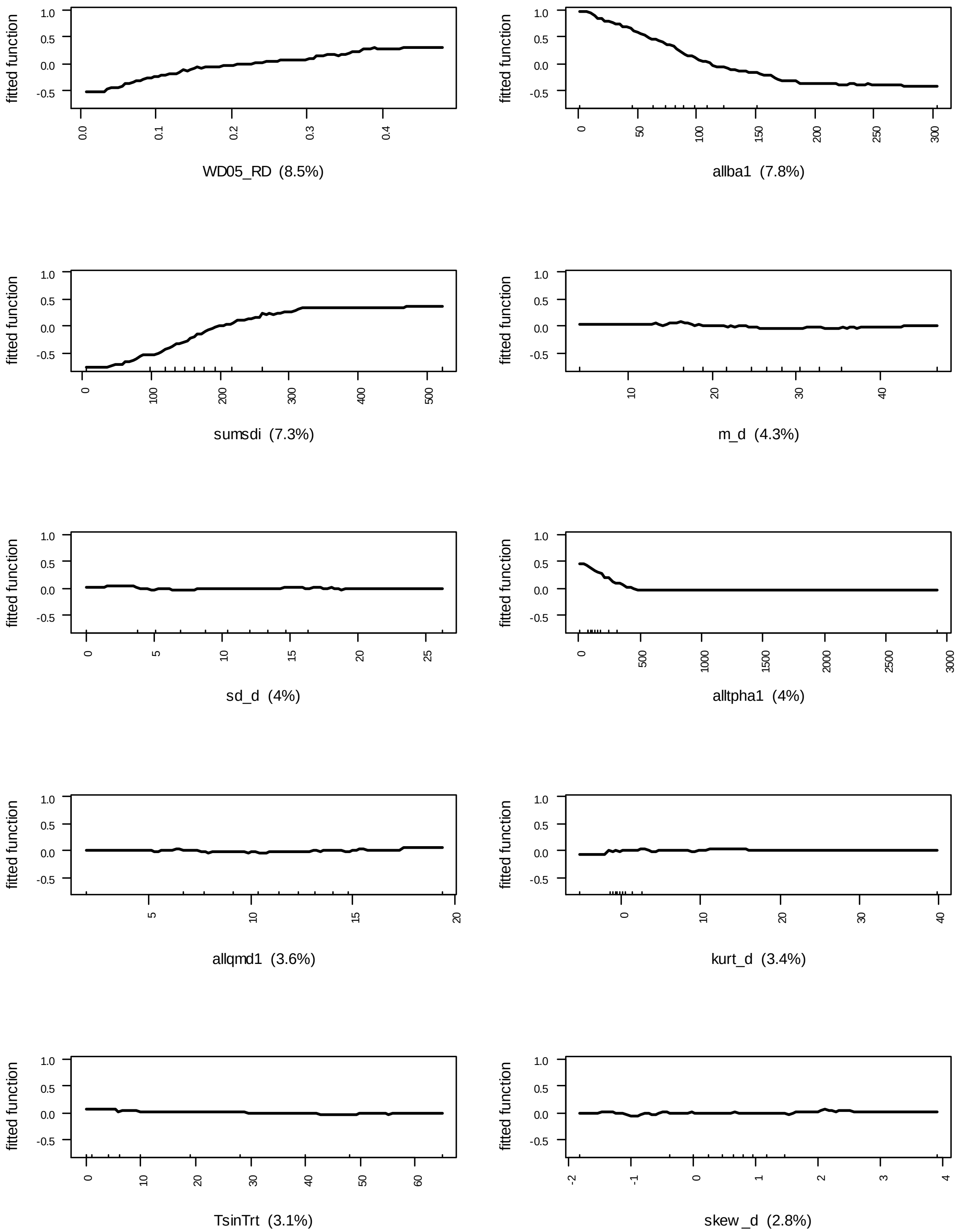

Figure 6. Partial dependency plots for the ten most influential independent variables of cross-validated PAI estimates of centered mean functions of comprehensive model [1]. Descriptions of variable names are in Table 3.

Interactions

BRT models can cross tabulate interaction effects and provide the relative influence. But interactions in BRT models can be visualized using three-dimensional partial dependence or perspective plots. As with partial dependency plots they show two way interactions of variable on the fitted function of final model as a default. Additionally three-way interactions can be plotted by the explicit documentation of the third variable at a specified value.

Using included covariates of climatic, soil, and stands characteristics, marginal effect of interactions on forest growth rates can visualized across multiple gradients. Two-way interactions of mean frost free period (*ffp2*) and diameter skewedness (*skew_d*) show when *ffp2* is between -1 and 1.5 that all levels of *skew_d* have less of an influence on PAI. Three way interactions between mean frost frees period diameter skewedness and levels of relative density show *skew_d* of -1 to 1.5 have lower impact on PAI than when *skew_d* are more extreme than those bounds (Figure 7 panel A) .

Three way interactions between basal area and relative density thinning regime (Figure 6 Panel B) show little difference between thinning regimes, i.e. that categorical silvicultural classes do not adequately explain difference across two-way interactions to an extents that a stand attribute such as relative density shows (Figure 7 Panel A).

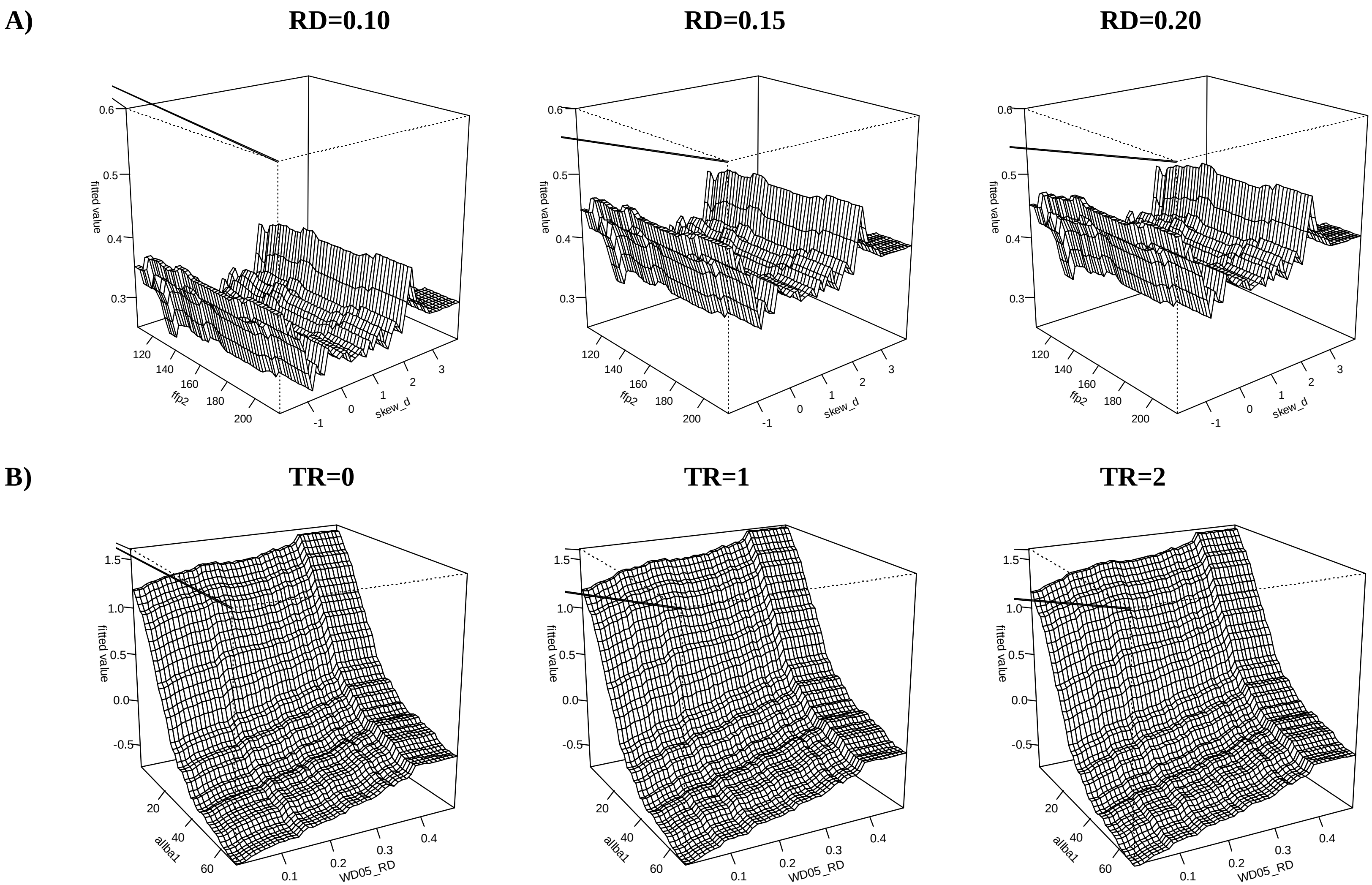

Figure 7. Three-way interaction of A) mean frost-free period~diameter skwedness (ffp2 ~ dd55) at three different relative densities, b) basal area of all trees~ relative density (allba1~WD05_RD) at three different levels of thinning regime where TR=0 (n=1996), TR=1 (n=586), TR=2 (n=31) and RD=0.10 (n=50), RD=0.15 (n=122), RD=0.20 (n=113).

Discussion

Within this analysis, data collected from a variety of sources were used to quantify the relative influence and interactions of multi-scale, non-congruent data structures data using a non-parametric technique known to perform well in the analysis of complex ecological data (Buston & Elith 2011, Elith et al. 2008). Historical forest growth records collected across a variety of forest types, silvicultural systems, and stand structures in conjunction with interpolated climatic and extracted soil data from multiple sources were used to quantify influential factors and interactions on growth response across multiple gradients presence in northern forests of the US.

Northern forest complexity

Northern forests of the United States are a complex mosaic of forest types, age, composition, density and with individual future concerns (Shifely et al. 2012) such as cover type have change (Stearns 1997), regenerating and maintaining diversity with high levels of browse pressure (Marquis et al. 1992), complex mixed species stands with multiple endemic forest pests (Lovett et al.2006, Robert et al. 2012). The complexity of managing multiple forest types for multiple goals make the northern forest an optimal region to evaluate the effect of multiple gradients and their interaction as affecting forest growth.

Growth rates of forest stands are affected by many factors including soil characteristics (Aertsen et al. 2012), climate (Fang et al. 2010, Nabeshima et al. 2010, Pinno & Belanger 2011), competition (Martin & Brister 1999), structure (Burkhart and Tomé 2012), and silvicultural treatment (Weiskittel et al. 2011, Powers et al. 2010). While traditional growth and yield models are the most common evaluation method of forest growth, non-parametric approaches are becoming become common in the evaluation of multiple forest management related issues (Baffetta et al. 2012, Yue et al. 2011, McRoberts et al. 2007, Gunnarsson et al. 1998).

Meta-analyses may be appropriate techniques to better understand long-term data trends across multiple gradients present in primary forestry studies (Griess and Knoke 2011, Vadeboncoeur 2010, Piotto 2008, Rustad 2001, Johnson and Curtis 2000). A MA uses previously published results extracted and standardized across independent studies extracted via extensive literature review(s) (Gurevitch & Hedges 1999, Gurevitch et al. 2001, Hedges & Pigott 2001).While a promising technique for some applications, MAs are prone to limitations such as publication bias (Egger & Smith 1998, Gurevitch et al. 2001), selection bias (van Kooten et al. 2009), and dependences on data quality (van Kooten et al. 2009, Sterne et al. 2000). These limitations are sometimes difficult to quantify as a result of the non-transparent nature of MAs. Yet MAs also provide methods for large-scale comparisons difficult to summarize in the field of forestry. Here PAI as calculated from standardized tree-lists from multiple long-term silvicultural experiments is equivalent to an effect size, the common metric of comparison used for traditional MA comparisons across studies (Hedges et al. 1999, Hedges & Pigott 2001).

This standardization effectively provided a compiled dataset of long-term tree-level forest growth records with structures designed to mitigate differences in study design not known to have an equal (Dave Rugg, USFS Data Archivist, personal com. 2011). These data of raw tree-level forest growth records with incorporated site and stand characteristics could be used for additional regional comparisons of PAI; a common metric which can be calculated across even age, uneven age, mixed and managed stands.

Model fits

A non-parametric approach was taken within this work with the intention of combining multiple growth related covariates. Non-parametric approaches require little or no assumptions of linearity, auto-correlation structures (hierarchical data), normality, and presence of outliers or homoscedasticity (Elith et al. 2008). Other parametric techniques may be a valid approach to summarize large-scale differences in similar data (De'ath 2007) including mixed models (GLMM, NLMM) or generalized linear and additive models (GLM, GAM).

This application of a non-parametric evaluation of forest growth is able utilize data previously collected data across multiple independent experiments, such found in long-term silvicultural trials; to understand broad trends across multiple gradients. BRTs were utilized within this work as they are shown to perform better than other parametric techniques with multiple data structures within ecological studies (Abeare 2009, De'ath 2000 & Fabricius, Moisen et al. 2006). While BRTs provide unique opportunities to summarize data, depending on type of data, they do not provide common (parametric) measures of model performance and outputs can be stochastic based on the iterative fitting processes (Elith et al. 2008, Abeare 2009). BRT available fit statistics in R (here in 'dismo') are based on fold variability.

To provide traditional fit statistics of BRT predictions of PAI were compared to the results from optimal BRT structures (Table 4). Comprehensive models across all forest types, silvicultural systems, and site characteristics performed well (Table 4) compared to other sub-regional models incorporating climatic and soils data (Yang et al. 2006), diversity and site index on PAI (Schuler 2004) and silvicultural systems (de Miguel et al 2012). Plot level models fit with BRT within had higher RMSE some species specific models (Teck and Hilt 1991) with lower RMSE than northern forest models (Lhotka and Loewenstien 2011, Kiernan et al. 2008).Using multiple northern forest types provided a robust data that had high correlation between observed and re-predicted values (Figure 4). Models fit within this work where relatively similar concerning the non-parametric evaluation statistics (Table 4) therefore a four-way interaction model was chosen to account for complex data structures.

Influential Factors

While a comprehensive model identifying the influential factors of PAI across sites was the initial impetus of this project, comparisons of site-level and regional drivers of forest growth merit discussion. Differences in ranking of individual variables and classification patterns within and between sites show different influential factors driving growth response across sites (Figure 5). Models with one highly influential factor, such as the comprehensive model [1], and the AEF [5] model were driven mainly by stand characteristics, encompassed in the measure of plot-level diameter kurtosis, highlight the strong influence of stand structure on growth across forest types. Other site-level models [6]-[12] had much more dynamic and relatively similar influential factors, indicating some stand’s growth rates were driven by many influential factors and presumably, interactions therein. These differences could be attributed to multiple factors including length or sample size of site-specific records.

The overall influence of diameter distribution statistics (Table 5) at a site and regional level were quite evident. While diameter distribution may be a component of silvicultural prescriptions, not all included treatments within this dataset had diameter related prescriptions, so it was classified more specifically. The classification between even and UEA stands was not influential at site or regional levels. If diameter related measures are considered a non-"silviculture" classification (Table 3), other classifications could presumably also be related to silvicultural system in place. Other factors that are influencing PAI, but not specifically classified as silvicultural impacts include diversity and density measures. If one considers these measures of stand dynamics, then each of included sites and comprehensive region were heavily driven by measures of stand dynamics.

Measures of density and diameter distributions were the most the ubiquitously influential factors across all even, uneven, mixed and monoculture sites included in this analysis (Figure 4). The importance of density and diameter on forest growth (or carbon storage) in both even (Buckman et al. 2006) and un-even aged (D'Amato et al. 2011) stands was an expected and commonly observed result. A seminal comparison of multiple forest types, silvicultural treatments, and interactions therein found stand age to be influential on carbon storage (D'Amato et al. 2011). This analysis did not use stand age, as no uniform measure or estimate of accurate stand-age across sites were available.

Other notable influential factors on growth response were differences in the prevalence of influential climatic factors within and across sites (Table 5). Individual sites were influenced more commonly by climatic variability than the mean or range of observations (Table 5). Five of the eight individual sites had PAI measures that were markedly influenced by climatic factors, while regional influential factors were more commonly diameter or density attributes. The importance of climate on growth response has been studied across regions with results highlighting the complex dynamics of climate as an influential factor with results showing importance of precipitation on afforestation (Yang et al. 2006), temperature interactions with other factors such as species mix and stand location (Lo et al. 2010), tree age (Gea-Izquierdo et al. 2009) and annual variation (Kilgore and Telewski 2004, Lo et al. 2010). Complex climatic relationships also are present within this work, evident by variable trends across site and comprehensive models.

Individual sites were more commonly influenced by temperature than precipitation in general; perhaps showing climatic influences may be more dependent on the limiting climatic factor within a site, which in the northern forest may be more related to length of growing season than precipitation. Regional trends show both precipitation and measures of temperature to be influential on PAI (Figure 5), indicating they both may be limiting to different degrees across the region. Influence of species composition was most evident in the two of the mixed northern hardwood stands (AEF and DEF), which had almost pure hardwood composition (Shannon diversity indices of 0.07-1.14) across observations. Some influential factors at the regional level were not highly influential at the site-level (Table 5). This result may be due to a variety of factors more specifically related to a site's PAI and the lack of general site characteristics influencing PAI, which are than better explained by other classification variables at a regional level.

Interactions

Differences of site and regionally influential factors may be better explained by complex (3+) interactions of factors. Interactions of climatic (Figure 6 panel A) and stand structure (Figure 6 panel B) interactions on regional PAI are possible to visualize using perspective plots. Additional interactions of influential factors within and between the attribute classifications of this project are possible, and could merit future climate related interaction effect models. Additional investigations of climatic interactions in relation to stand structures could provide more detailed understanding of complex growth dynamics across multi-cohort and species stands. Quantifying the influences and interactions of climatic, geologic, and stand conditions at regional scales using long-term tree-level data can allow foresters to better understand differences at concurrent forest scales.

Recent comparisons of long-term historical silvicultural studies using a variety of statistical techniques (Olson et al. 2010, D'Amato et al. 2011, Yue et al. 2012,) have shown conclusions drawn from diverse study areas. Olson and Wagner (2012) found that through time different interactions of initial stand structures and implementation of silvicultural system (harvest disturbance) were evident in multi-decadal change in composition. Yue et al. (2012) used periodically repeated measurements of experimental plots in southwest Germany to evaluate the effect of multiple components of stand and climatic components on predicting growth trends in Norway spruce stands. Yue et al. (2012) utilize spatially interpolated meteorological data and measures of stand productivity to predict PAI using a composite tree and stand level GAM approach and provide interactions of stand characteristics. D’Amato et al. (2011) utilize long term silvicultural experiments to quantify main effects and interactions of influential factors on carbon storage. D’Amato et al. identify differences in structural and compositional complexity affect patterns of tree size and species diversity and reinforce the need of multi-forest type comparisons. These comparisons and prediction of forest growth across gradients provide forest scientists detailed, empirical understandings of complex, large-scale forest dynamics.

Limitations

A comparison across forest types and stand structures using raw data spanning of up to 80 years is an opportunity to better understand the regional and site-level influences of forest growth and yield, but technical complexity and independence of historical silvicultural trial data merit discussion. Incorporating multiple data structures required gaining access to raw and descriptive data from long-term silvicultural trials, which is generally not readily available. Standardization and extensive QAQC was required prior to large-scale comparisons resulting in high initial time investments of data preparation. Additional standardization of new data are required to test prediction power of included trials in similar and variable stand structures without reducing the relatively small sample of plot-level PAI. In general, the accessibility to long-term raw forest data records are low, and framework for research with these data could be initiated to facilitate future data and research collaboration. Additional resources to obtain, prepare, standardize and implement additional comparisons are required.

Data simplification within this work occurred. Standardization of data to certain characteristics was required to facilitate across-site comparisons, and is detailed in Ch. 1. Grouping of both climatic and soil data were done within this project. Climatic characteristics were collected at a site-level, with an assumption that climatic differences were minimal within a silvicultural trial. Soils information was grouped at the replicate or plot-level where un-replicated. However, some areas had plot sizes up to 4.04 ha. Soil variability in some areas was notable and may have affected stand-level growth influences.

This work provided one example of assessing regional growth trends, but may also benefit from additional analyses using independent subsets of data collected across additional forest types and stand structures. This preliminary model does not address all prevalent forest types or stand structures across the northern US, and should not be used for extrapolations outside of similar forest types without additional model validation. BRTs results are dependent on the data used for model fitting and results may be stochastic (Elith et al. 2008). Due to the unique nature of this dataset, no test set was available to use for prediction of the resulting model. Additional efforts to standardize long-term forest growth records in the Northeast could provide a viable independent test data set required to test prediction strength of these models. These model evaluations are intended to show exploratory summarization of trends across the Northeastern forests, and additional model validation is necessary for predictions of PAI utilizing BRTs as a standalone method.

Conclusions

This work is a preliminary endeavor to assess feasibility of utilizing long-term forest growth records to more fully understand key drivers of forest growth at multiple scales. Understanding complex growth dynamics, influential factors, and their potential interactions across a gradient of forest types and silvicultural systems may increase future understanding of a changing climate's effect on local and regional growth trends. While multi-scale historical data provides unique opportunities for novel comparisons, data availability and completeness need to be preliminarily addressed and may require extensive data preparation.

Stand structure and density outcomes, perhaps from silvicultural systems, were influential at a local and regional level across all studies. The incorporation of climatic variables, soil characteristics, and measures of stand structures provided evaluation metrics for relative ranking of multiple factors across a wide climatic gradient. While common influential factors are evident across sites, many sites have unique influential factors affecting PAI to a notable degree. Comparing the relative influential factors using long-term data from multiple forest types and initial stand structures begins to depict spatially explicit influential forest growth dynamics and differences related to spatial scale.

Here BRTs were used for the explanation, not prediction, of influential factors on growth response across a subset of forest types across the northern United States. BRTs evaluated the relative influence and interaction of factors of the periodic annual increment at a regional and site-specific level. Influential factor categories were broken into seven characteristic groupings, which allow for more general. Utilizing data from a variety of sources in a nonparametric framework is one possible technique to incorporate the vast quantity of useful data available in the scientific community, but not the only. Future comparison of additional sites, silvicultural treatments or independent variables may show different results.

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APPENDIX A. Plot level stand attributes through study period by unique treatment and USFS silvicultural trial

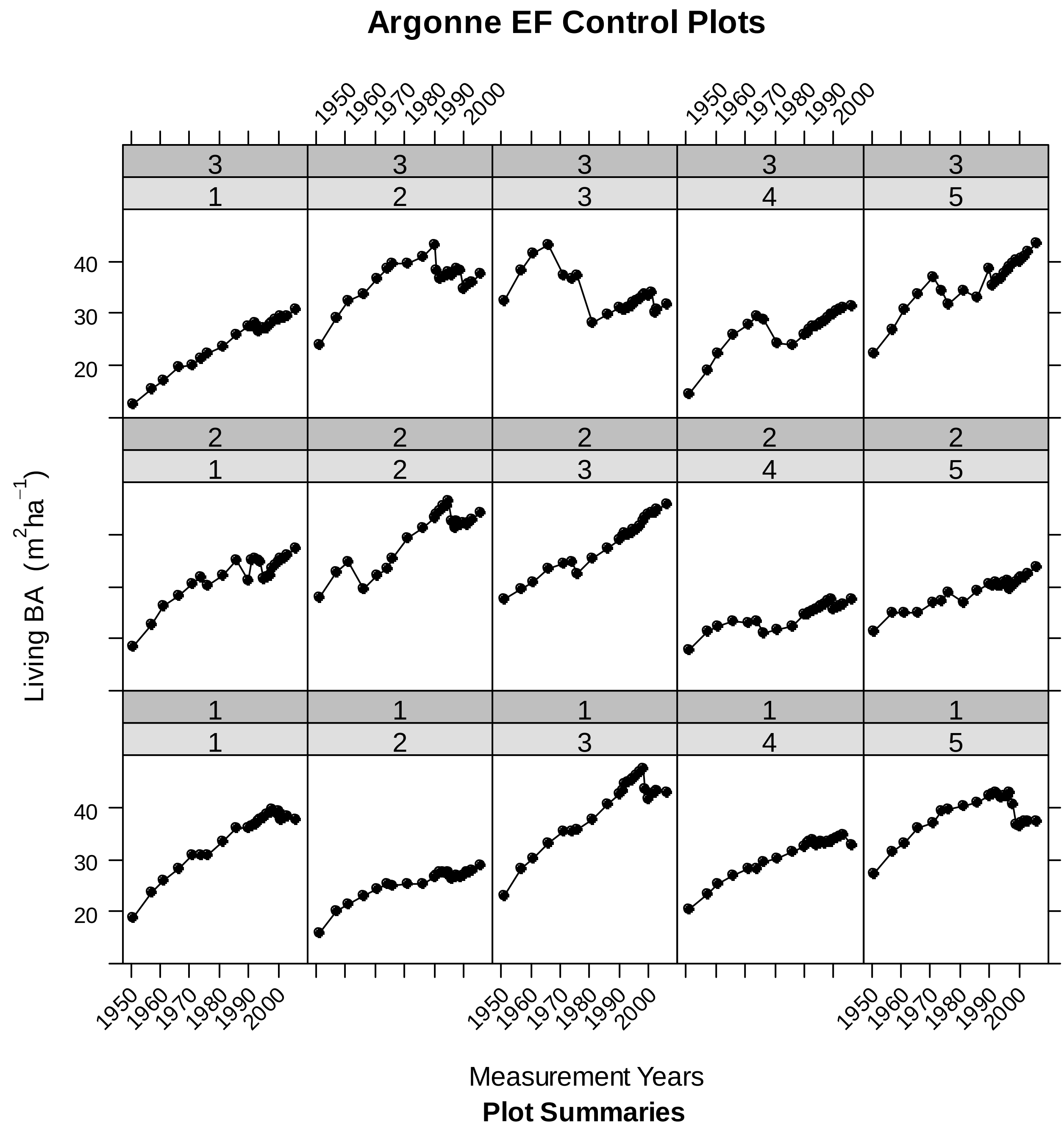


Figure A1. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) control plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

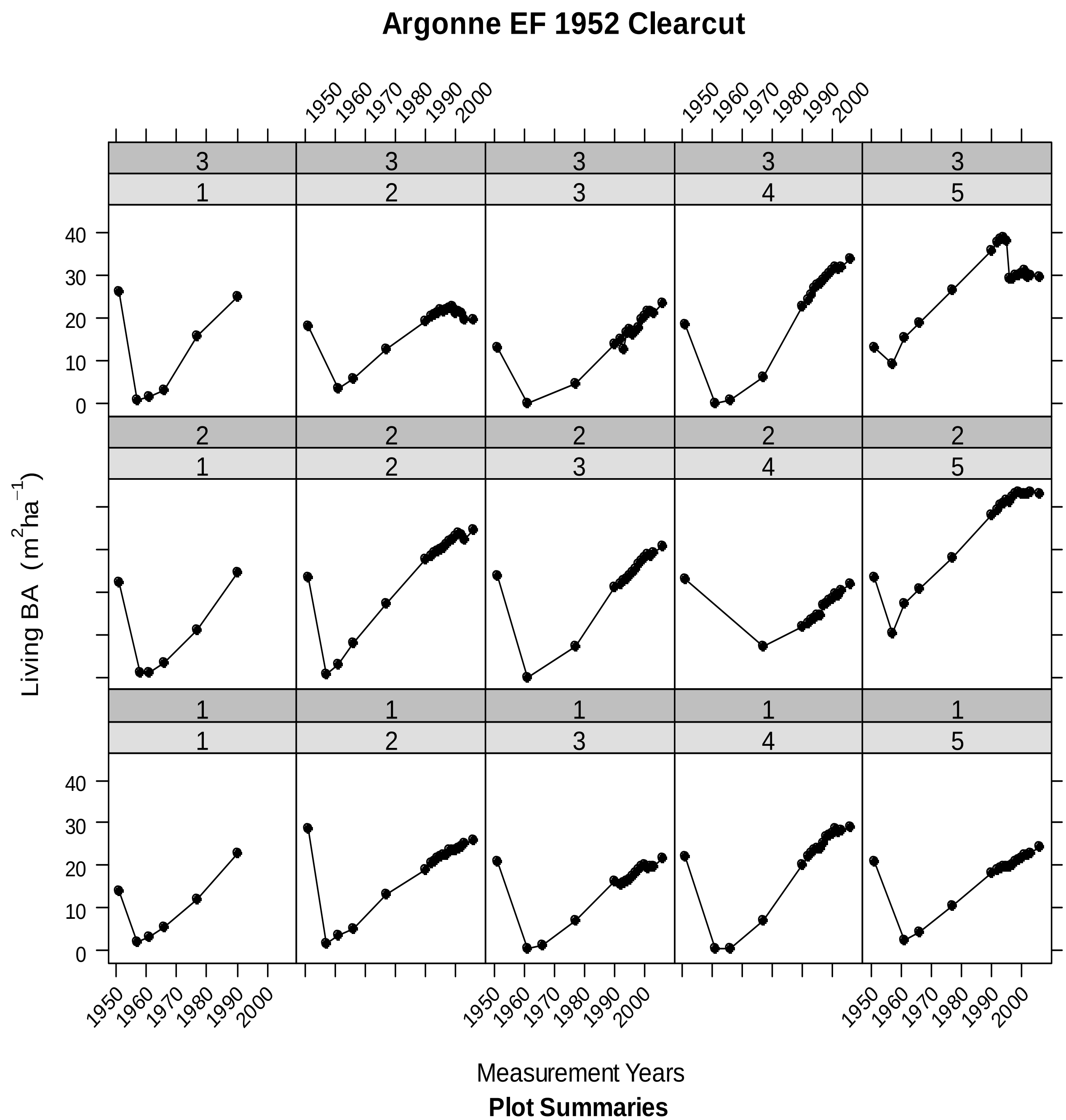


Figure A1. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) control plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

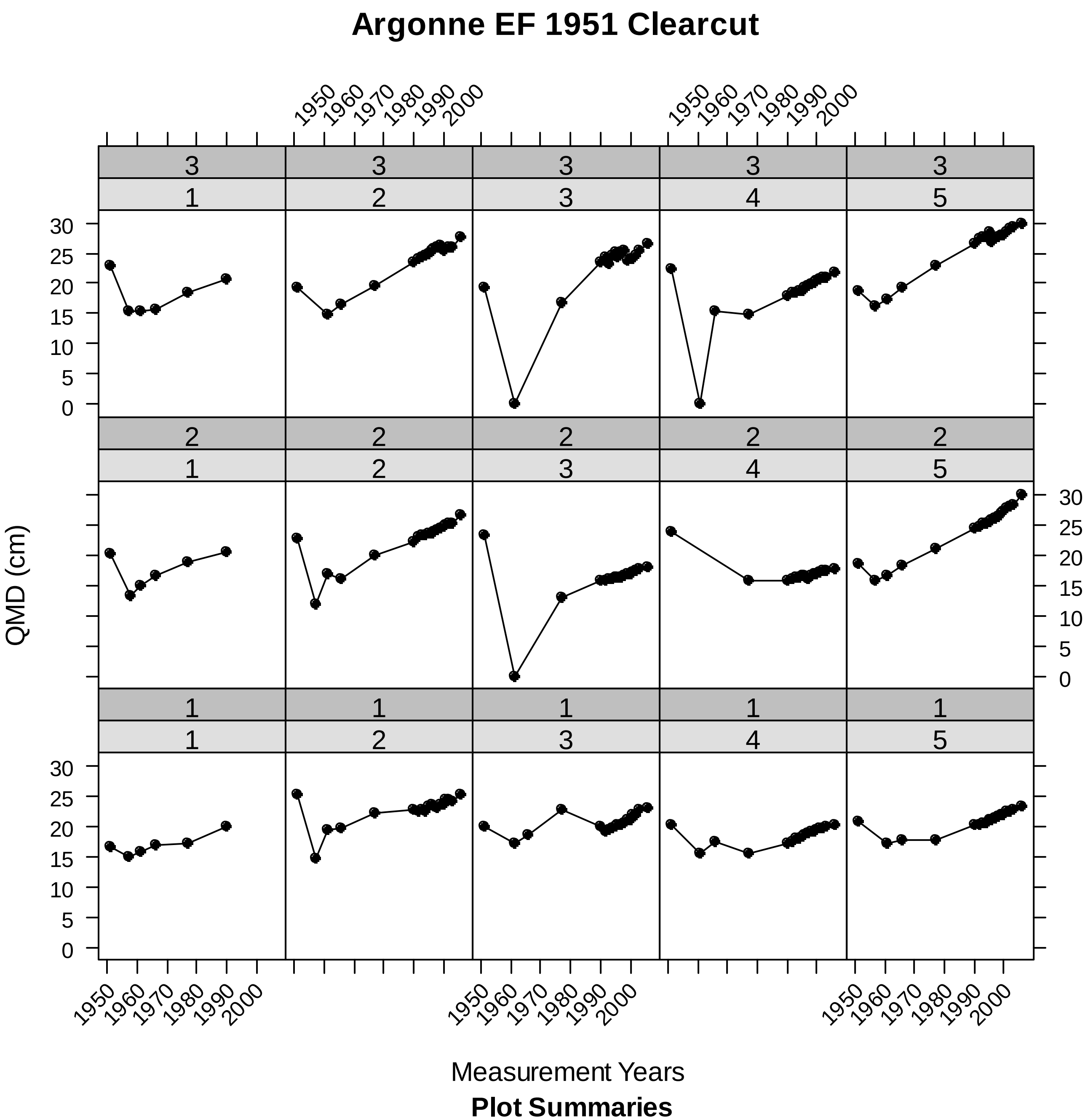


Figure A2. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) clearcut (ca. 1951) plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

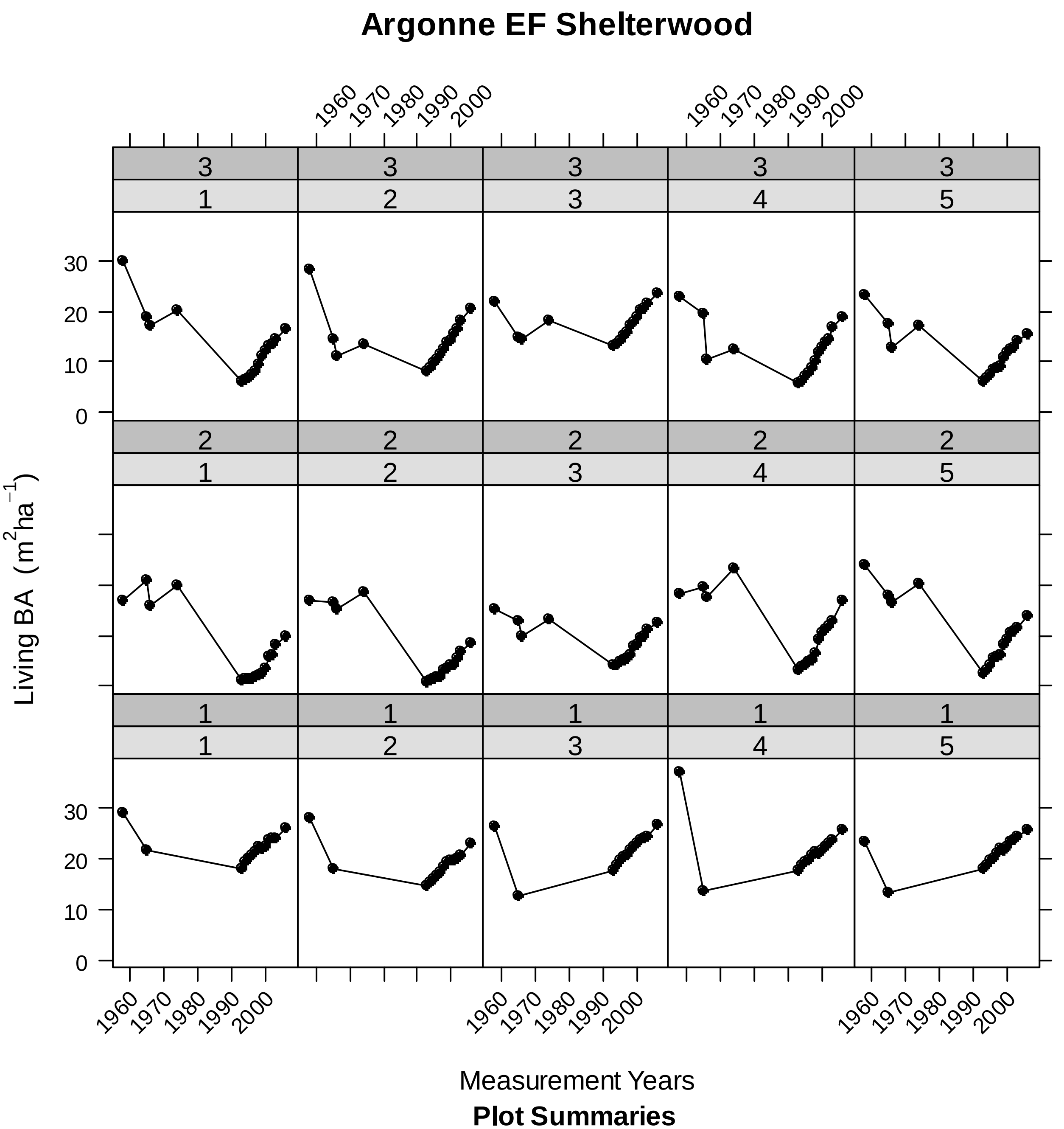


Figure A3. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) two-stage shelterwood plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

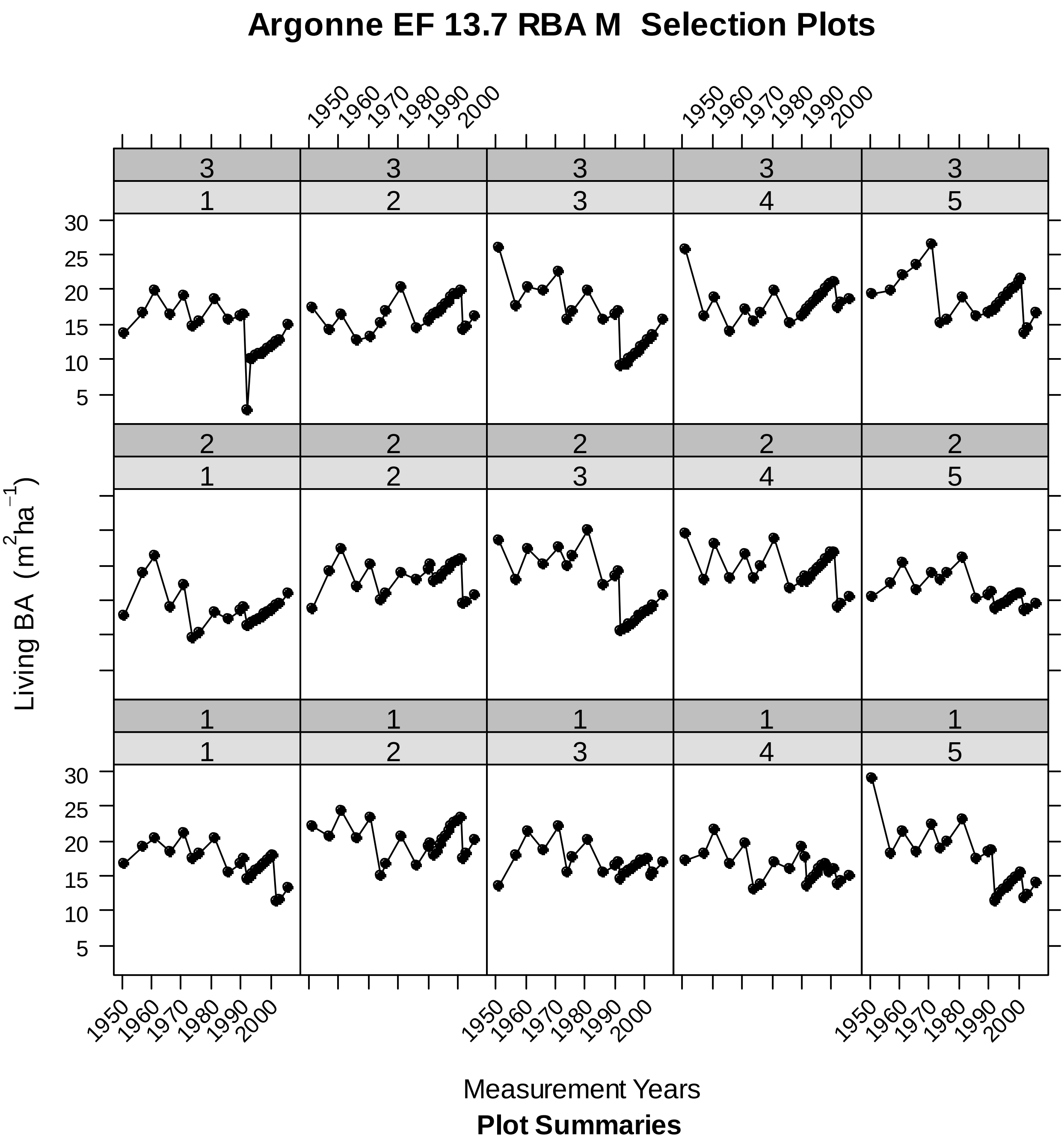


Figure A4. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

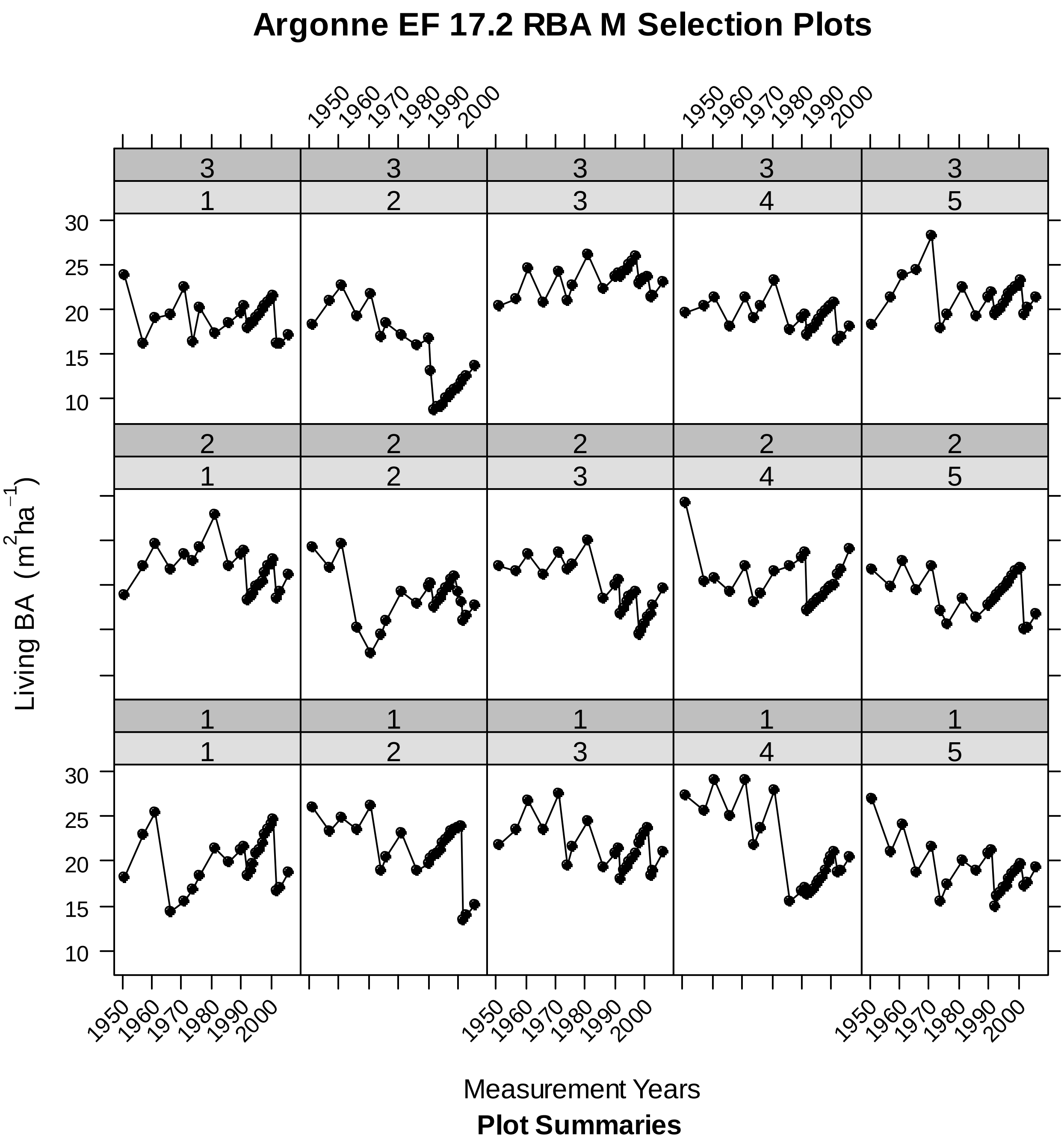


Figure A5. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

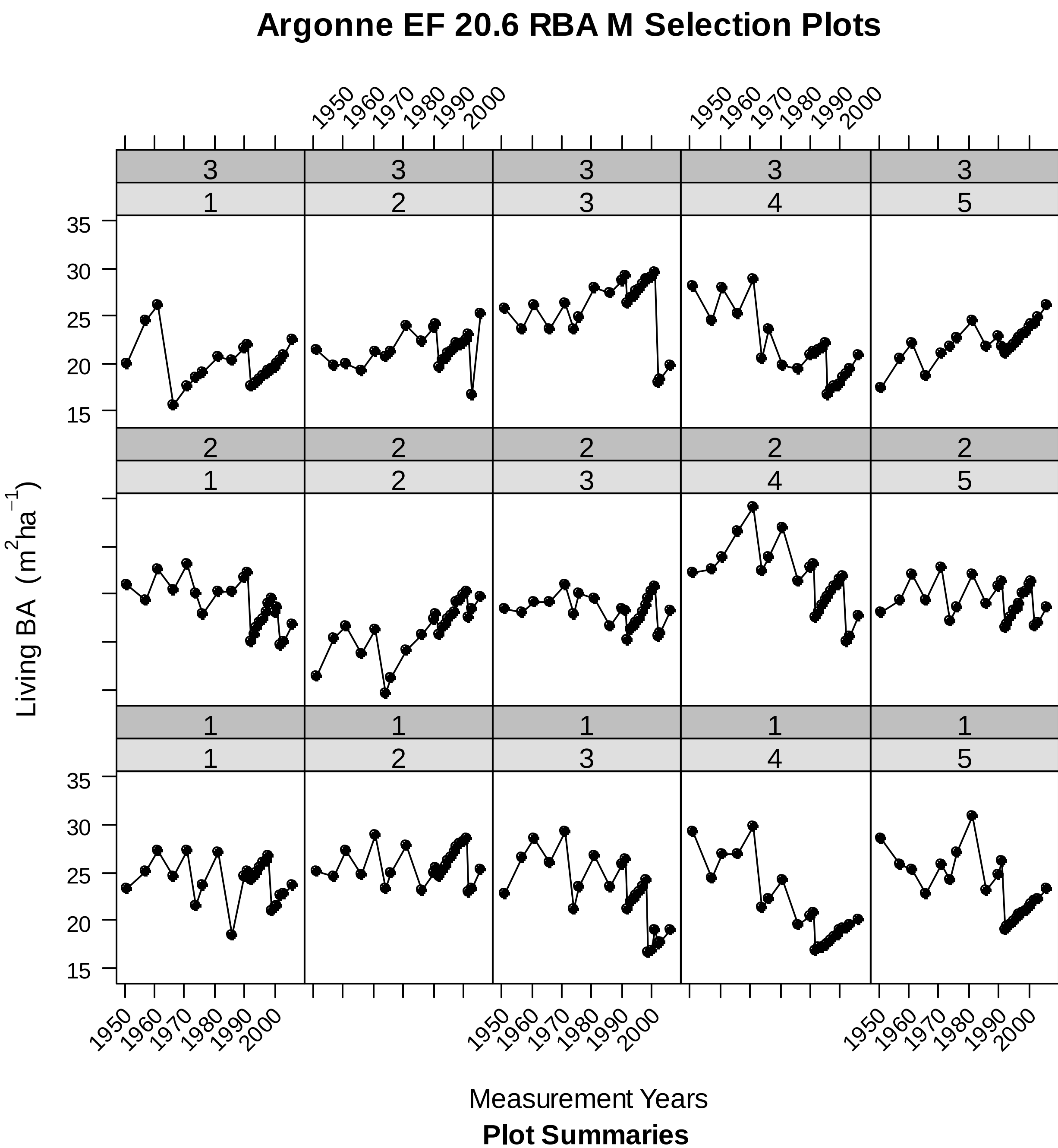


Figure A6. Live basal area (m^2 ha^{-1}) through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

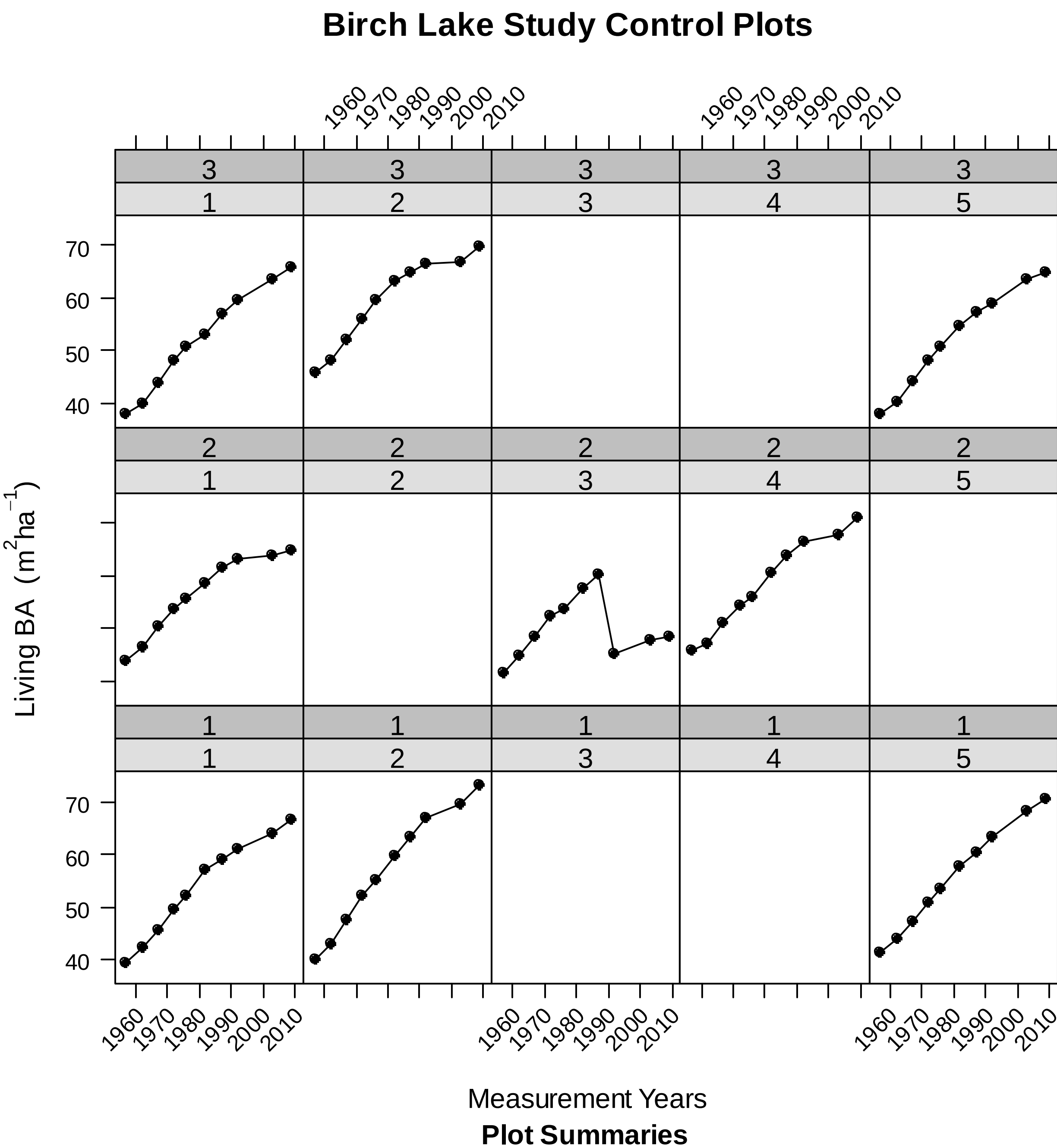


Figure A7. Live basal area (m^2 ha^{-1}) through time on the Birch Lake Study (BLS) control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is standardized plot number. Standardized replicates 1-3 are BLS blocks 5,9,16 respectively while standardized plots1-5 are Center, East, North East, Southwest, and West BLS plots respectively.

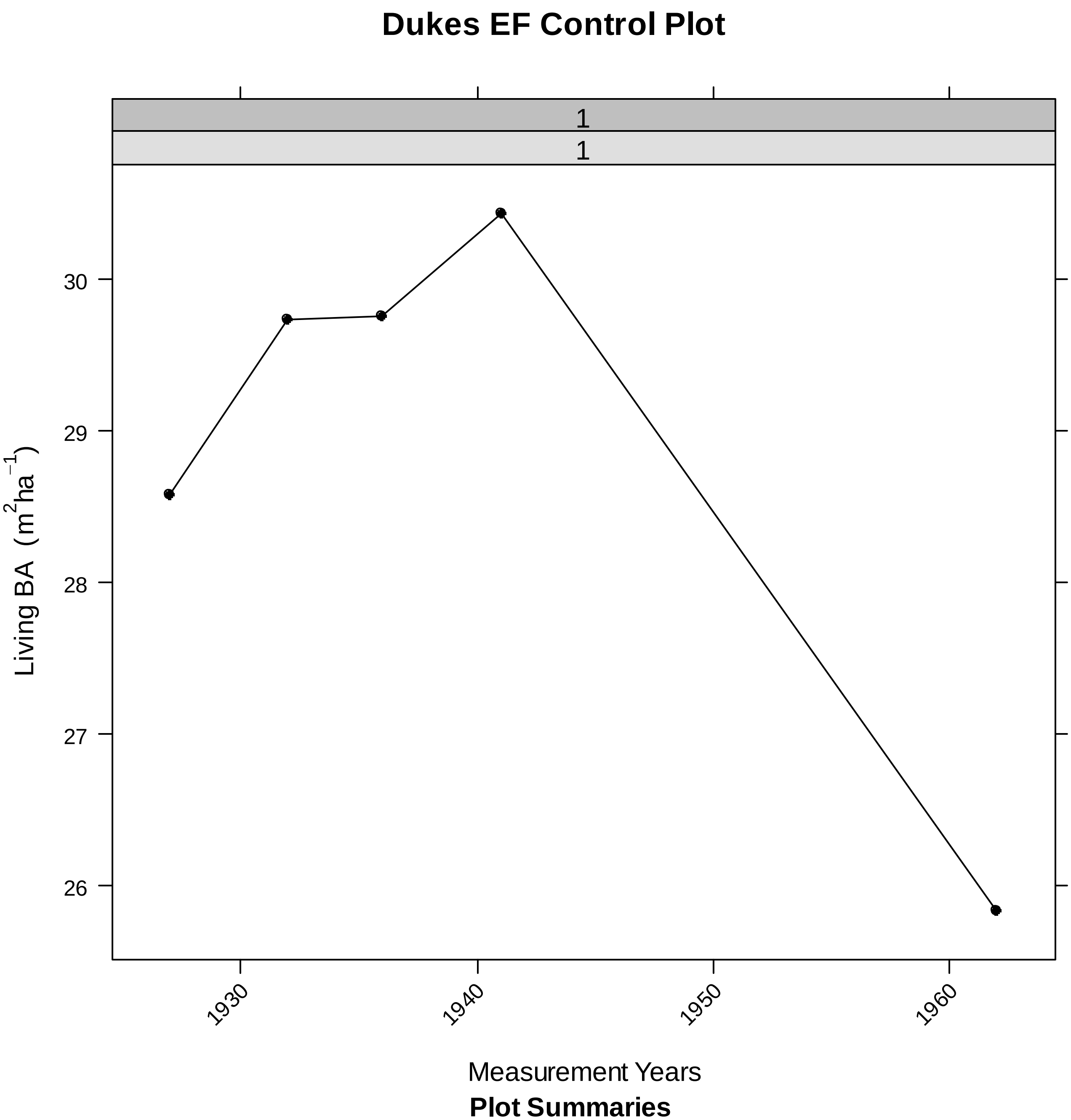


Figure A8. Live basal area (m^2 ha^{-1}) through time on the Dukes Experimental Forest (DEF) control plot. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

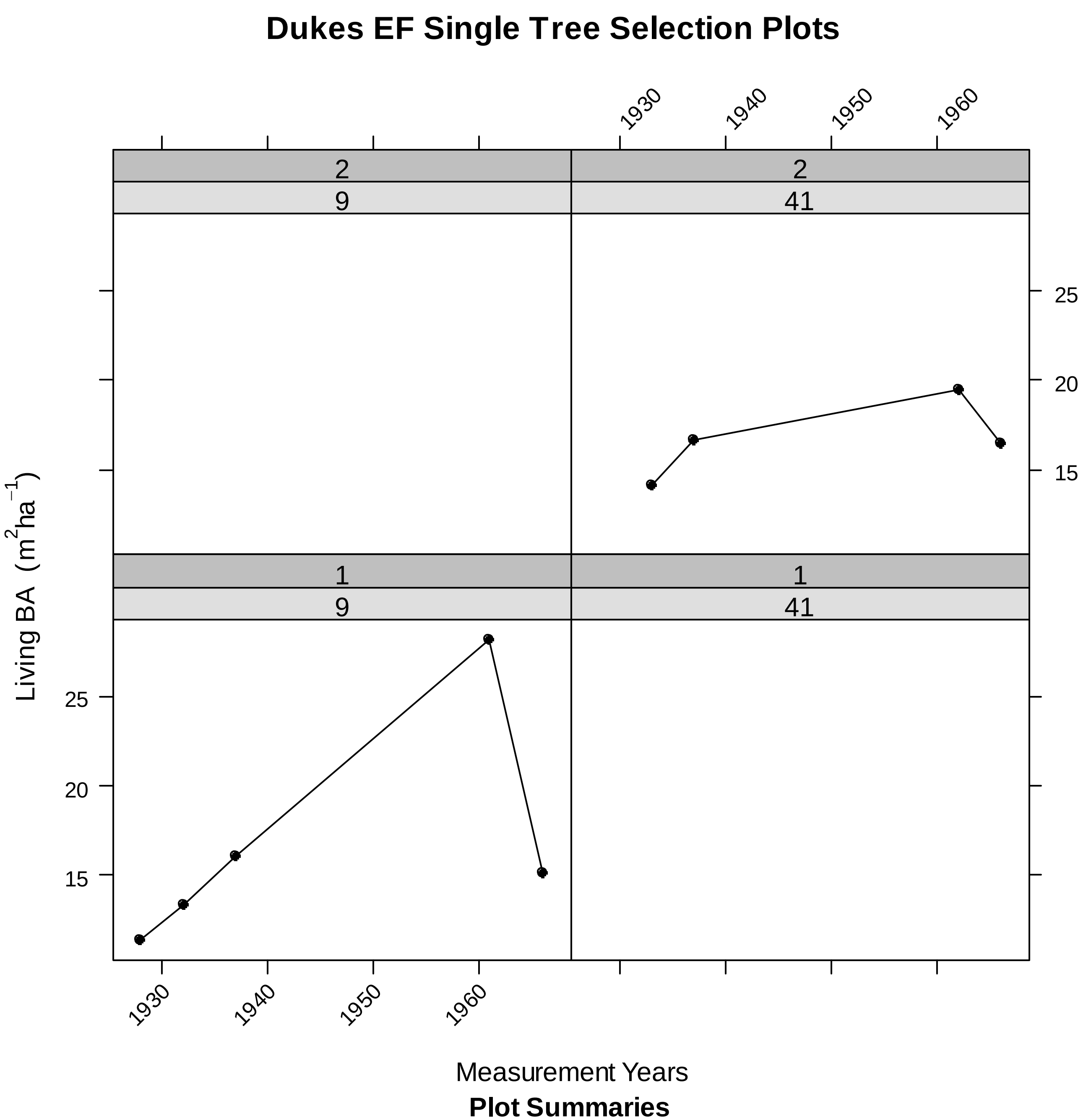


Figure A9. Live basal area (m^2 ha^{-1}) through time on the Dukes Experimental Forest (DEF) single tree selection plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

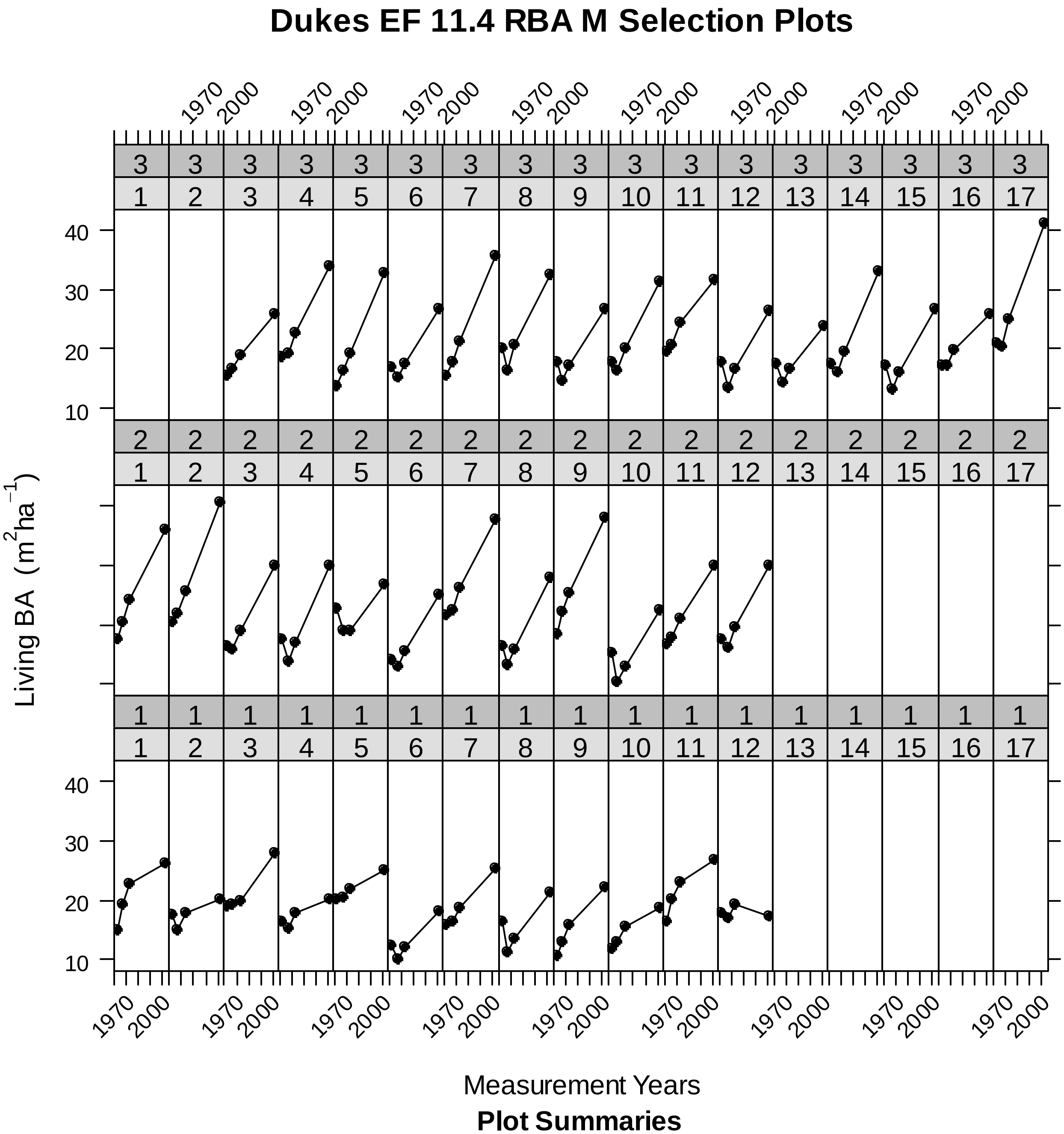


Figure A10. Live basal area (m^2 ha^{-1}) through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

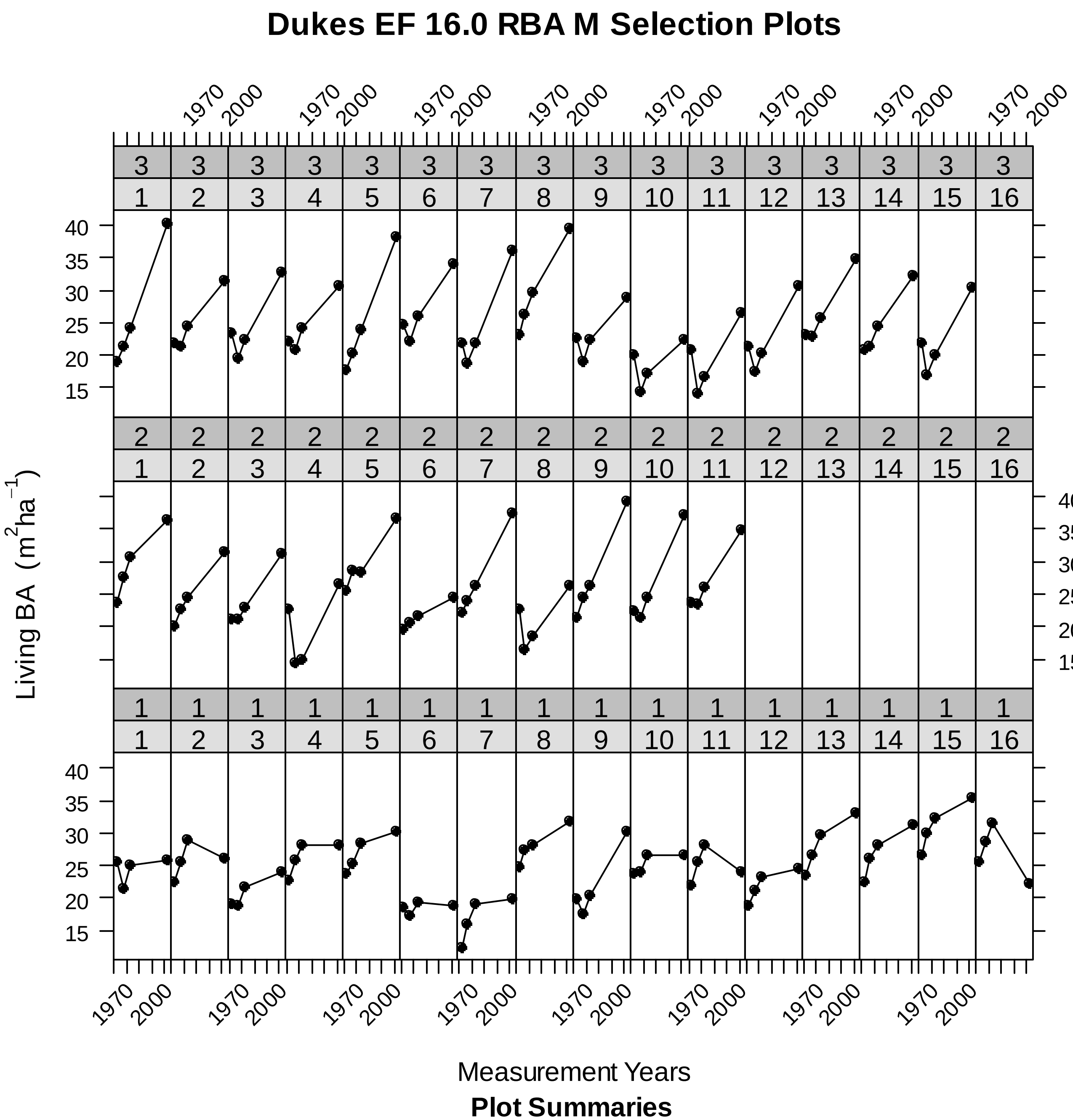


Figure A11. Live basal area (m^2 ha^{-1}) through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

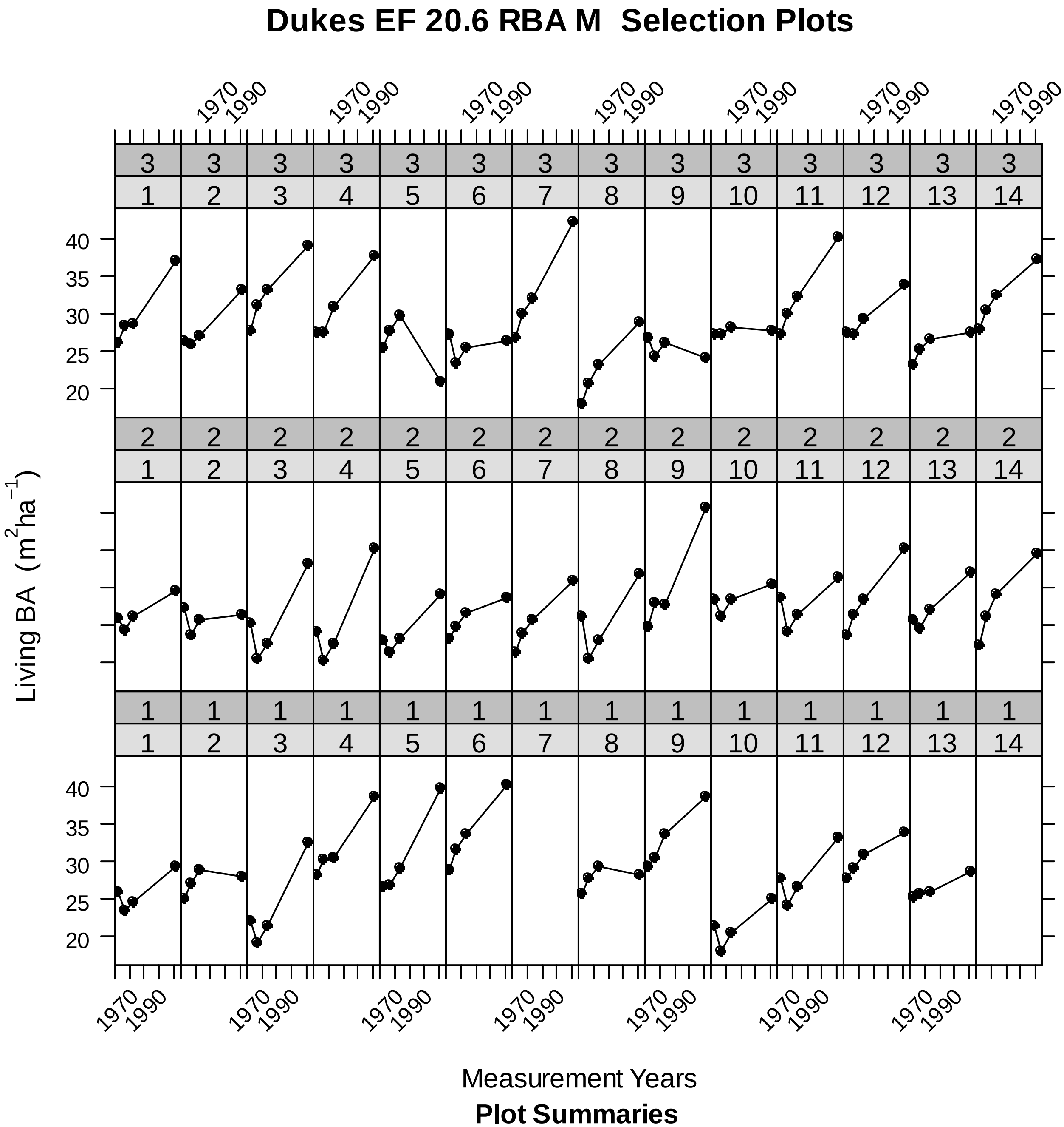


Figure A12. Live basal area (m^2 ha^{-1}) through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

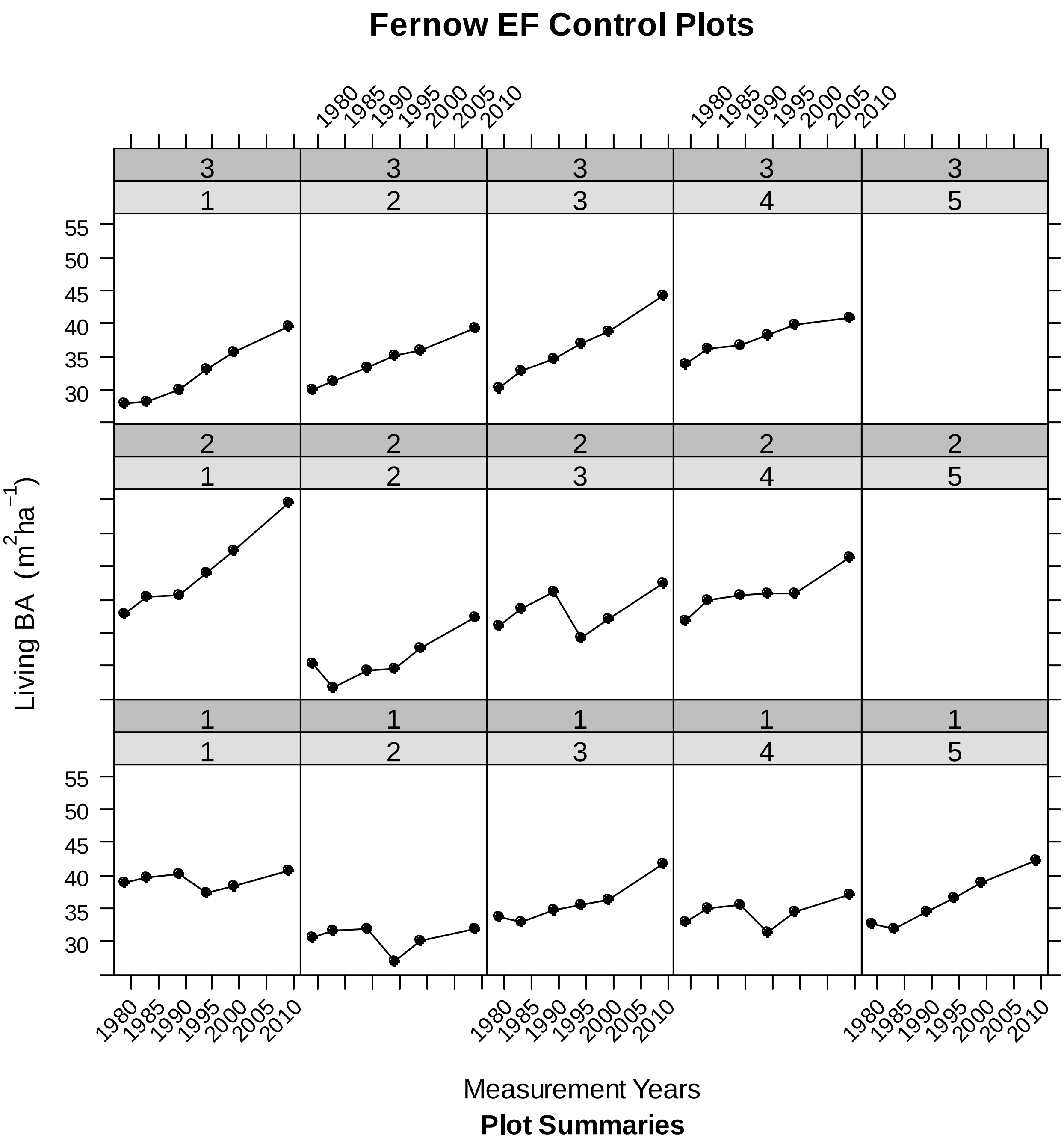


Figure A13. Live basal area (m^2 ha^{-1}) through time on the Fernow Experimental Forest (FEF) control plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

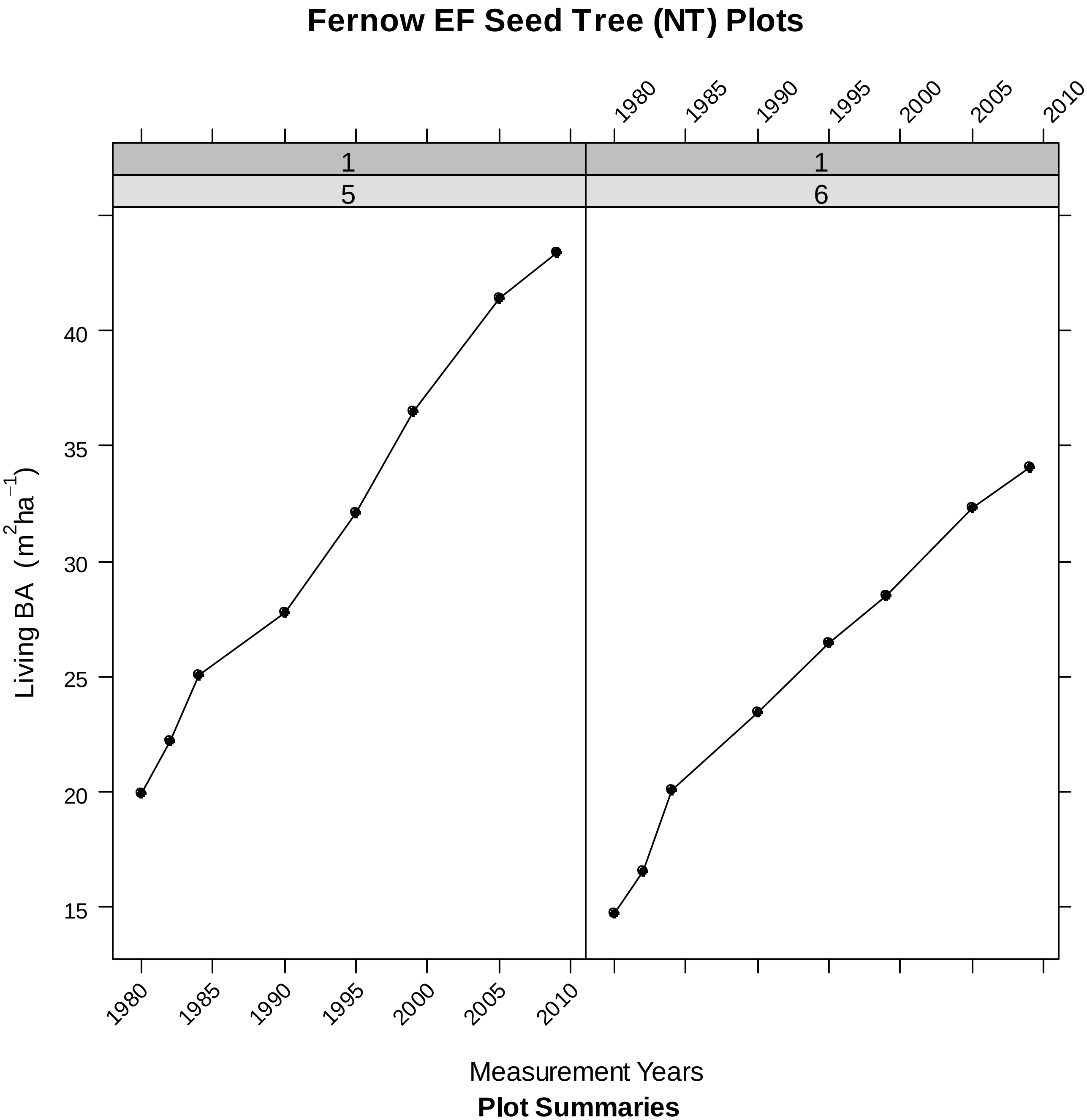


Figure A14. Live basal area (m^2 ha^{-1}) through time on the Fernow Experimental Forest (FEF) non-thinned seed tree plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

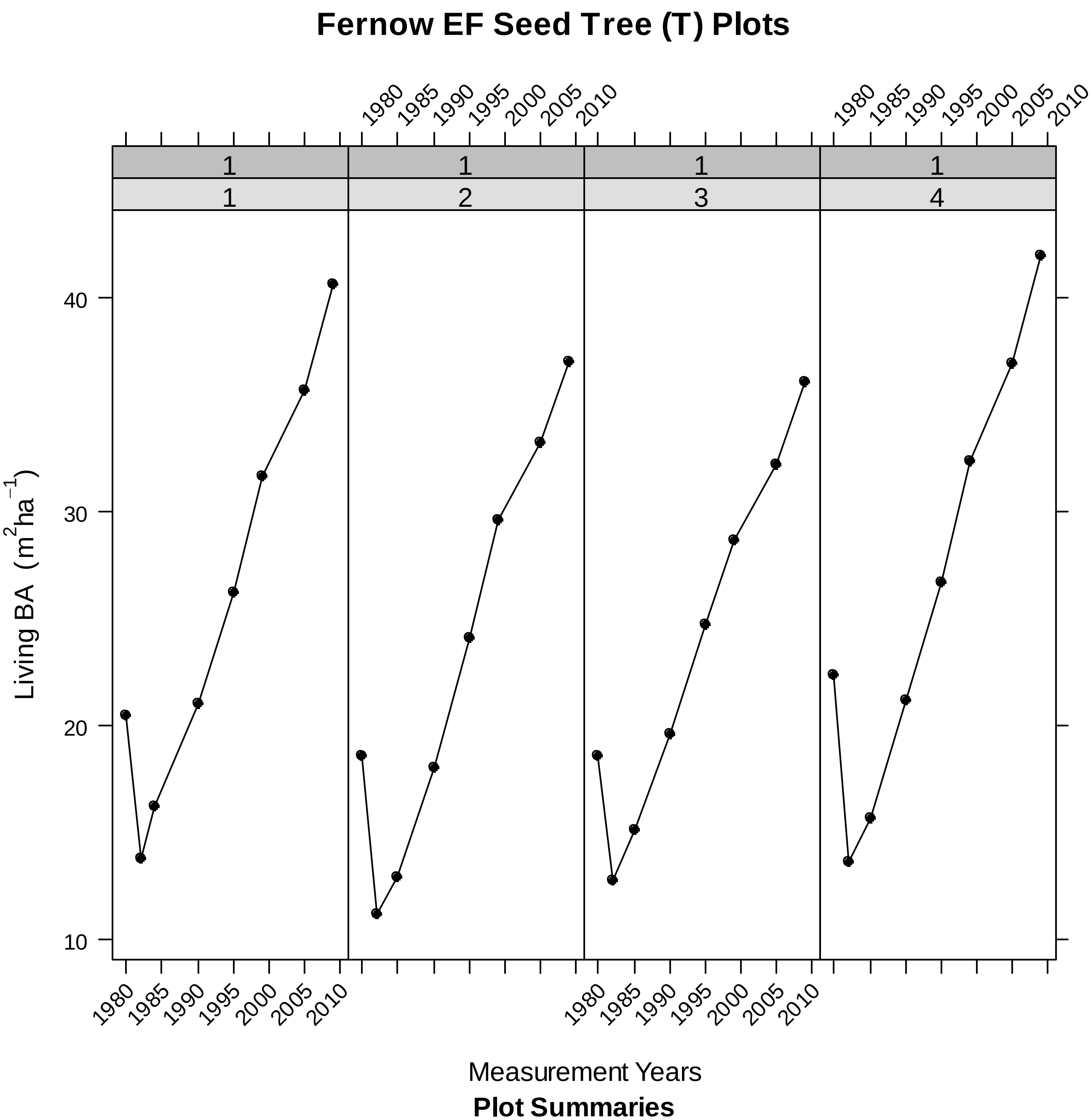


Figure A15. Live basal area (m^2 ha^{-1}) through time on the Fernow Experimental Forest (FEF) thinned seed tree plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

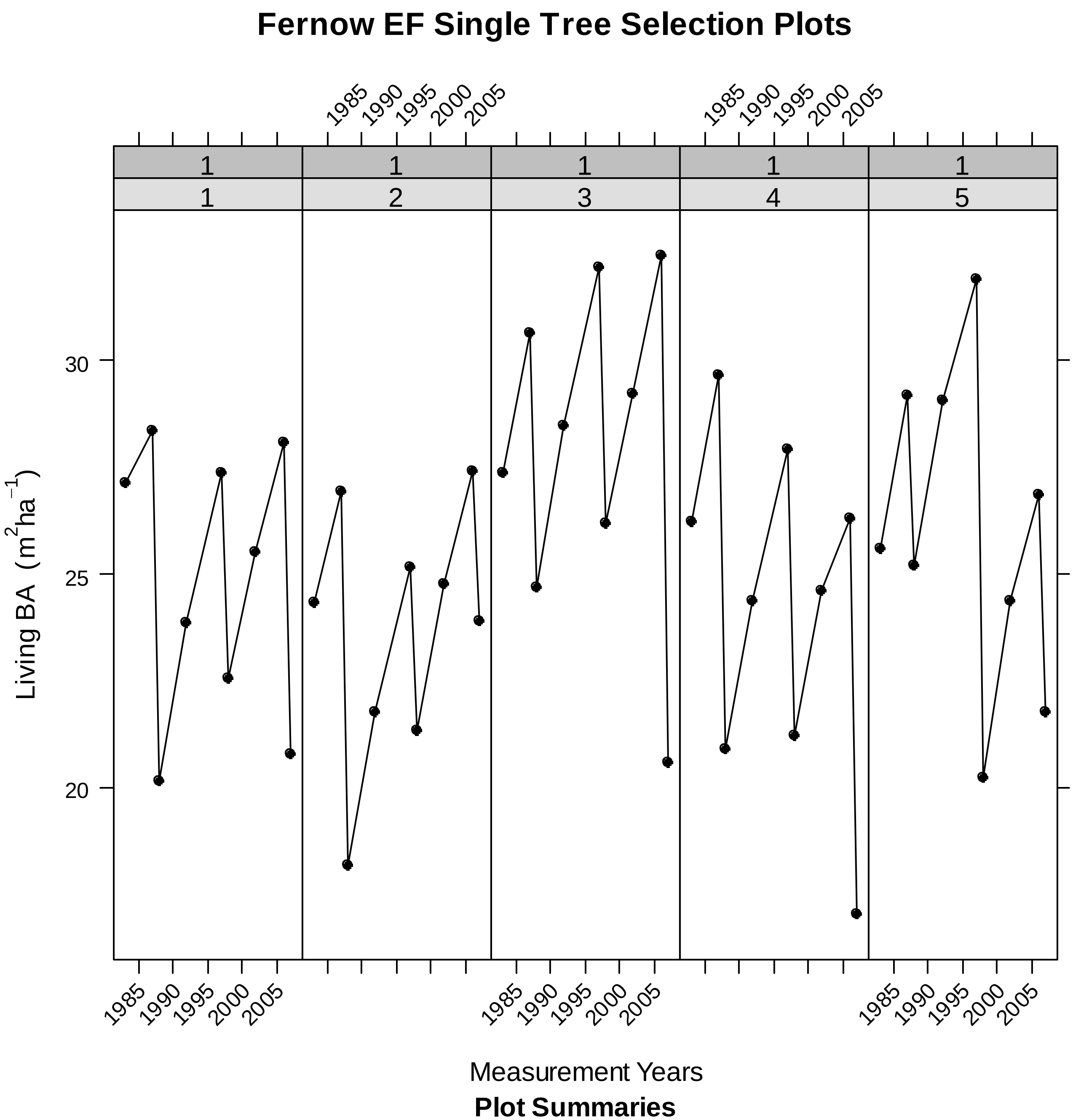


Figure A16. Live basal area (m^2 ha^{-1}) through time on the Fernow Experimental Forest (FEF) single-tree selection plots. The value in darker grey section is standardized treatment replicate (A:1), while the value is in light grey section is actual plot number.

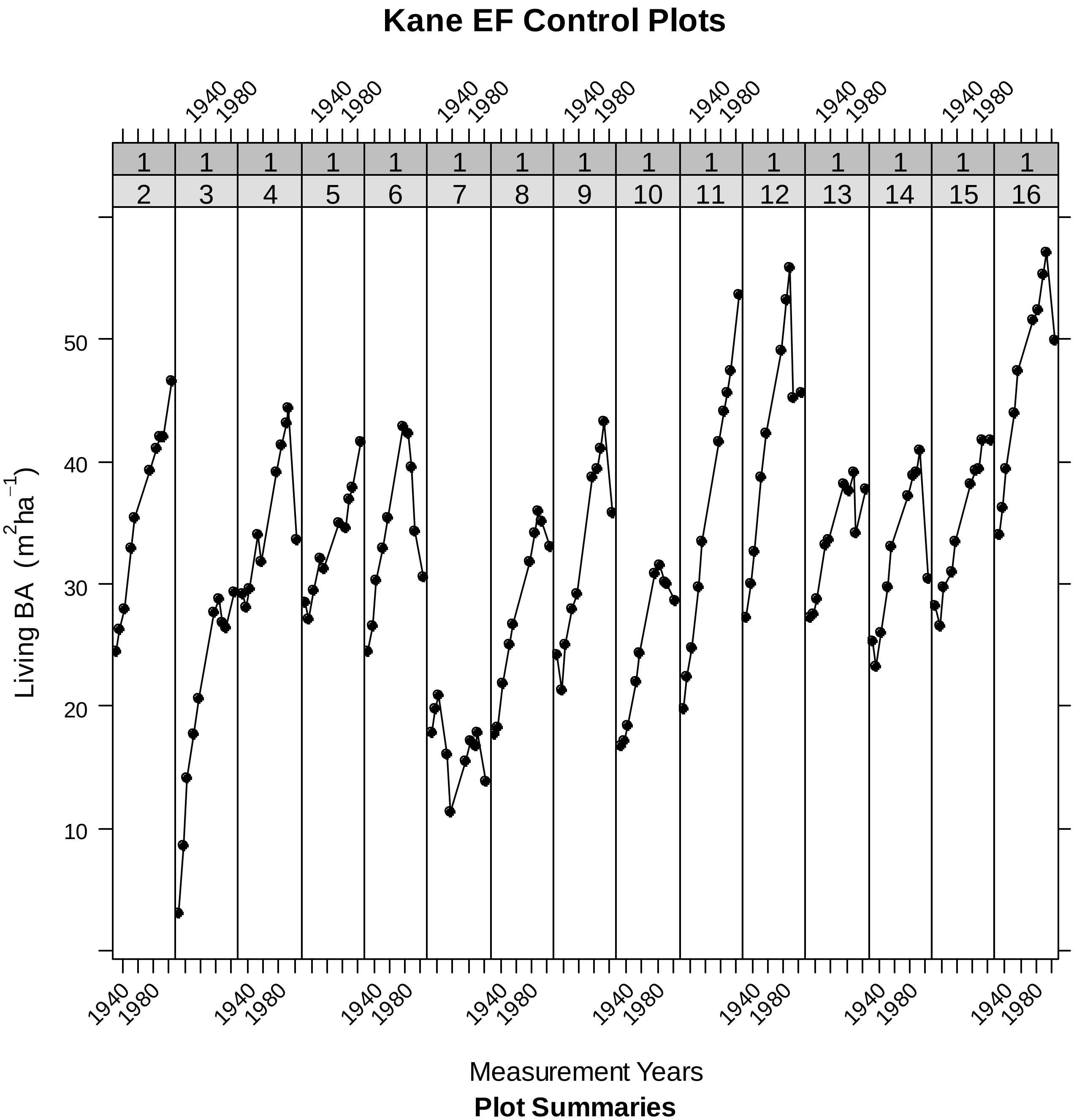


Figure A17. Live basal area (m^2 ha^{-1}) through time on the Kane Experimental Forest (KEF) control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

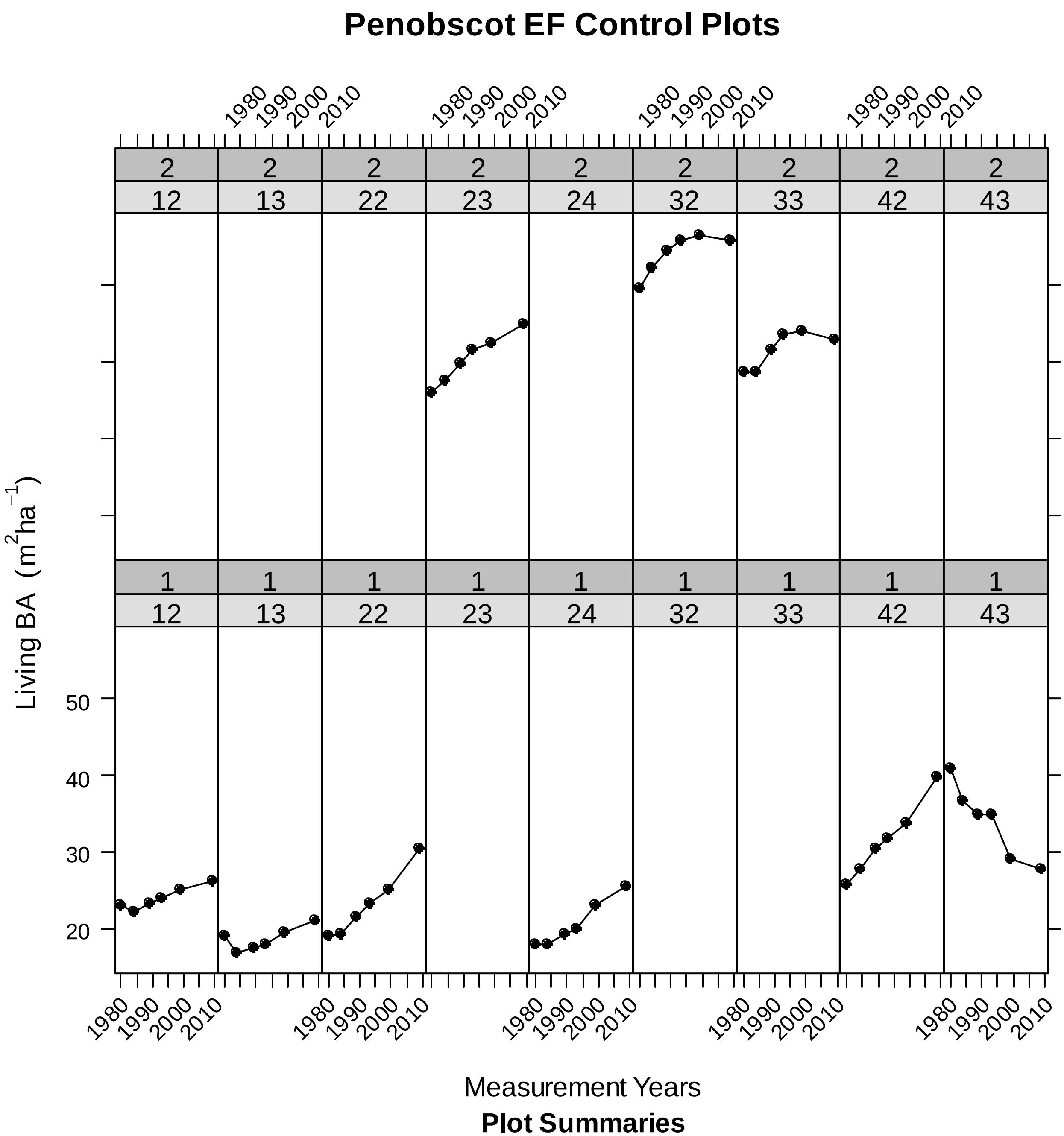


Figure A18. Live basal area (m^2 ha^{-1}) through time on the Penobscot Experimental Forest (PEF) control plots. The value in darker grey section is standardized treatment replicate (1: MU 32A, 2: MU 32B), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

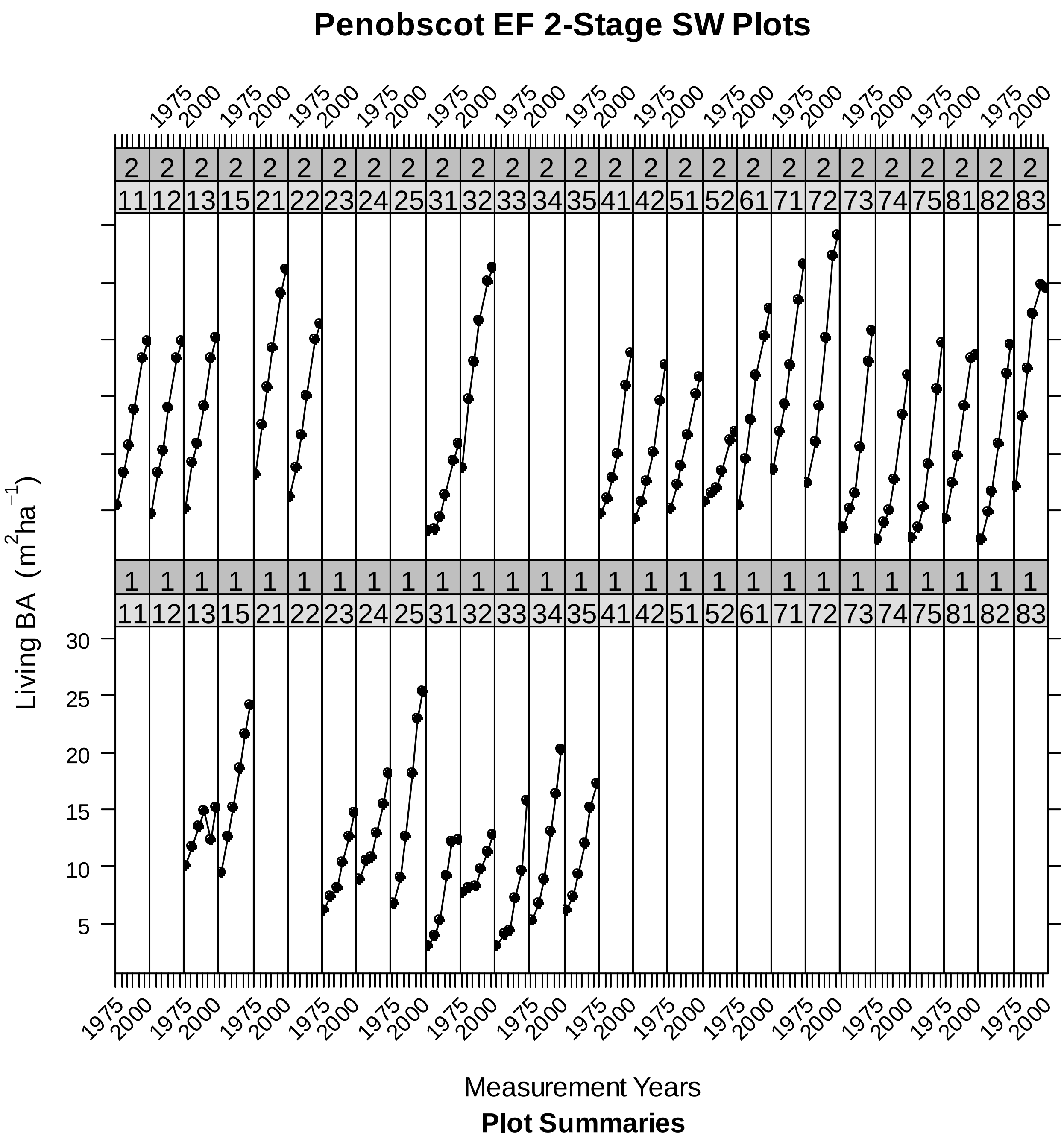


Figure A19. Live basal area (m^2 ha^{-1}) through time on the Penobscot Experimental Forest (PEF) two-stage shelterwood plots. The value in darker grey section is standardized treatment replicate (1: MU 21, 2: MU 30), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

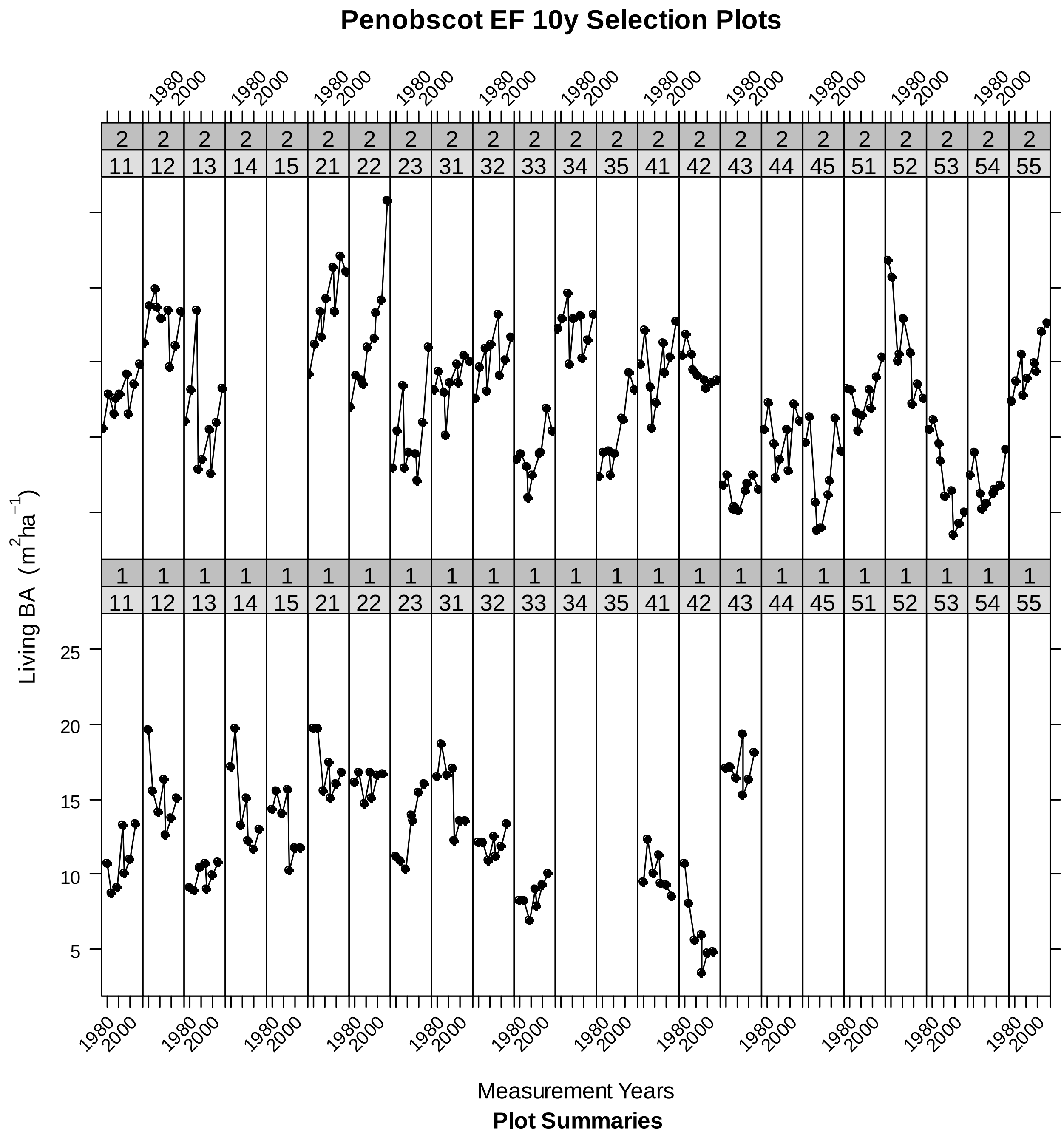


Figure A20. Live basal area (m^2 ha^{-1}) through time on the Penobscot Experimental Forest (PEF) ten-year selection plots. The value in darker grey section is standardized treatment replicate (1:MU 12, 2: MU 20), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

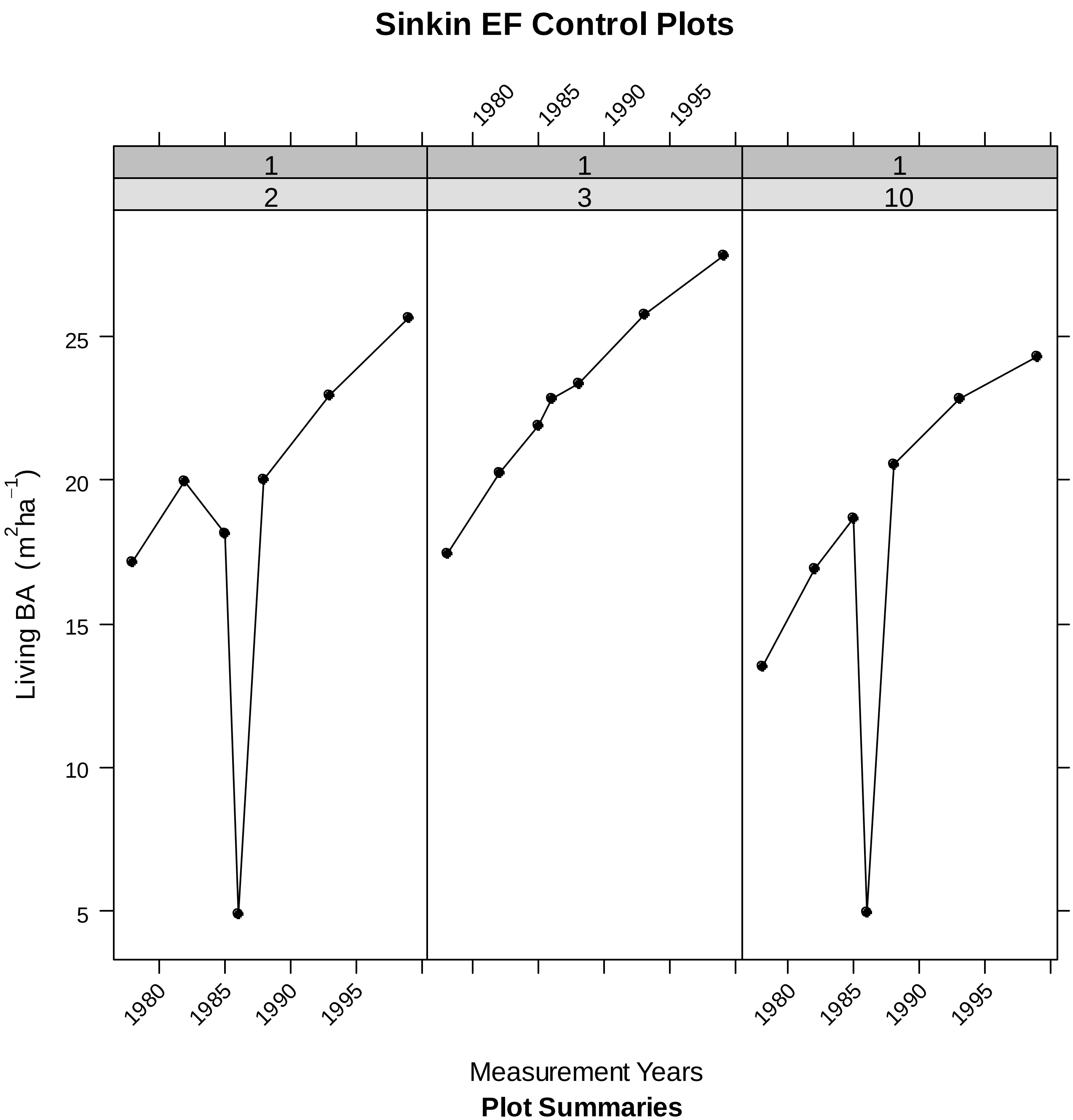


Figure A21. Live basal area (m^2 ha^{-1}) through time on the Sinkin Experimental Forest (SEF) spatial distribution control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

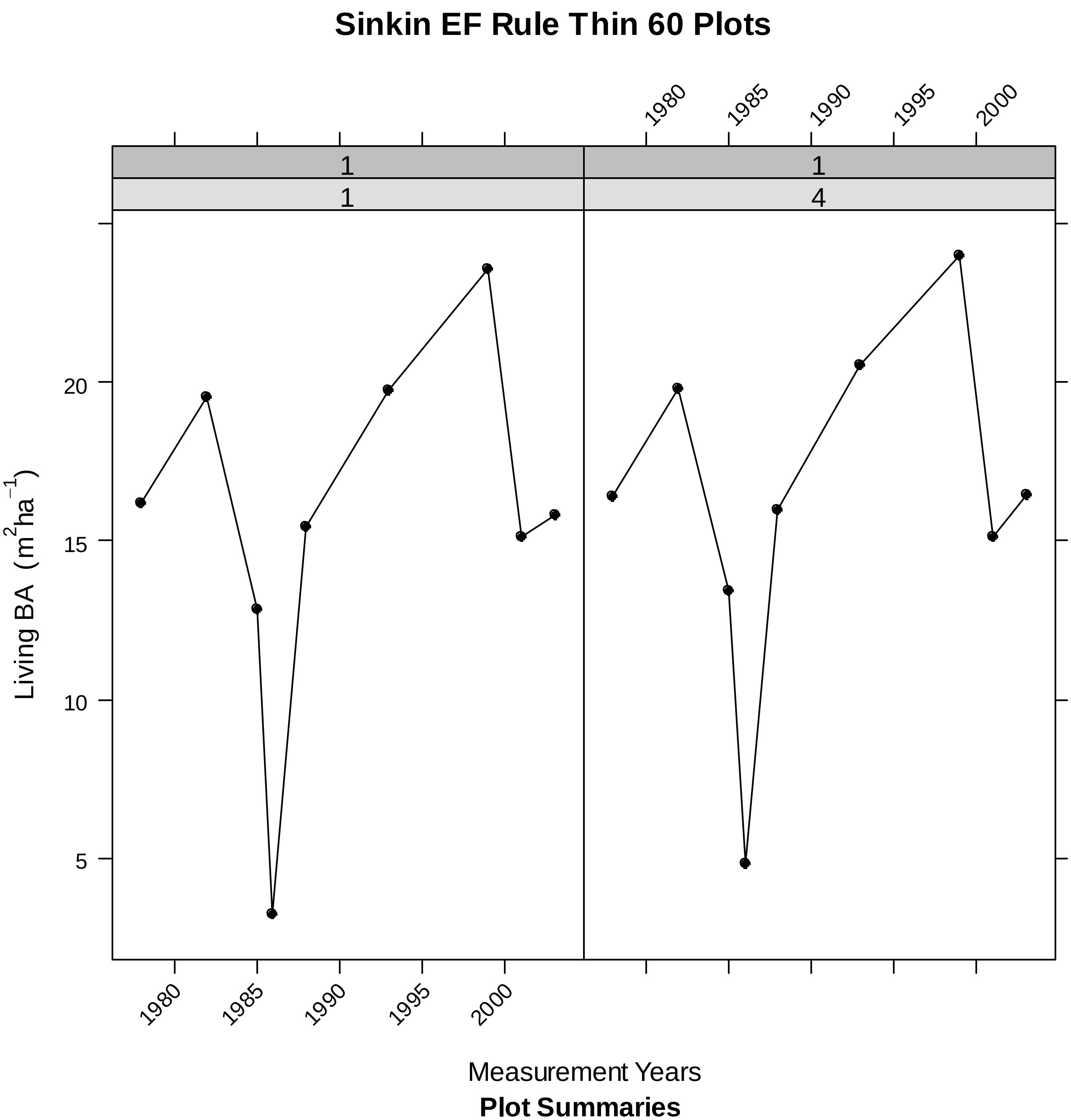


Figure A22. Live basal area (m^2 ha^{-1}) through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (60%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

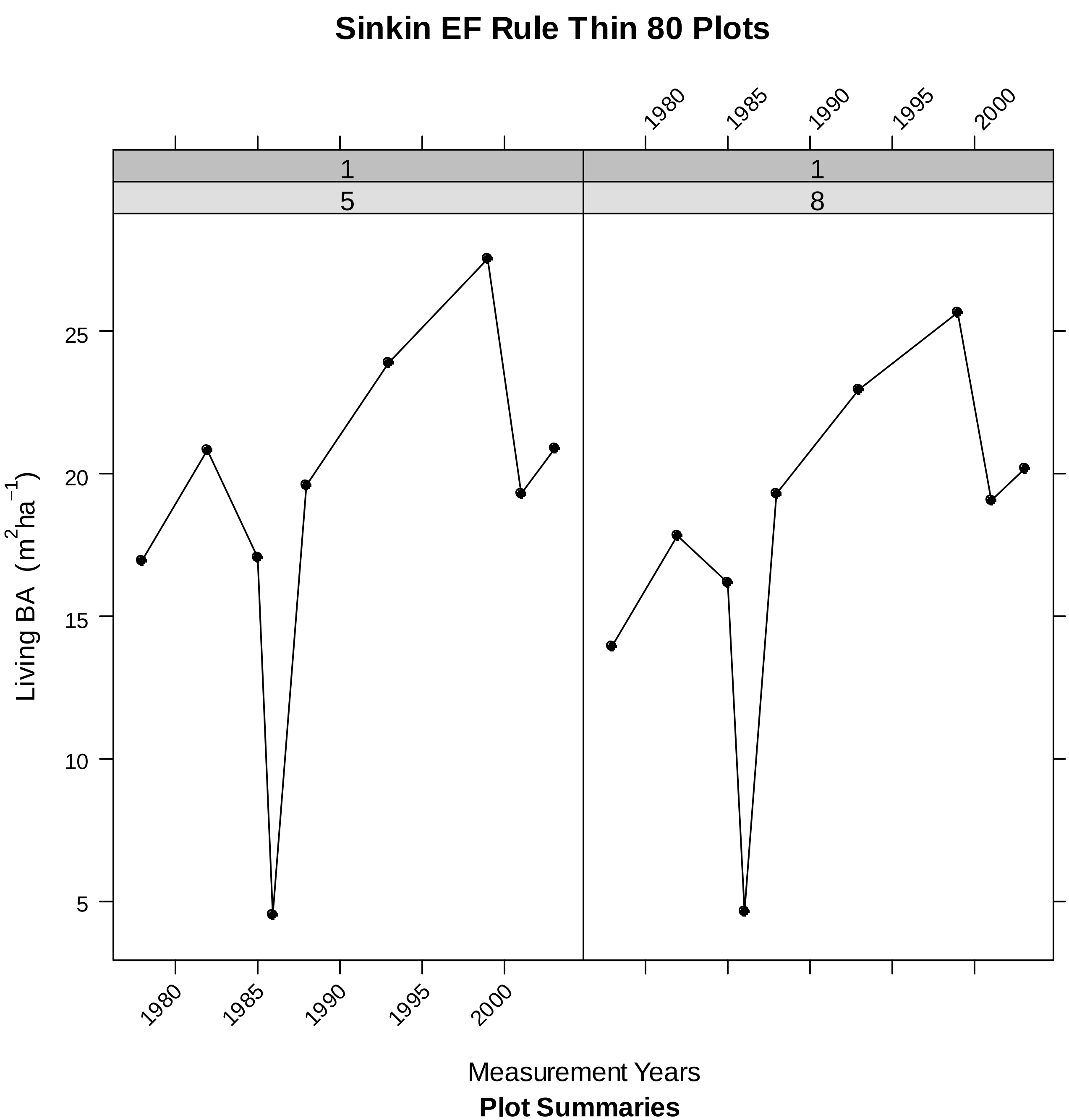


Figure A23. Live basal area (m^2 ha^{-1}) through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (80%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

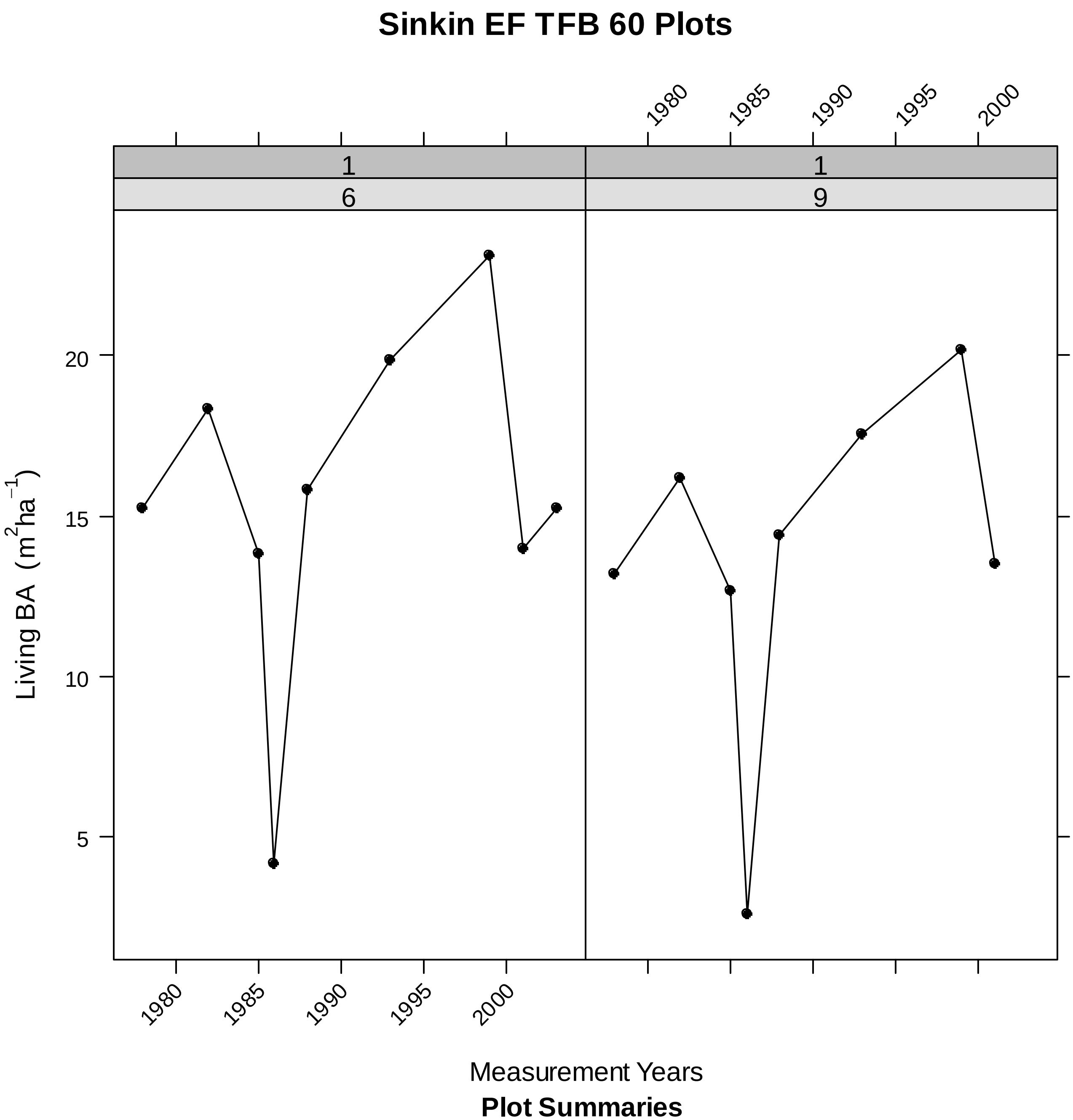


Figure A24. Live basal area (m^2 ha^{-1}) through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (60%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

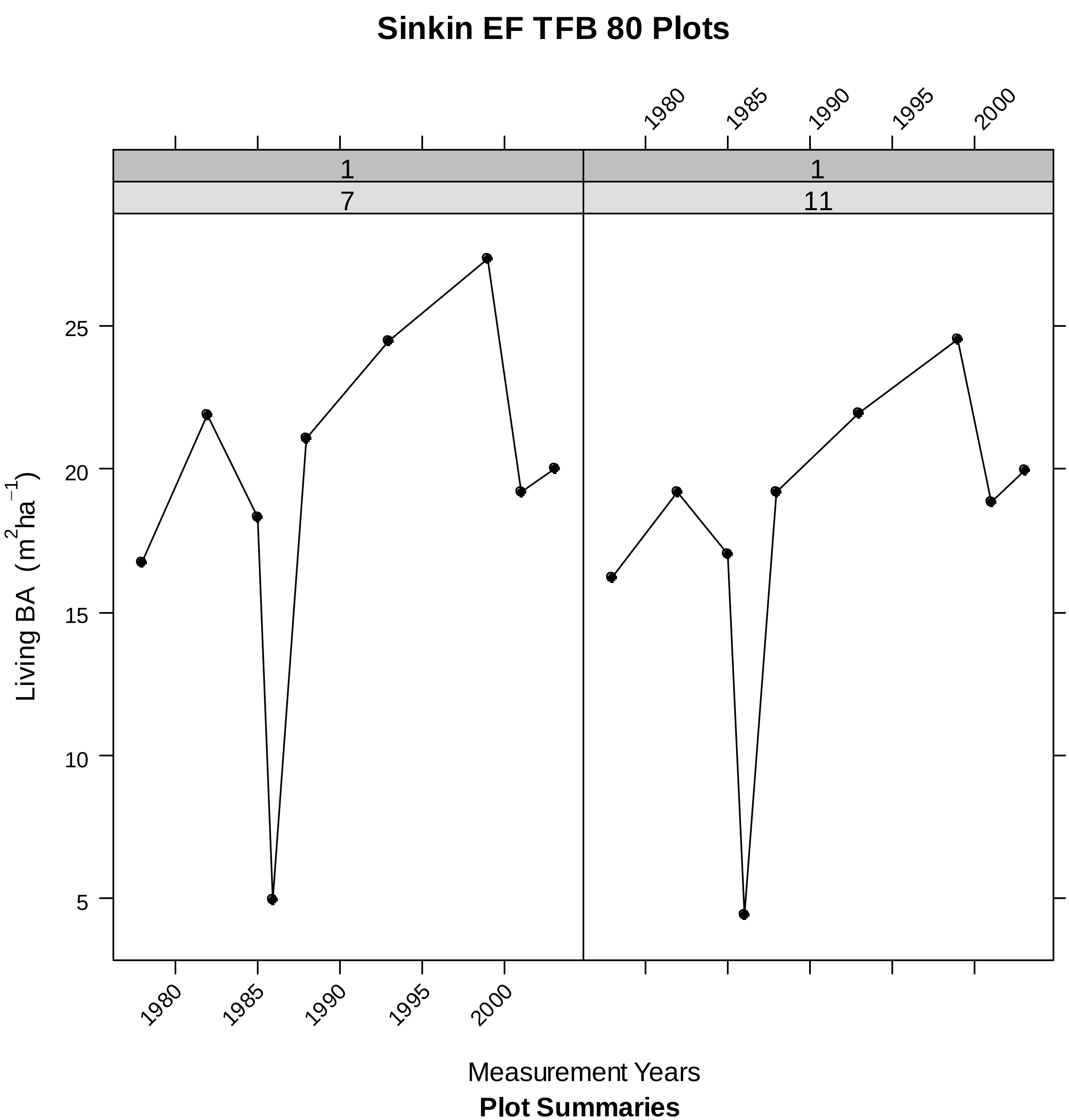


Figure A25. Live basal area (m^2 ha^{-1}) through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (80%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

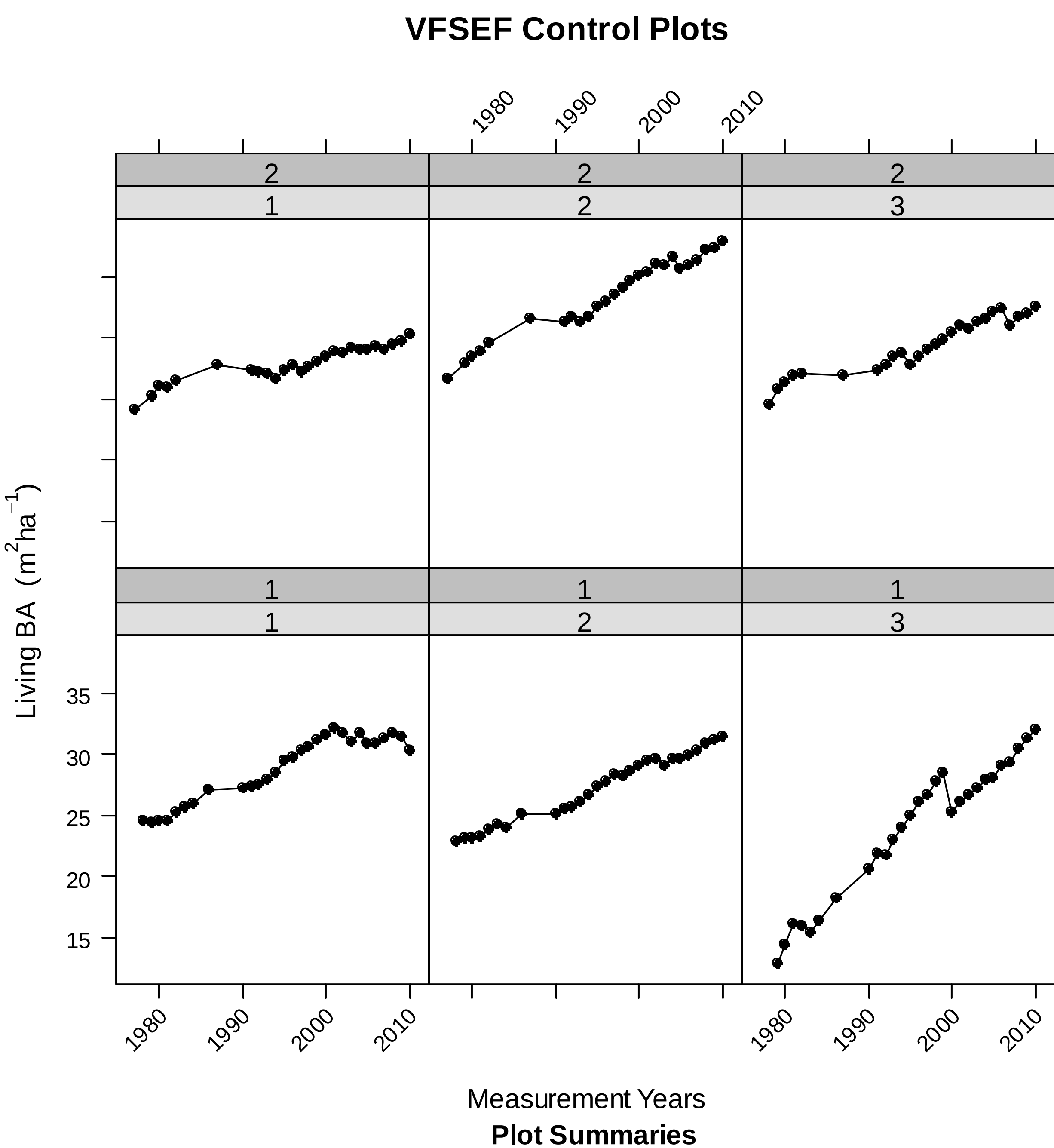


Figure A26. Live basal area (m^2 ha^{-1}) through time on the Vinton-Furnace State Experimental Forest (VFSEF) control plots. The value in darker grey section is standardized treatment replicate (1-2, Study 25, 27 respectively) , while the value is in light grey section is actual plot number.

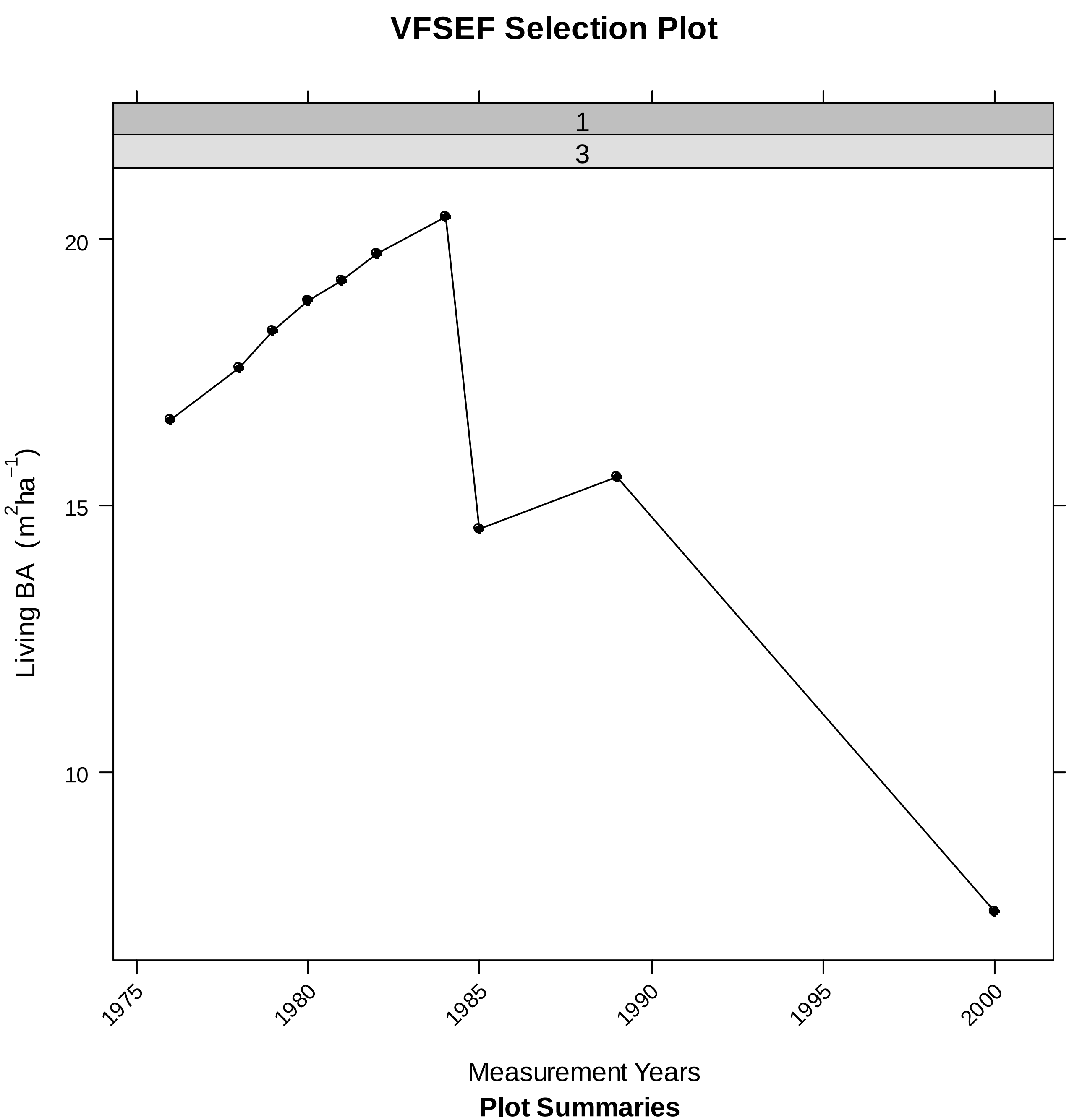


Figure A27. Live basal area ($m^2\ ha^{-1}$) through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

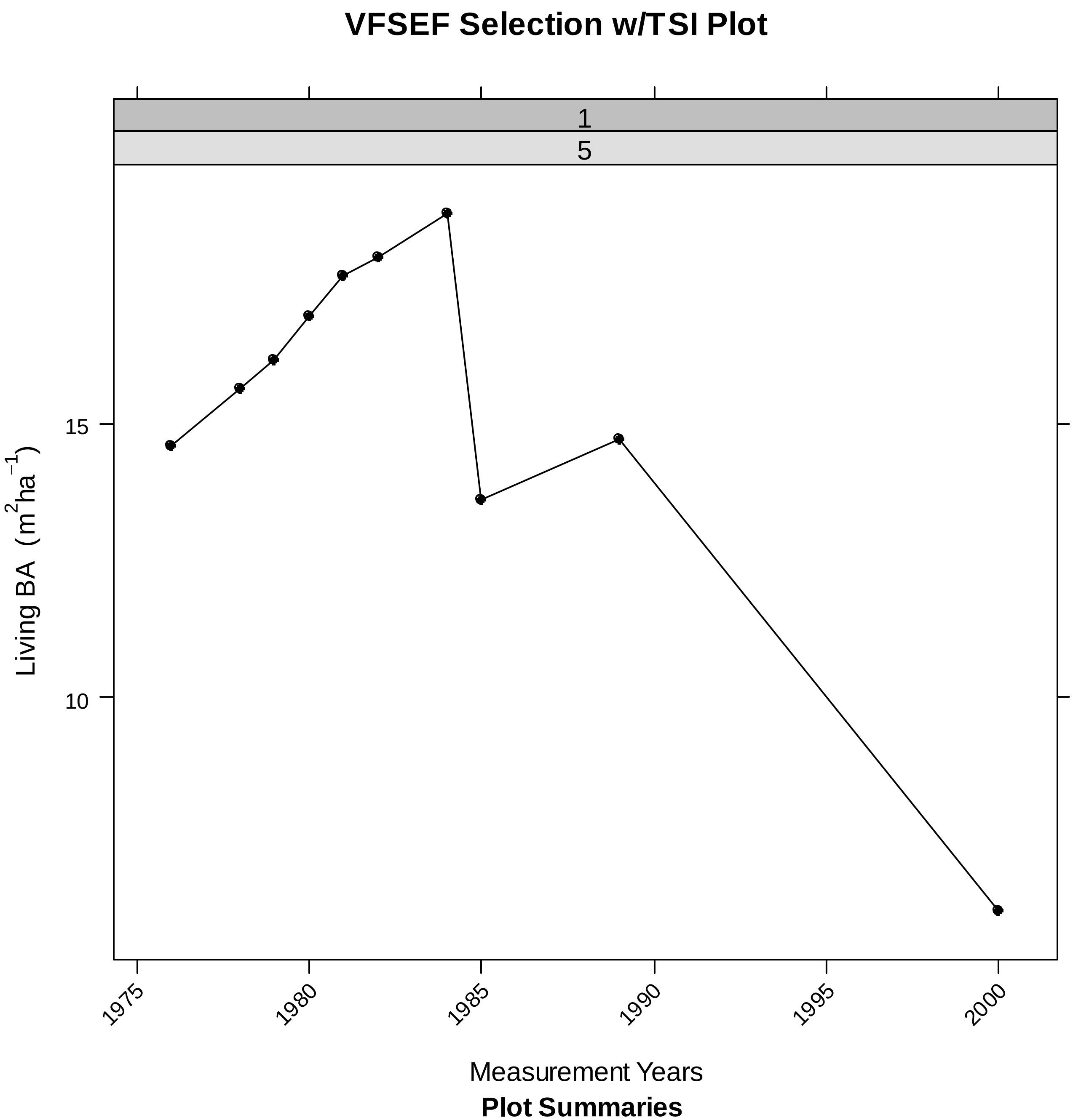


Figure A28. Live basal area (m^2 ha^{-1}) through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection with timber stand improvement plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

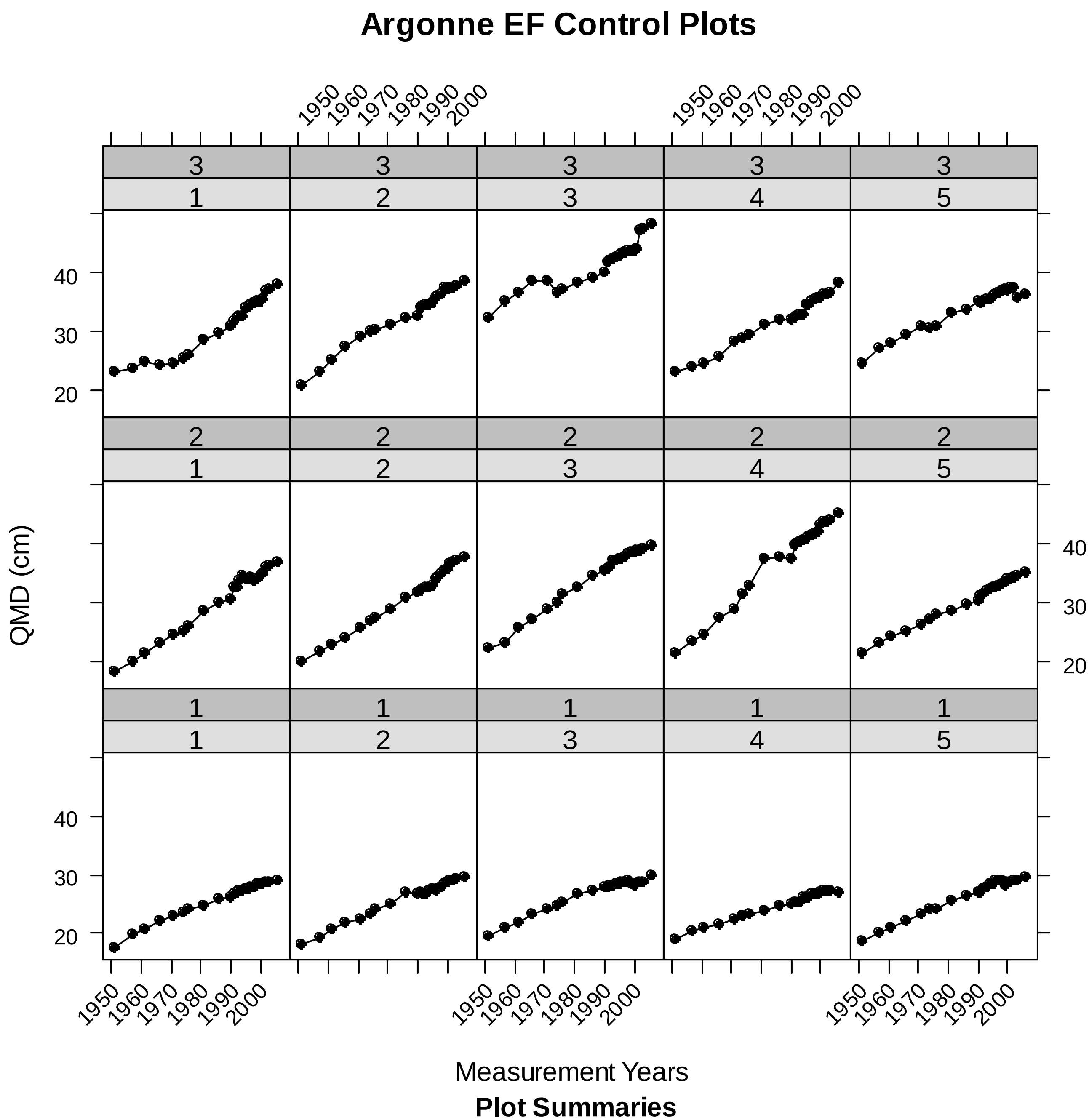


Figure A29. Quadratic mean diameter (cm) through time on the Argonne Experimental Forest (AEF) control plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

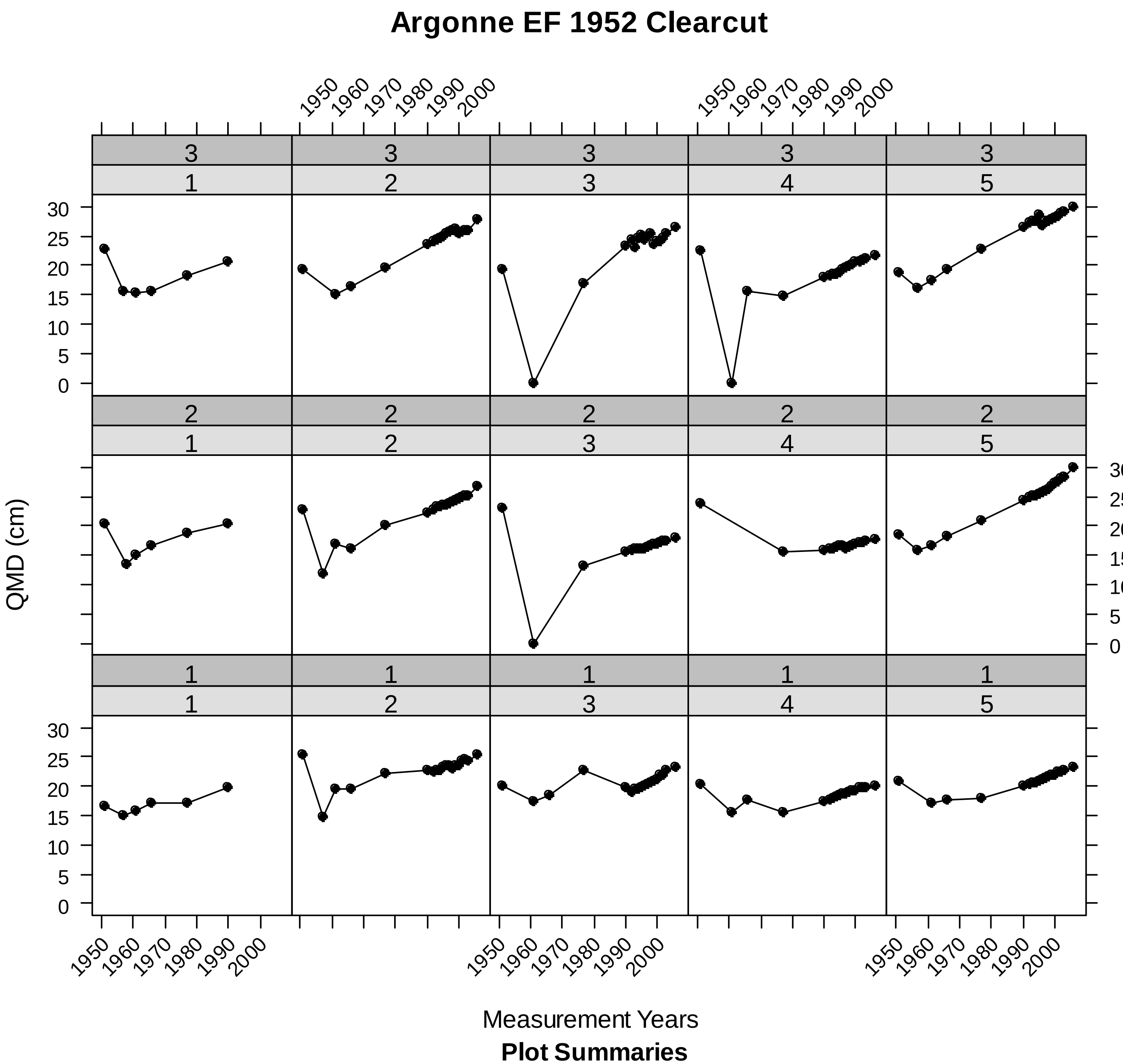


Figure A30. Quadratic mean diameter (cm) through time on the Argonne Experimental Forest (AEF) clearcut (ca. 1951) plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

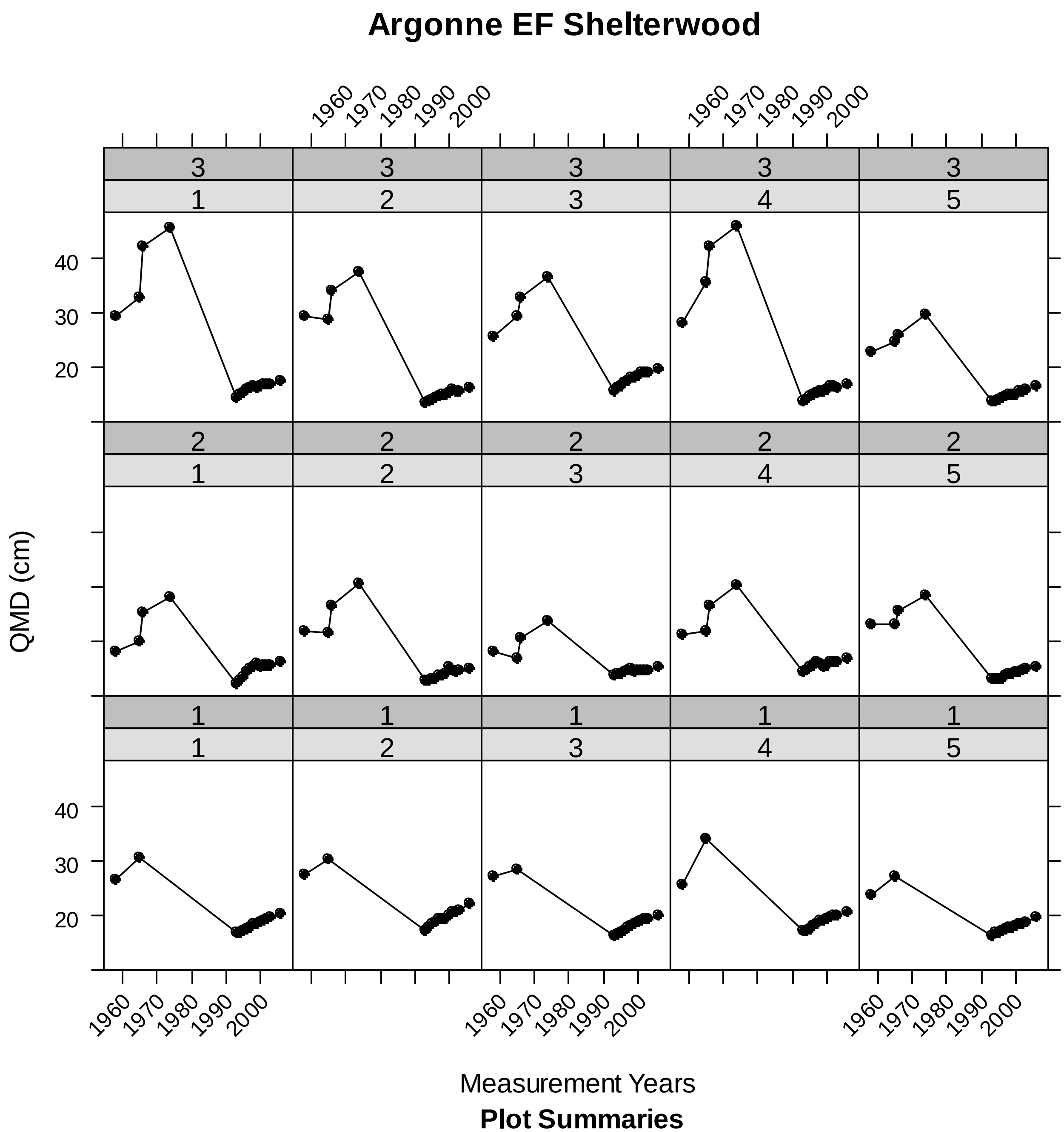


Figure A31. Quadratic mean diameter (cm) through time on the Argonne Experimental Forest (AEF) two-stage shelterwood plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

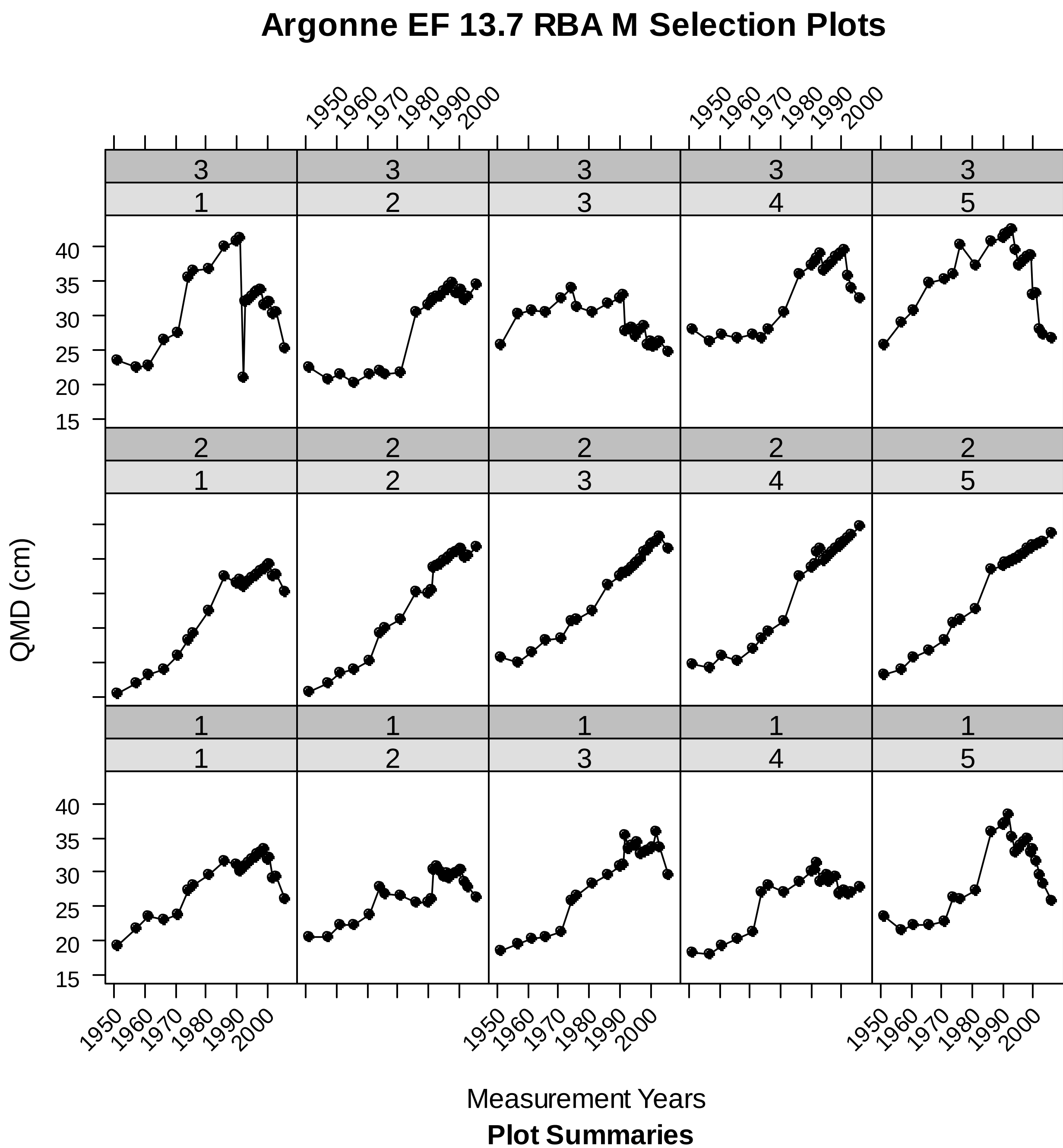


Figure A32. Quadratic mean diameter (cm) through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

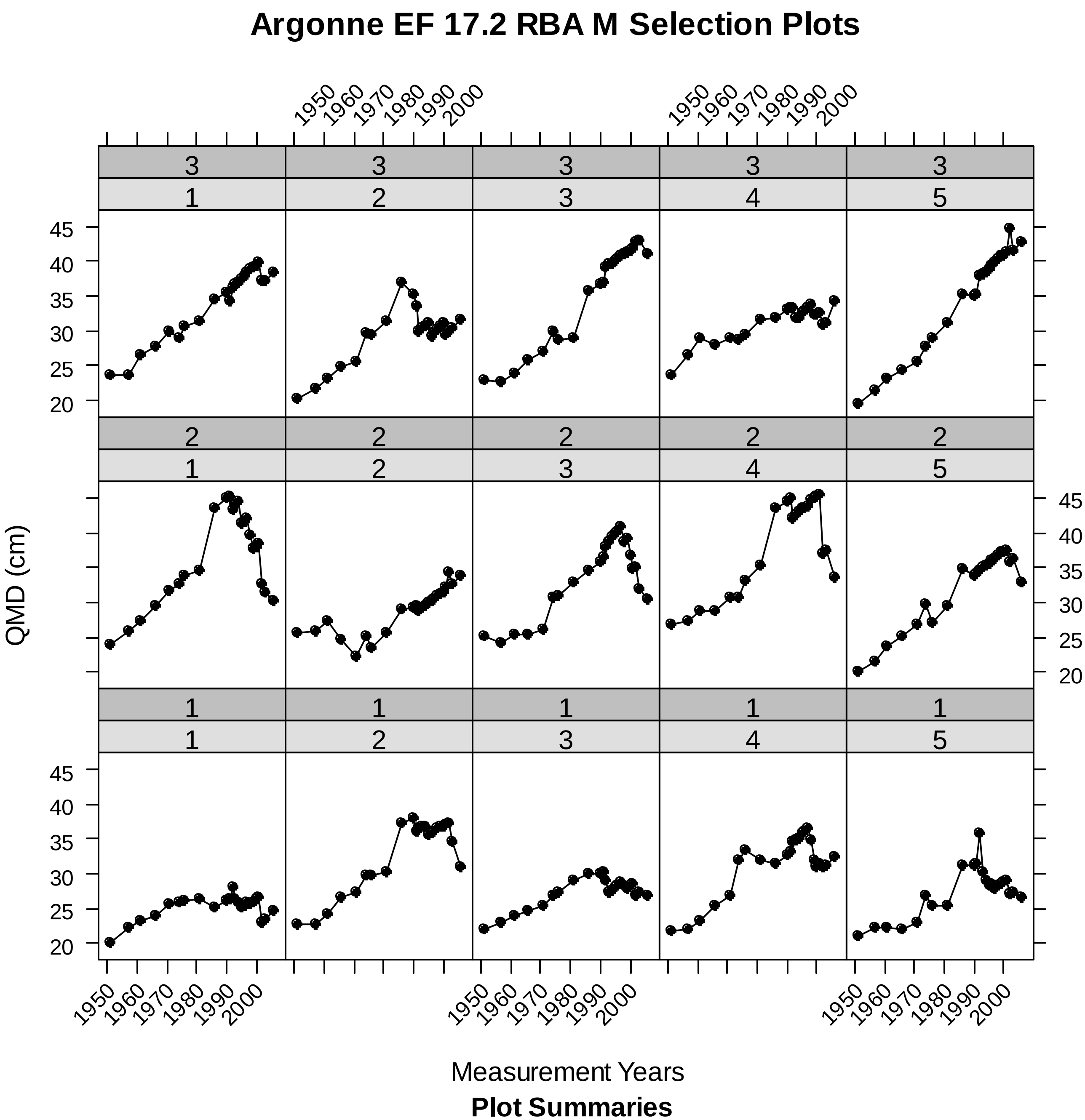


Figure A33. Quadratic mean diameter (cm) through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

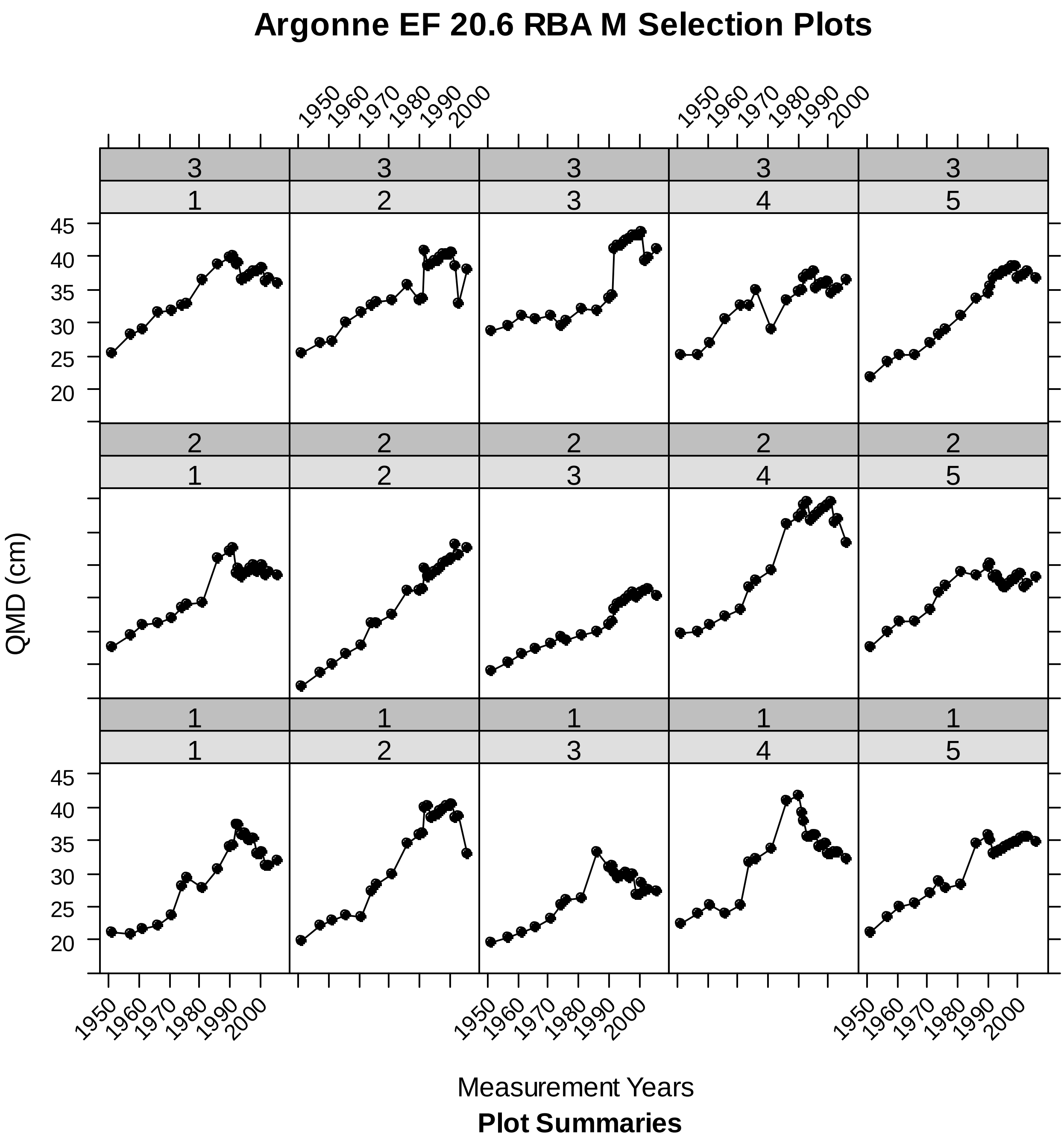


Figure A34. Quadratic mean diameter (cm) through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

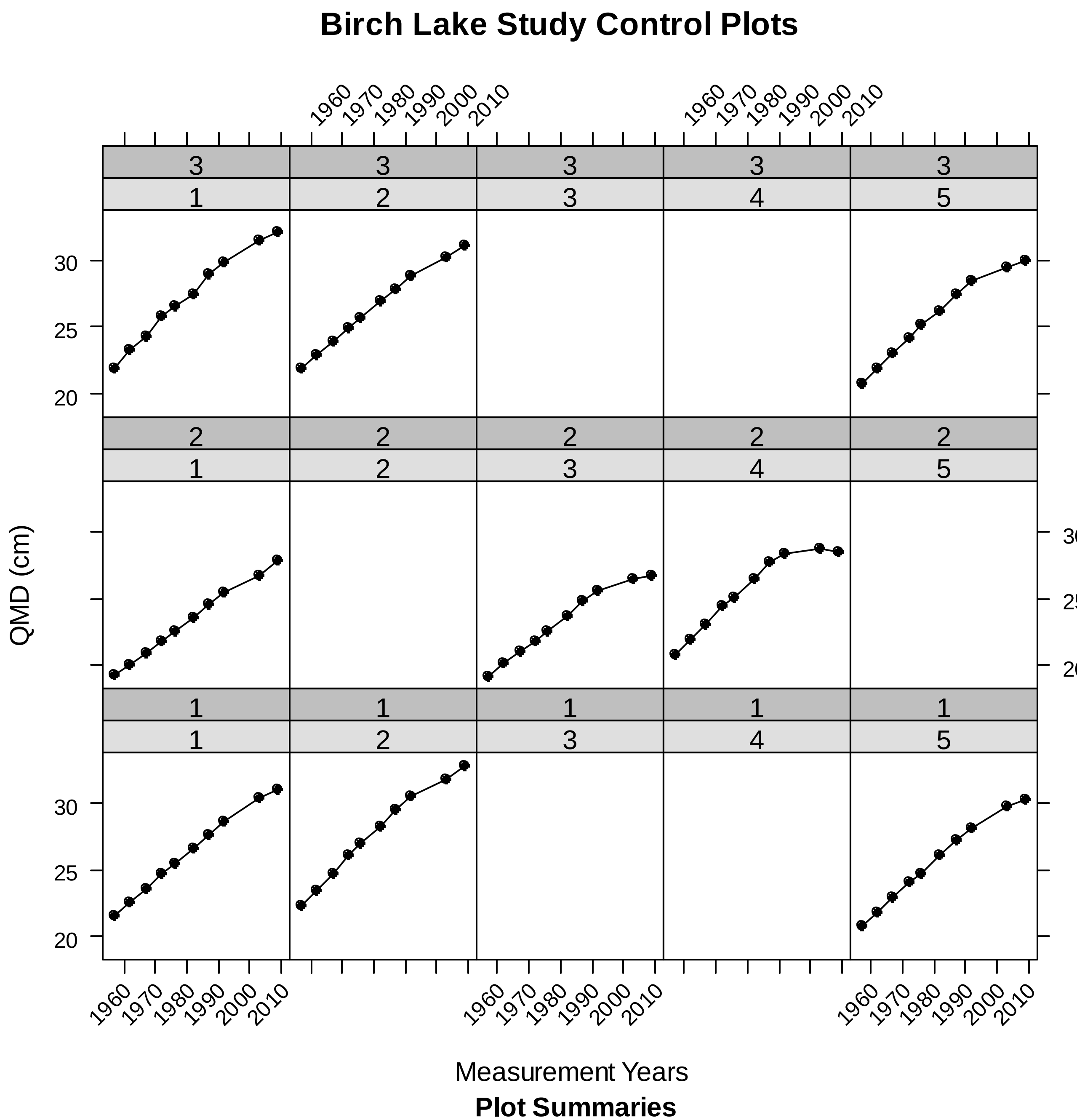


Figure A35. Quadratic mean diameter (cm) through time on the Birch Lake Study (BLS) control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is standardized plot number. Standardized replicates 1-3 are BLS blocks 5,9,16 respectively while standardized plots1-5 are Center, East, North East, Southwest, and West BLS plots respectively.

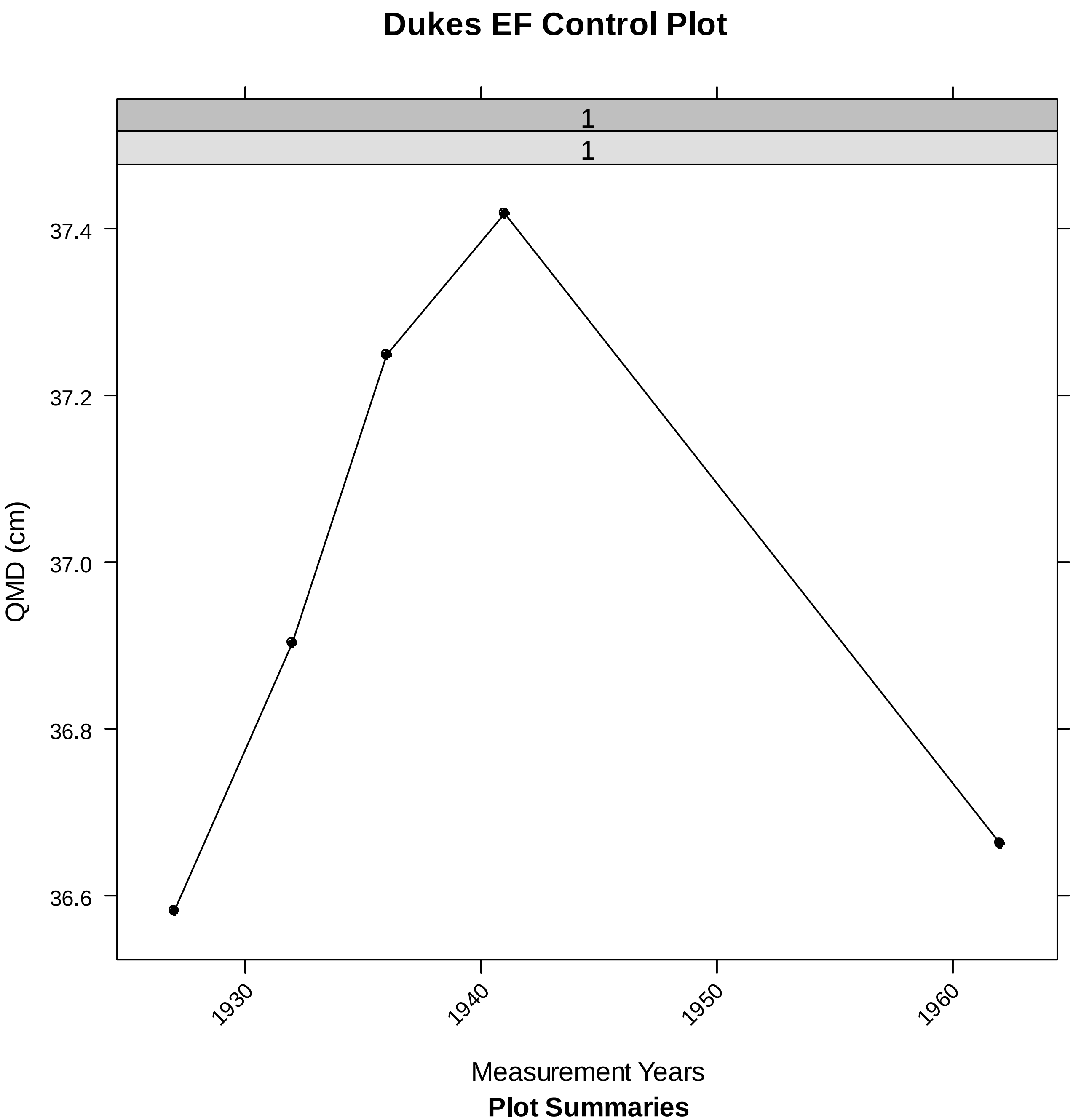


Figure A8. Quadratic mean diameter (cm) through time on the Dukes Experimental Forest (DEF) control plot. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

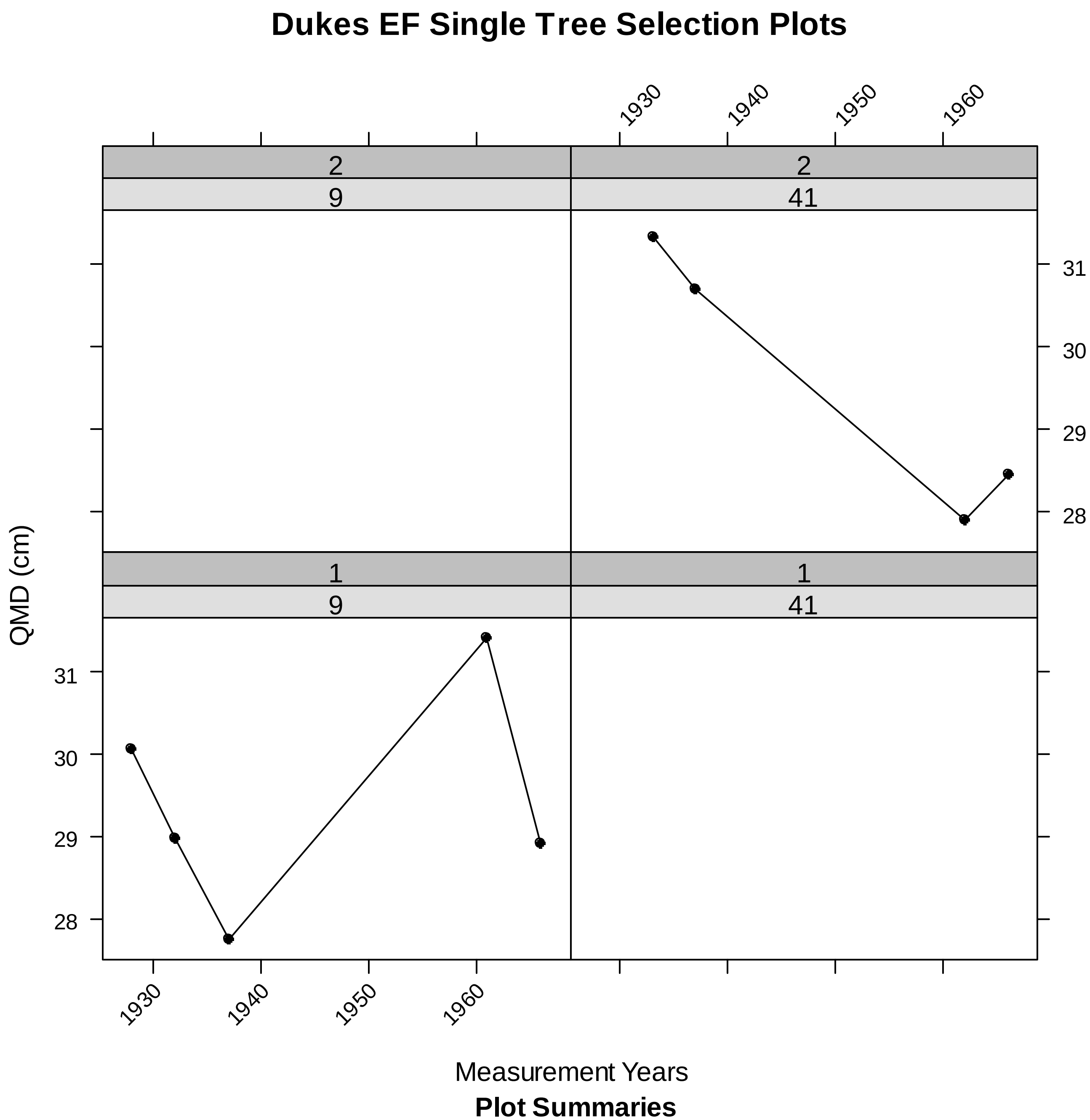


Figure A37. Quadratic mean diameter (cm) through time on the Dukes Experimental Forest (DEF) single tree selection plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

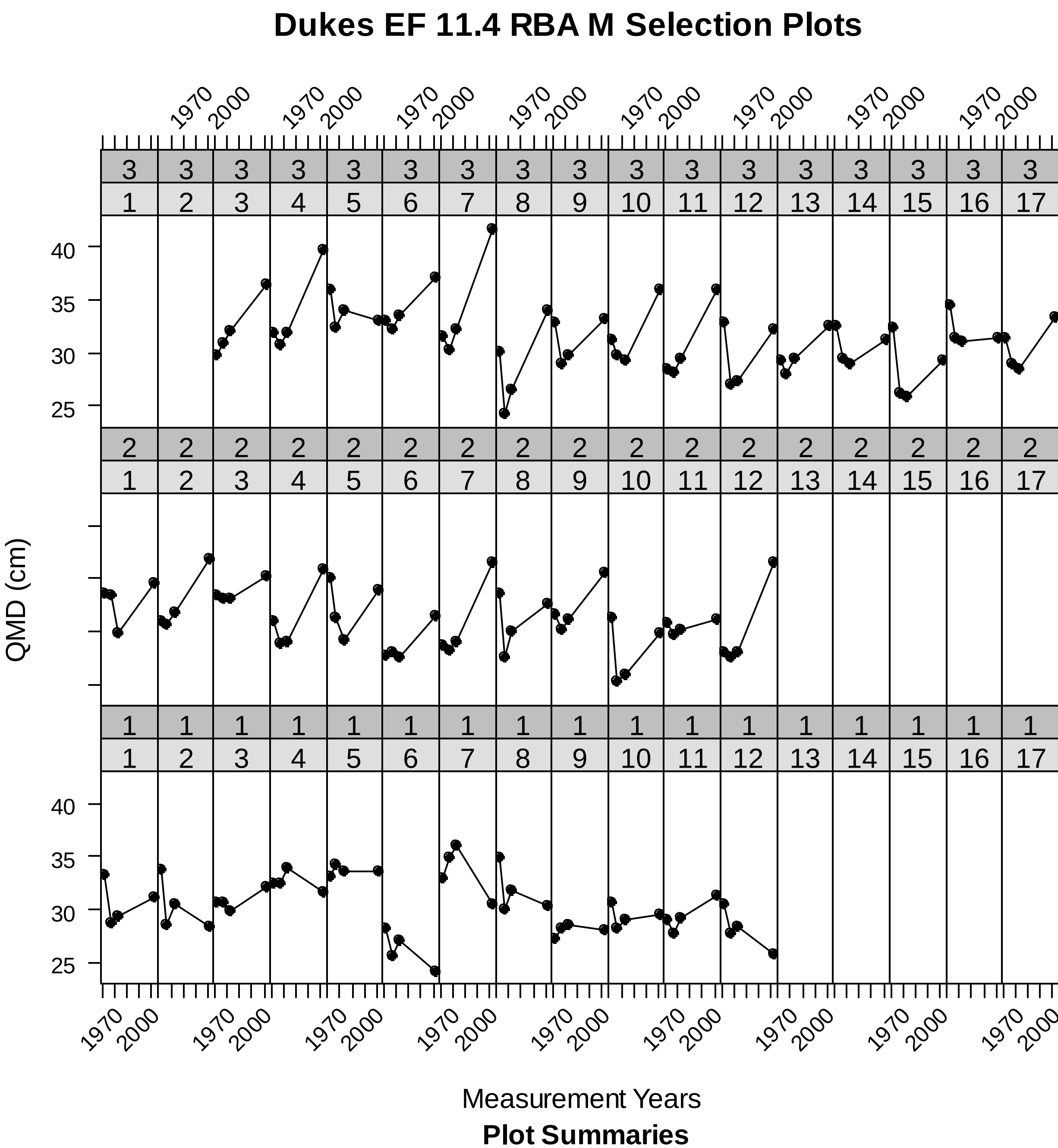


Figure A38. Quadratic mean diameter (cm) through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

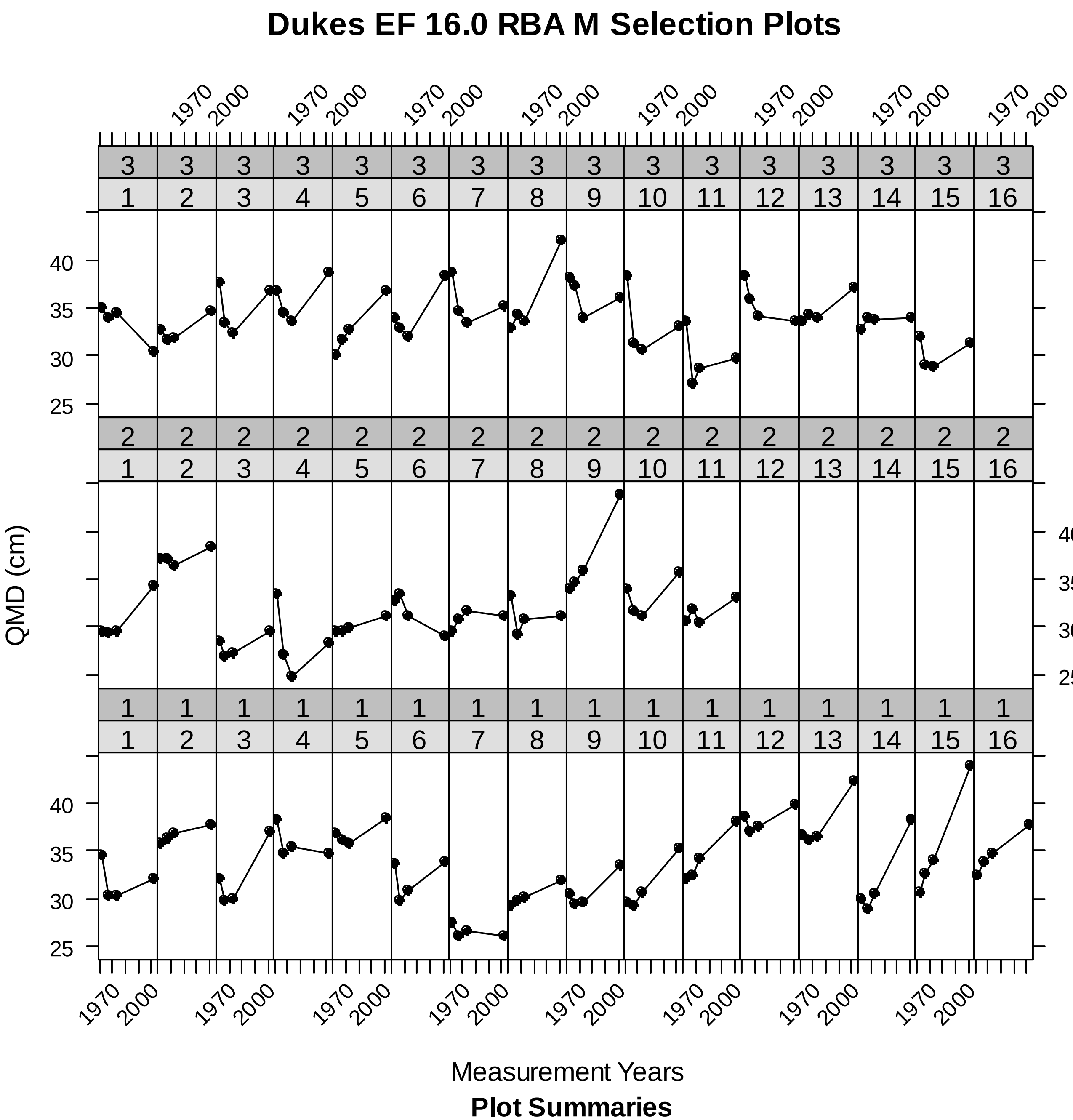


Figure A39. Quadratic mean diameter (cm) through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

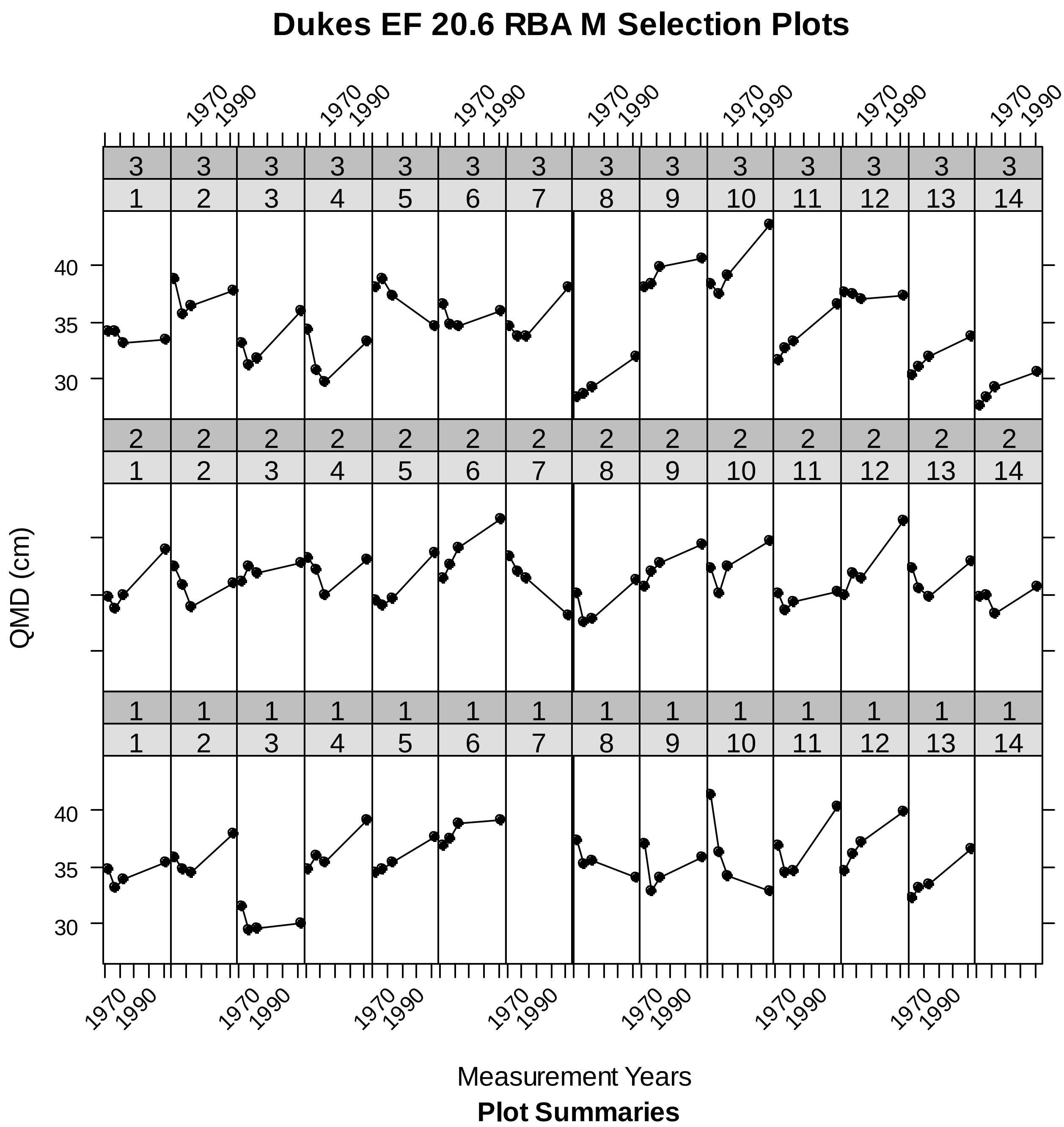


Figure A40. Quadratic mean diameter (cm) through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

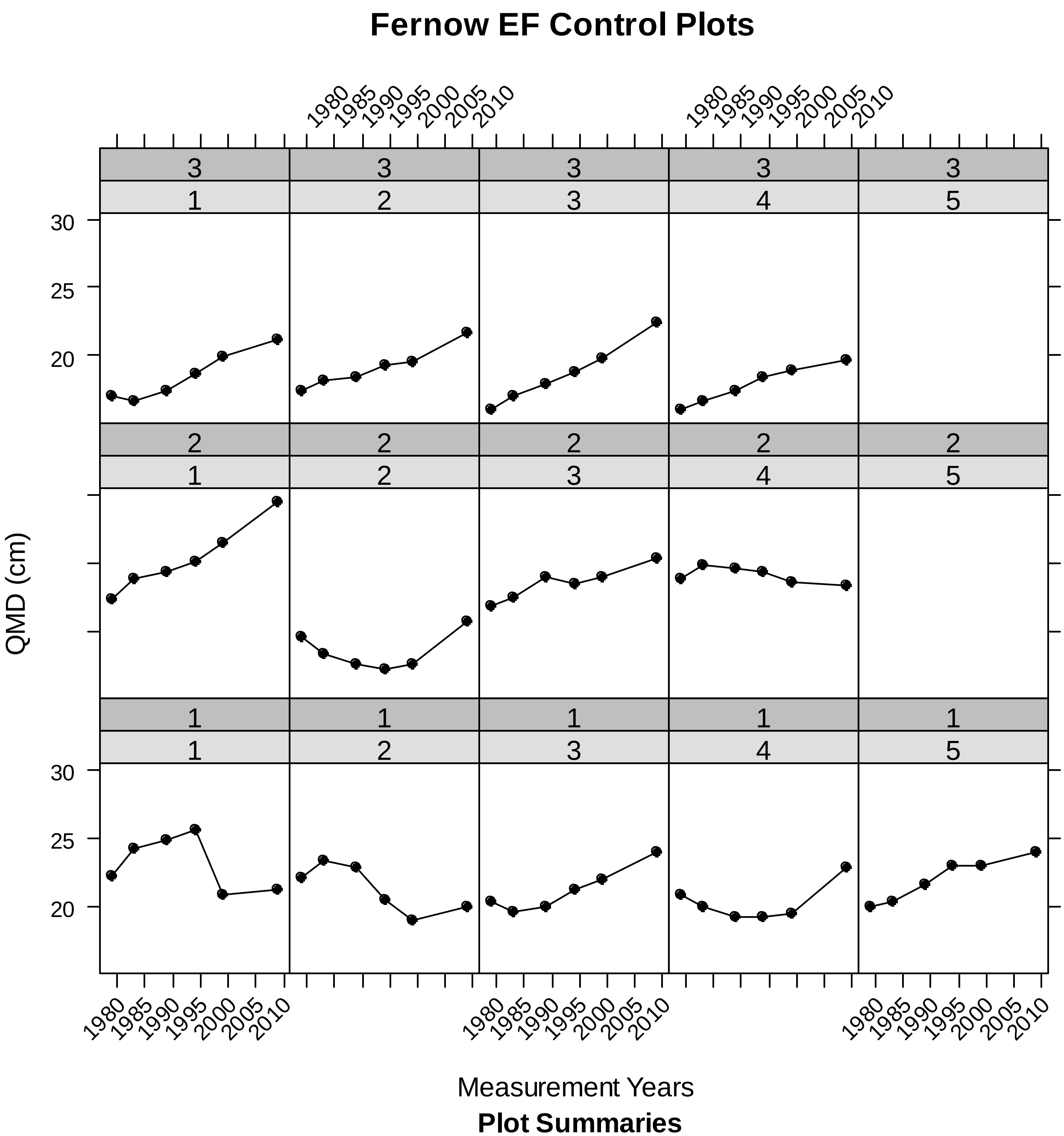


Figure A41. Quadratic mean diameter (cm) through time on the Fernow Experimental Forest (FEF) control plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

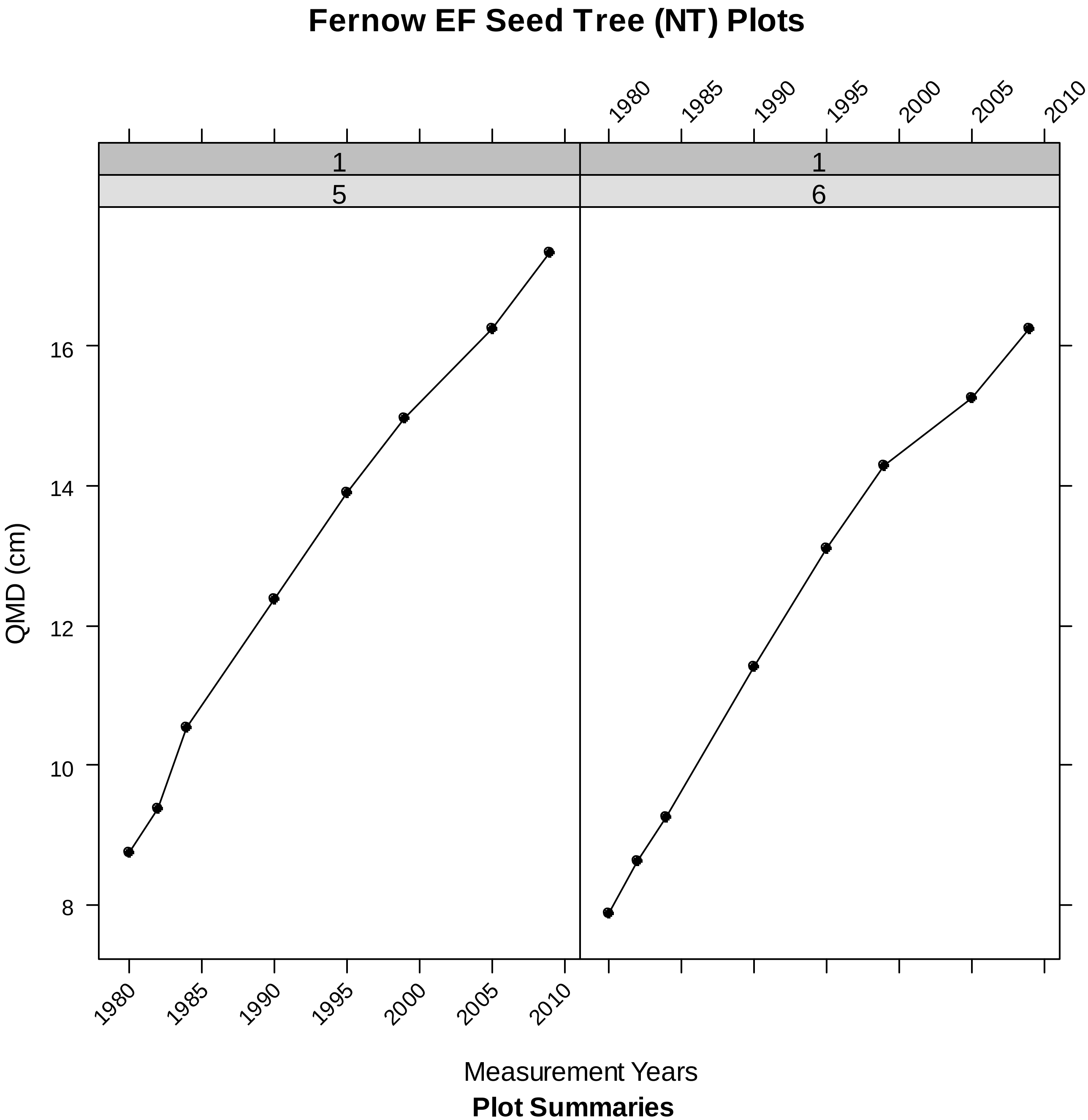


Figure A42. Quadratic mean diameter (cm) through time on the Fernow Experimental Forest (FEF) non-thinned seed tree plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

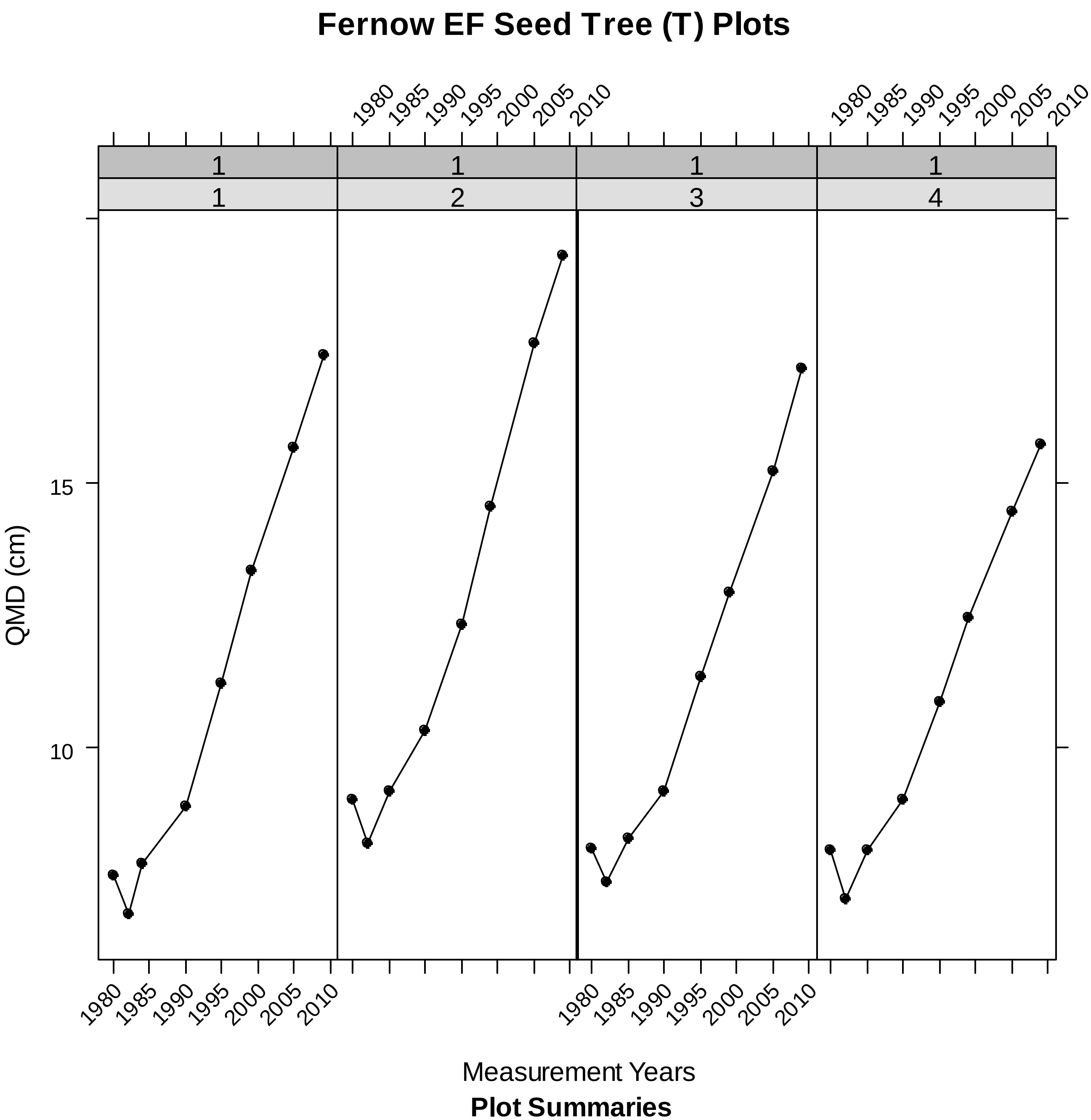


Figure A43. Quadratic mean diameter (cm) through time on the Fernow Experimental Forest (FEF) thinned seed tree plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

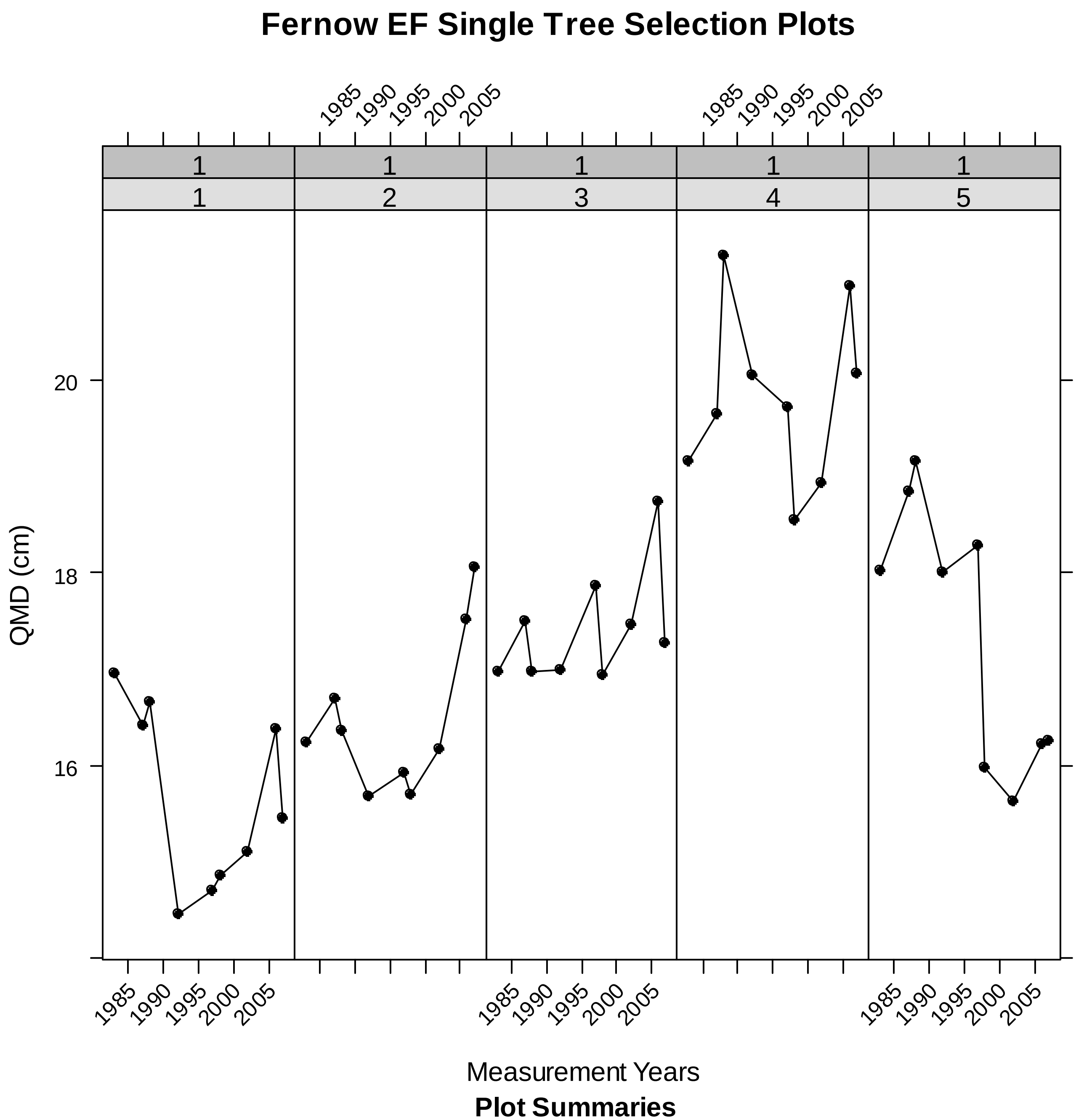


Figure A44. Quadratic mean diameter (cm) through time on the Fernow Experimental Forest (FEF) single-tree selection plots. The value in darker grey section is standardized treatment replicate (A:1), while the value is in light grey section is actual plot number.

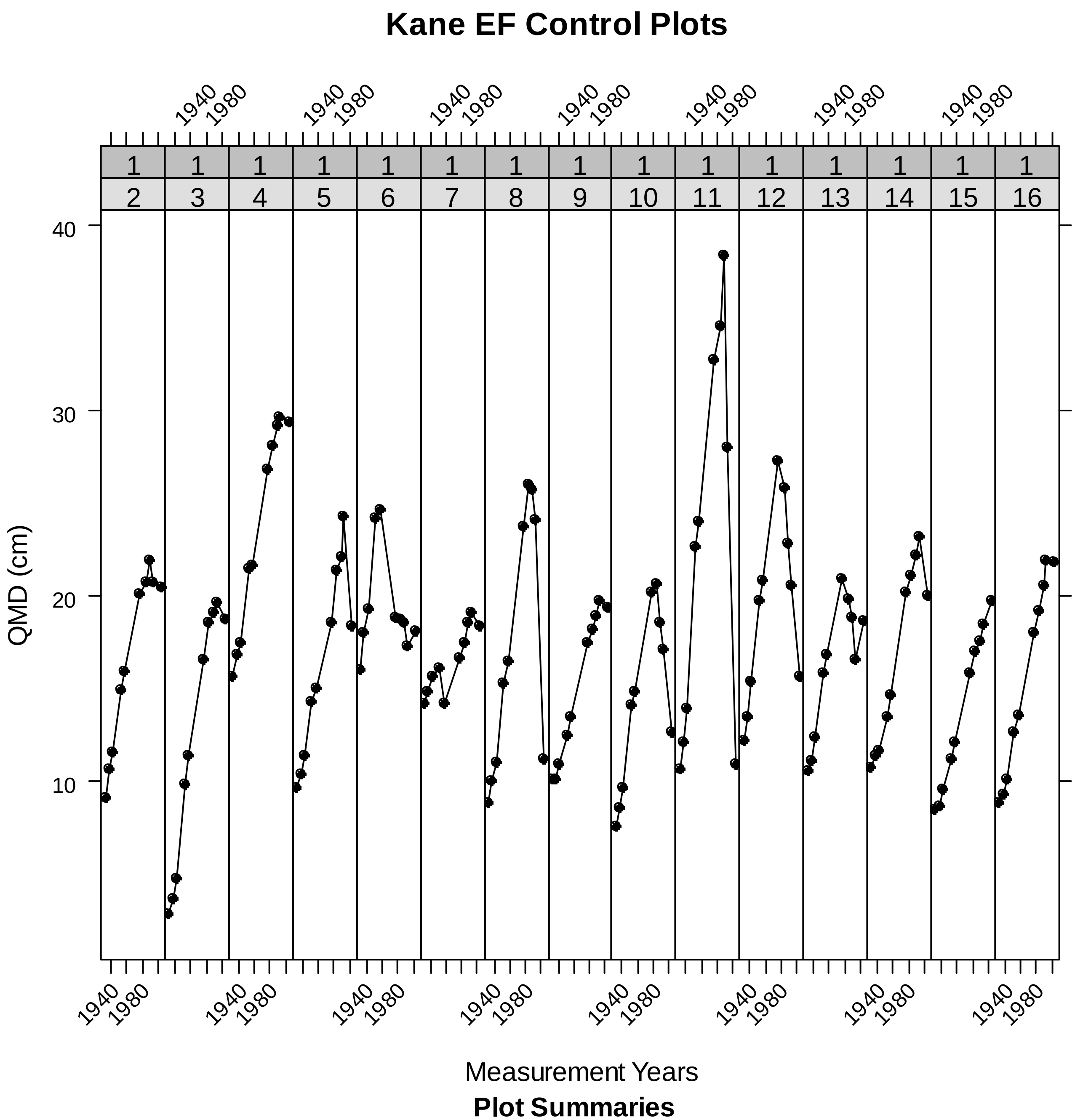


Figure A45. Quadratic mean diameter (cm) through time on the Kane Experimental Forest (KEF) control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

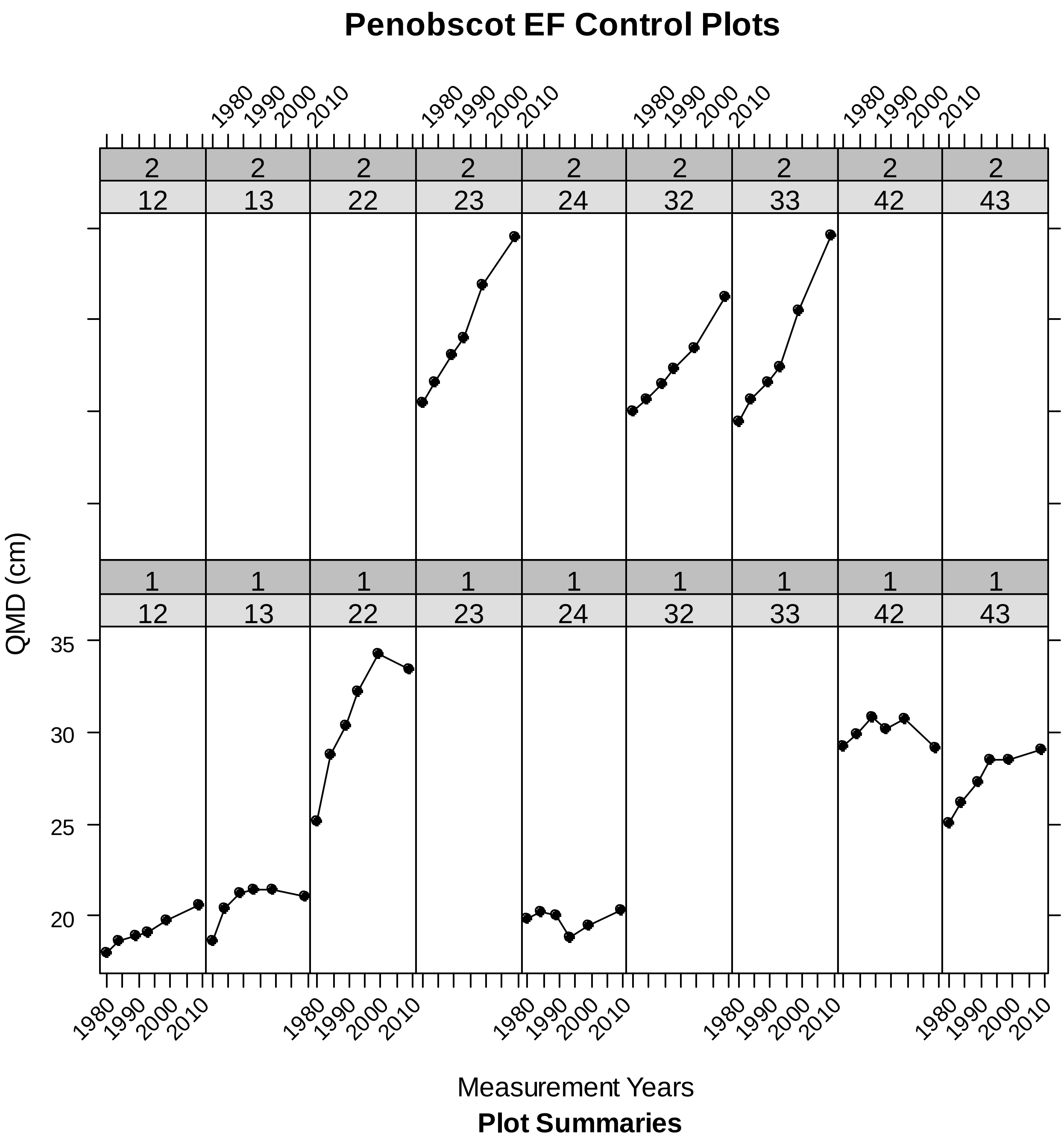


Figure A46. Quadratic mean diameter (cm) through time on the Penobscot Experimental Forest (PEF) control plots. The value in darker grey section is standardized treatment replicate (1: MU 32A, 2: MU 32B), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

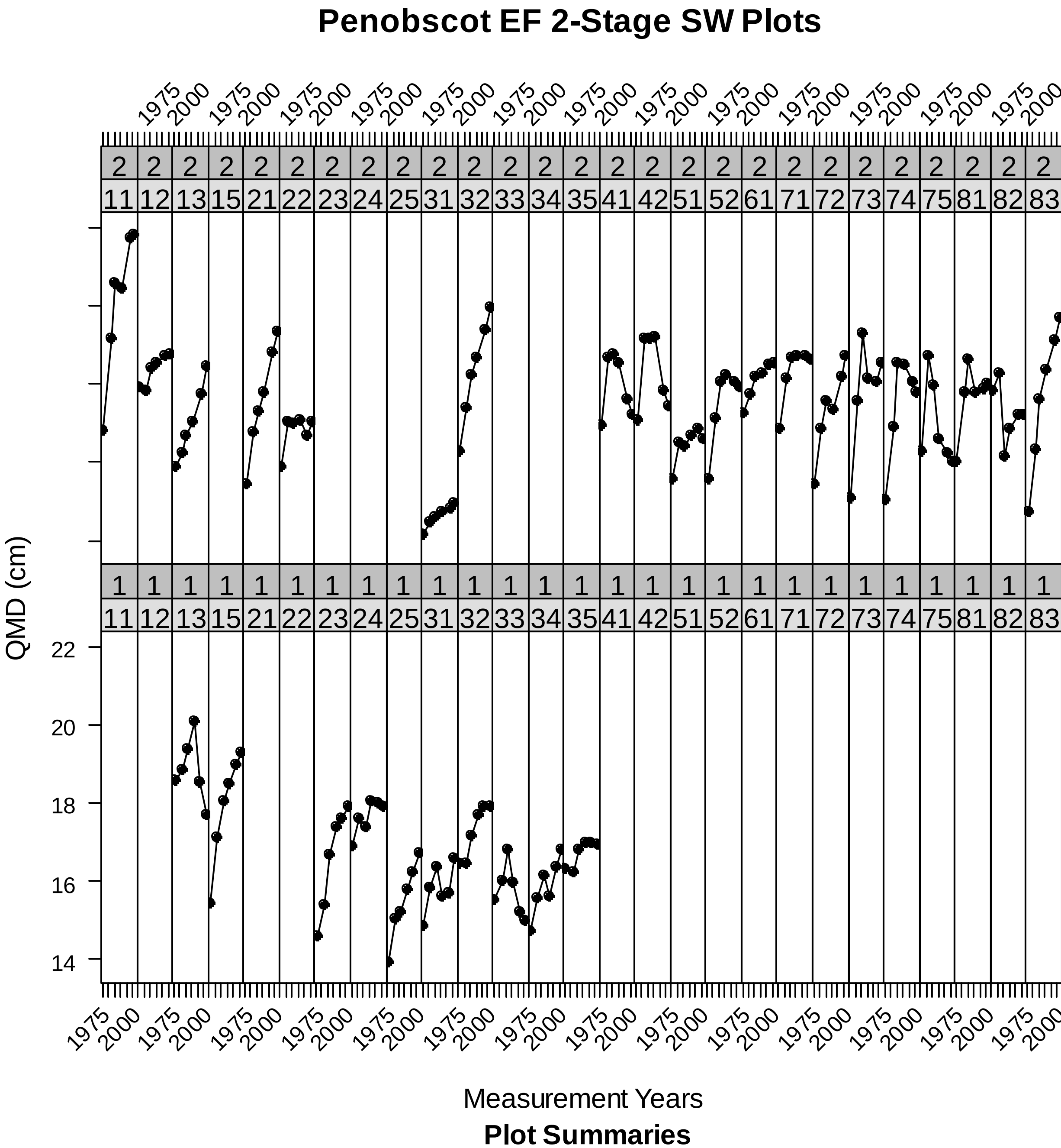


Figure A47. Quadratic mean diameter (cm) through time on the Penobscot Experimental Forest (PEF) two-stage shelterwood plots. The value in darker grey section is standardized treatment replicate (1: MU 21, 2: MU 30), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

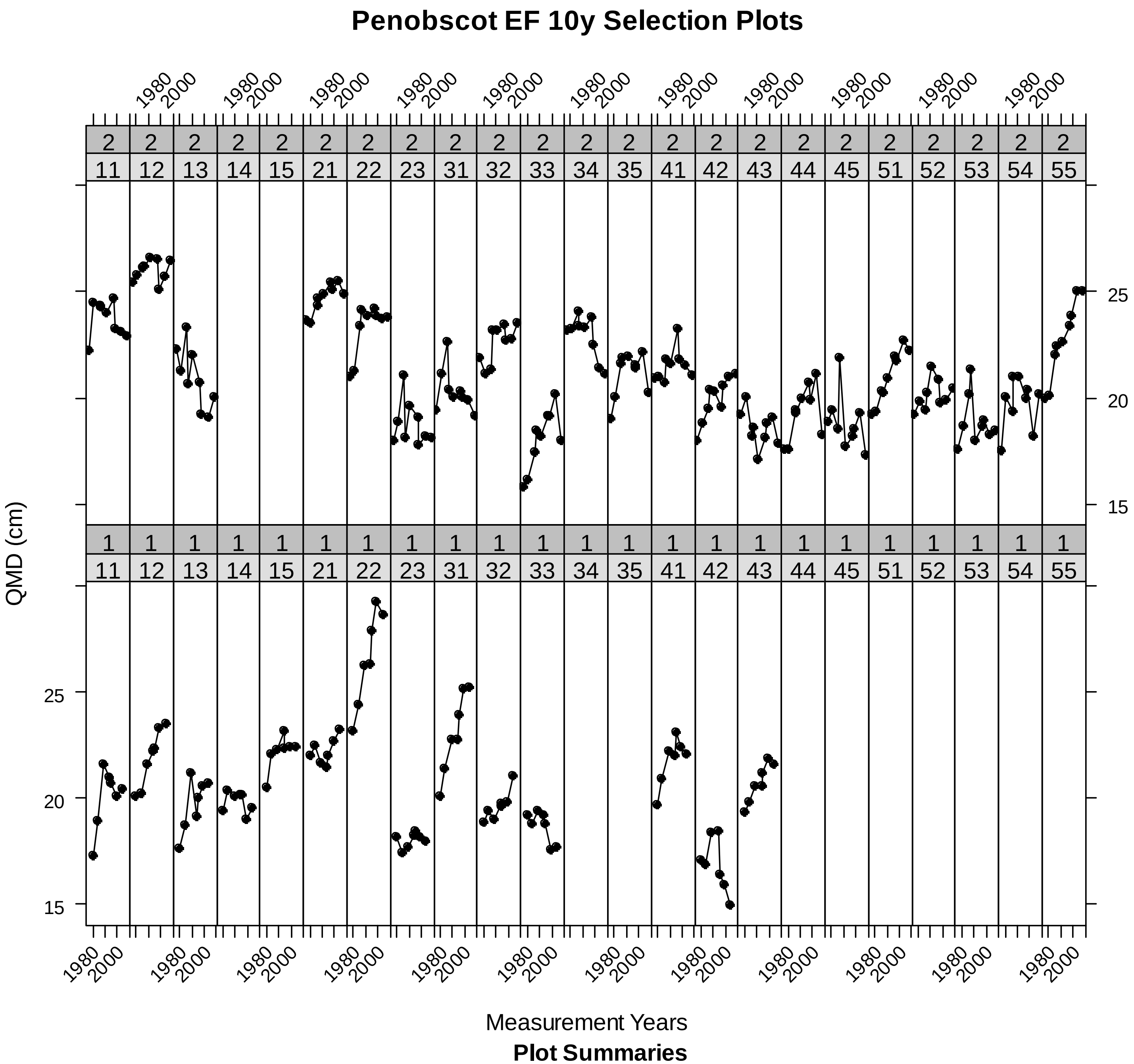


Figure A48. Quadratic mean diameter (cm) through time on the Penobscot Experimental Forest (PEF) ten-year selection plots. The value in darker grey section is standardized treatment replicate (1:MU 12, 2: MU 20), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

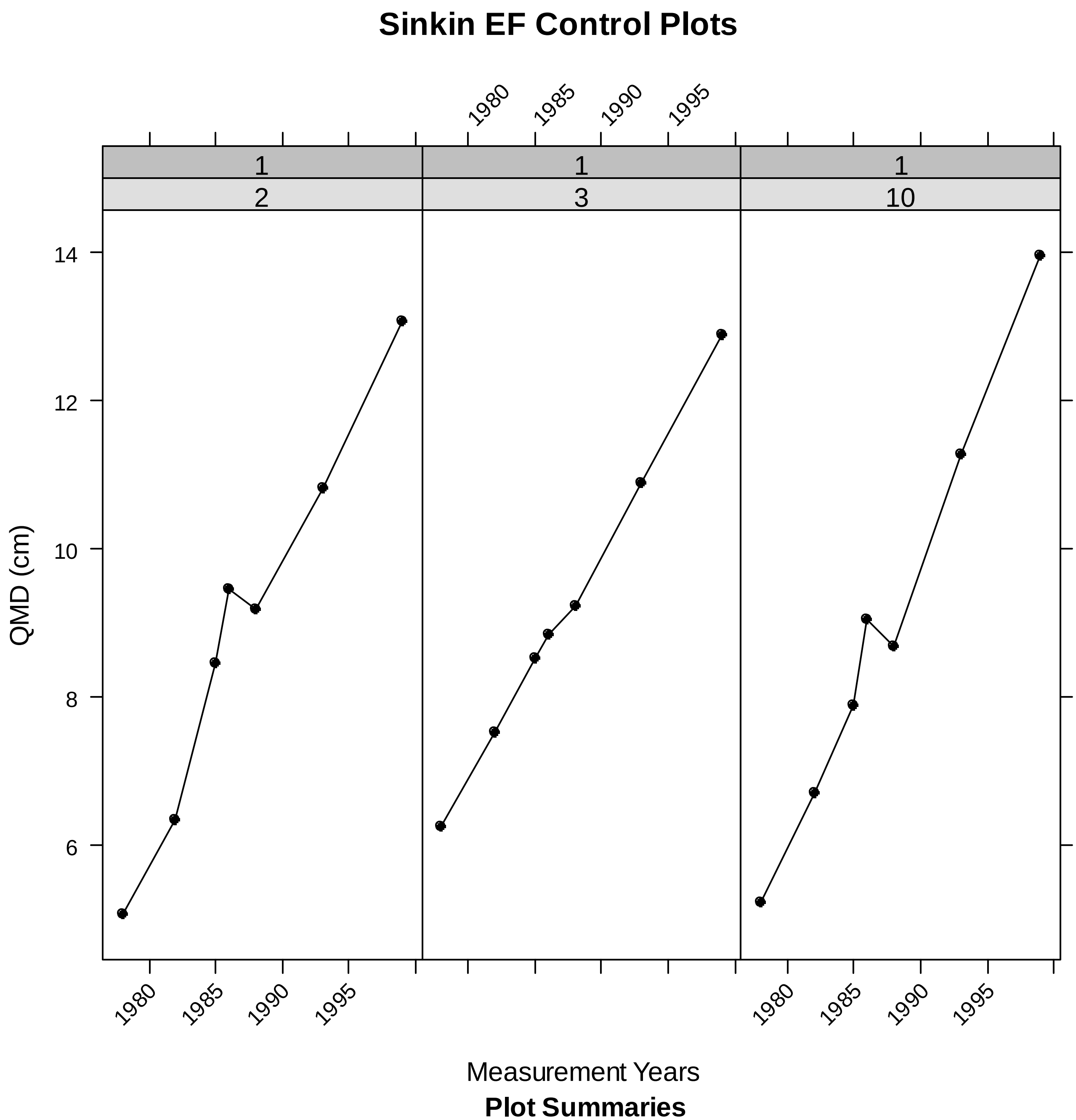


Figure A49. Quadratic mean diameter (cm) through time on the Sinkin Experimental Forest (SEF) spatial distribution control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

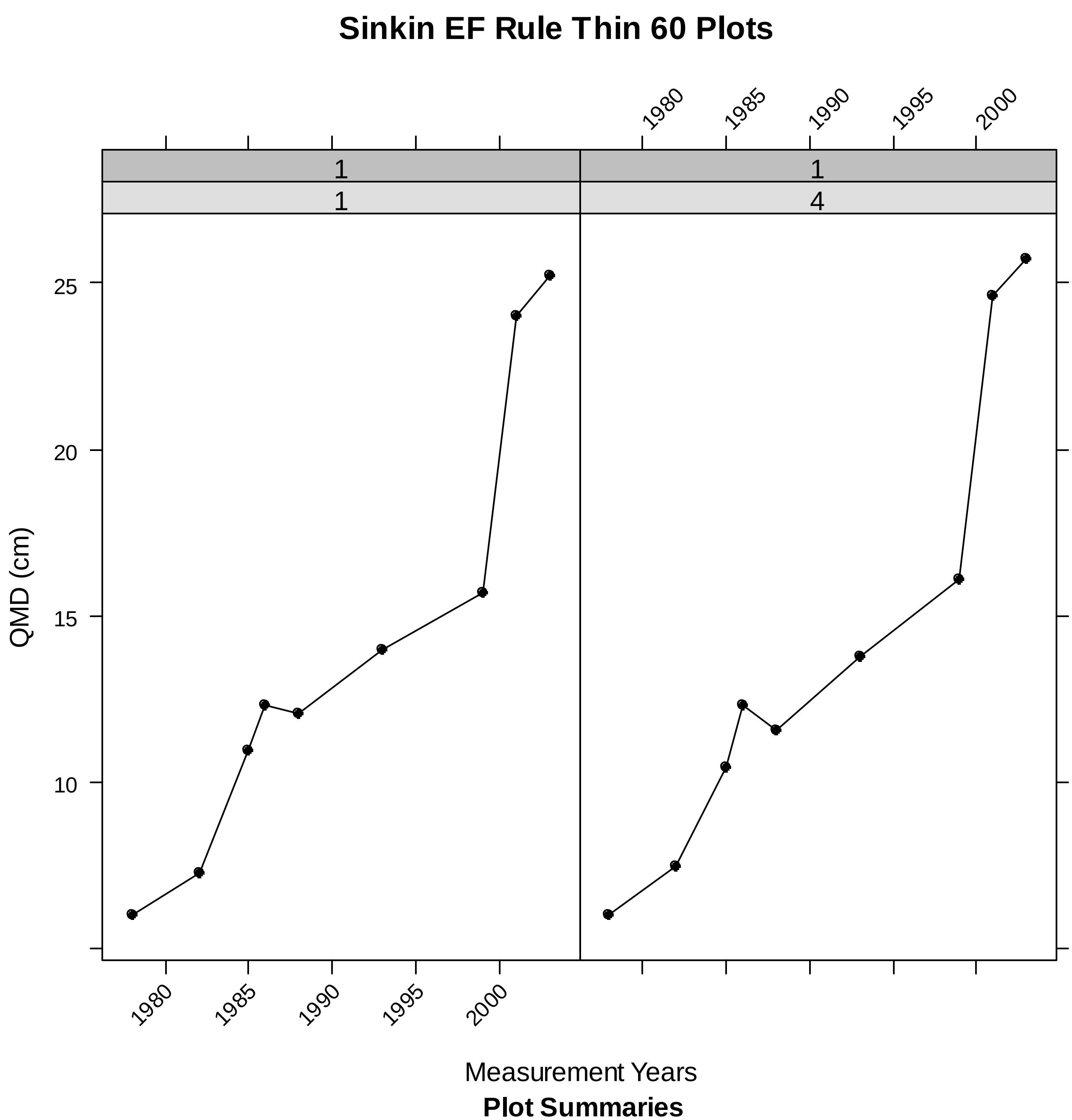


Figure A50. Quadratic mean diameter (cm) through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (60%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

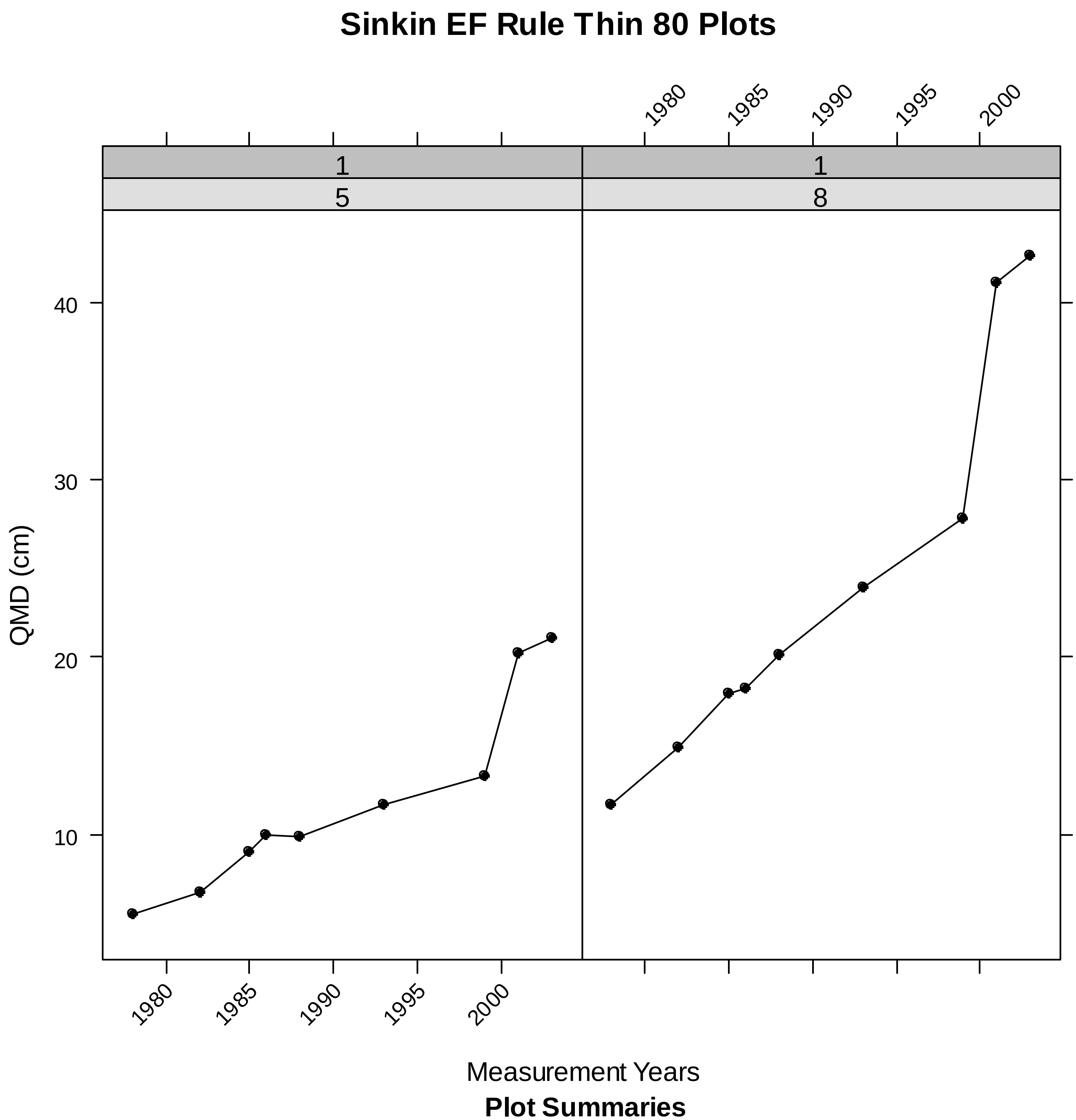


Figure A51. Quadratic mean diameter (cm) through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (80%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

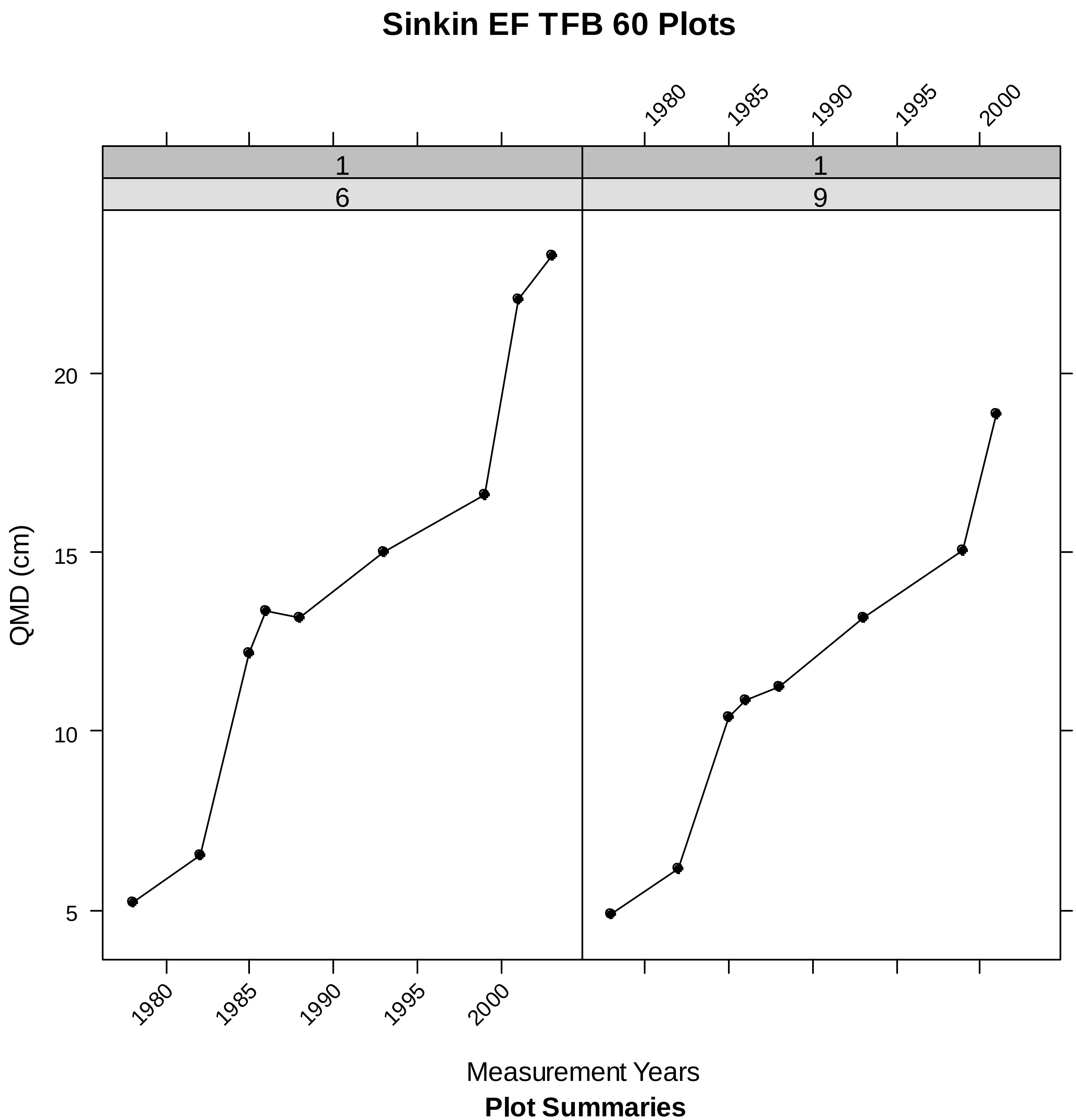


Figure A52. Quadratic mean diameter (cm) through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (60%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

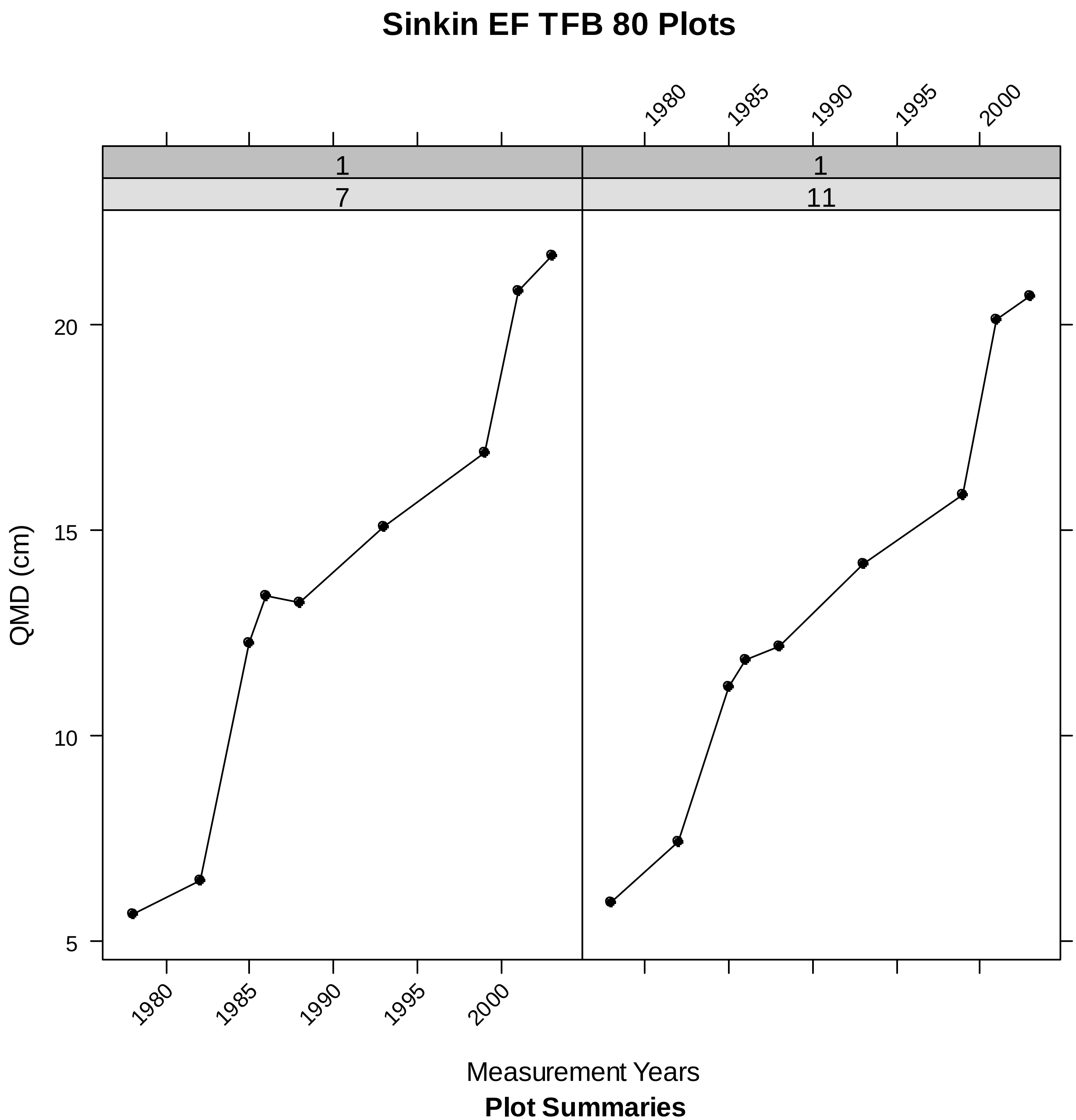


Figure A53. Quadratic mean diameter (cm) through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (80%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

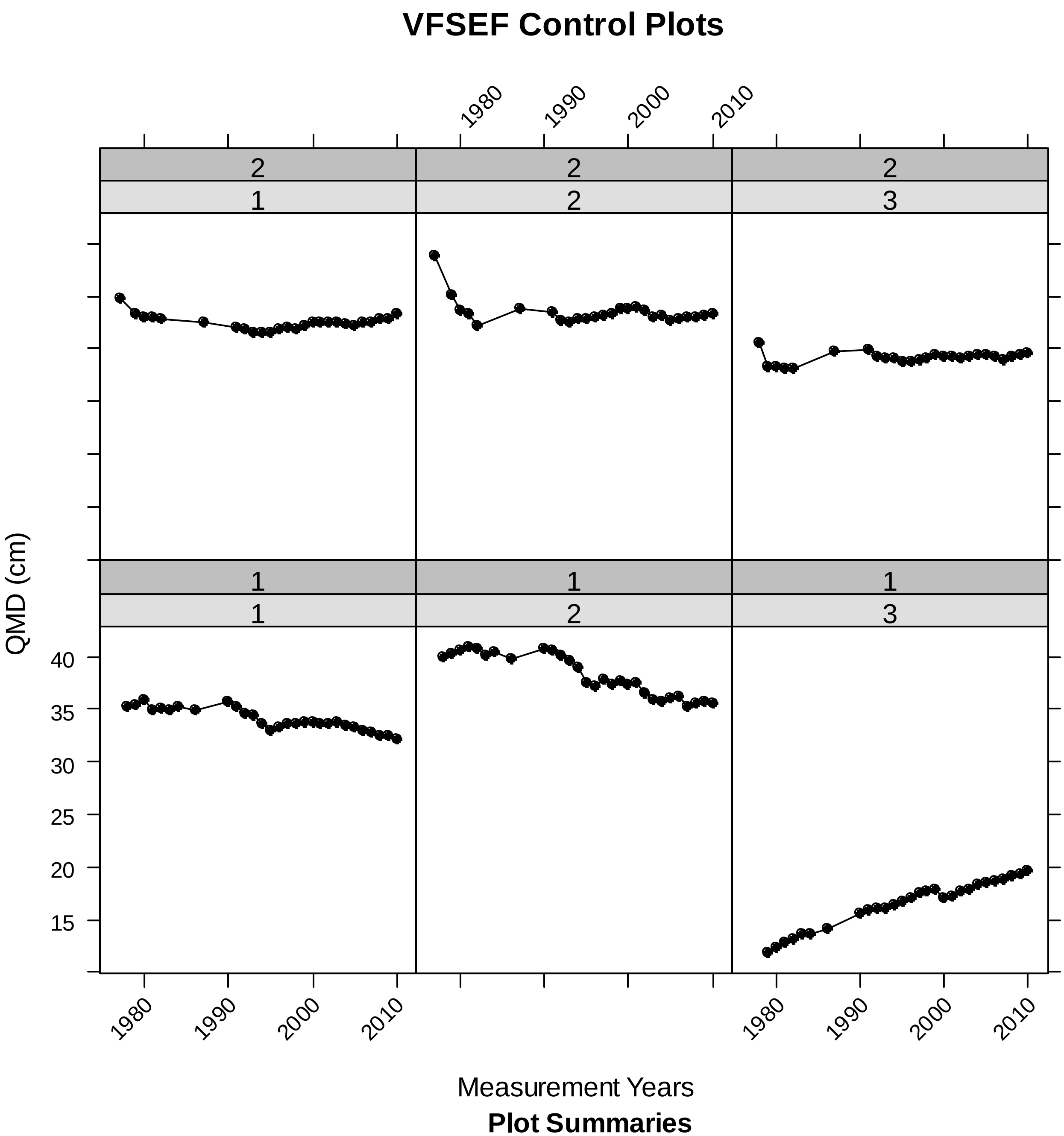


Figure A54. Quadratic mean diameter (cm) through time on the Vinton-Furnace State Experimental Forest (VFSEF) control plots. The value in darker grey section is standardized treatment replicate (1-2, Study 25, 27 respectively) , while the value is in light grey section is actual plot number.

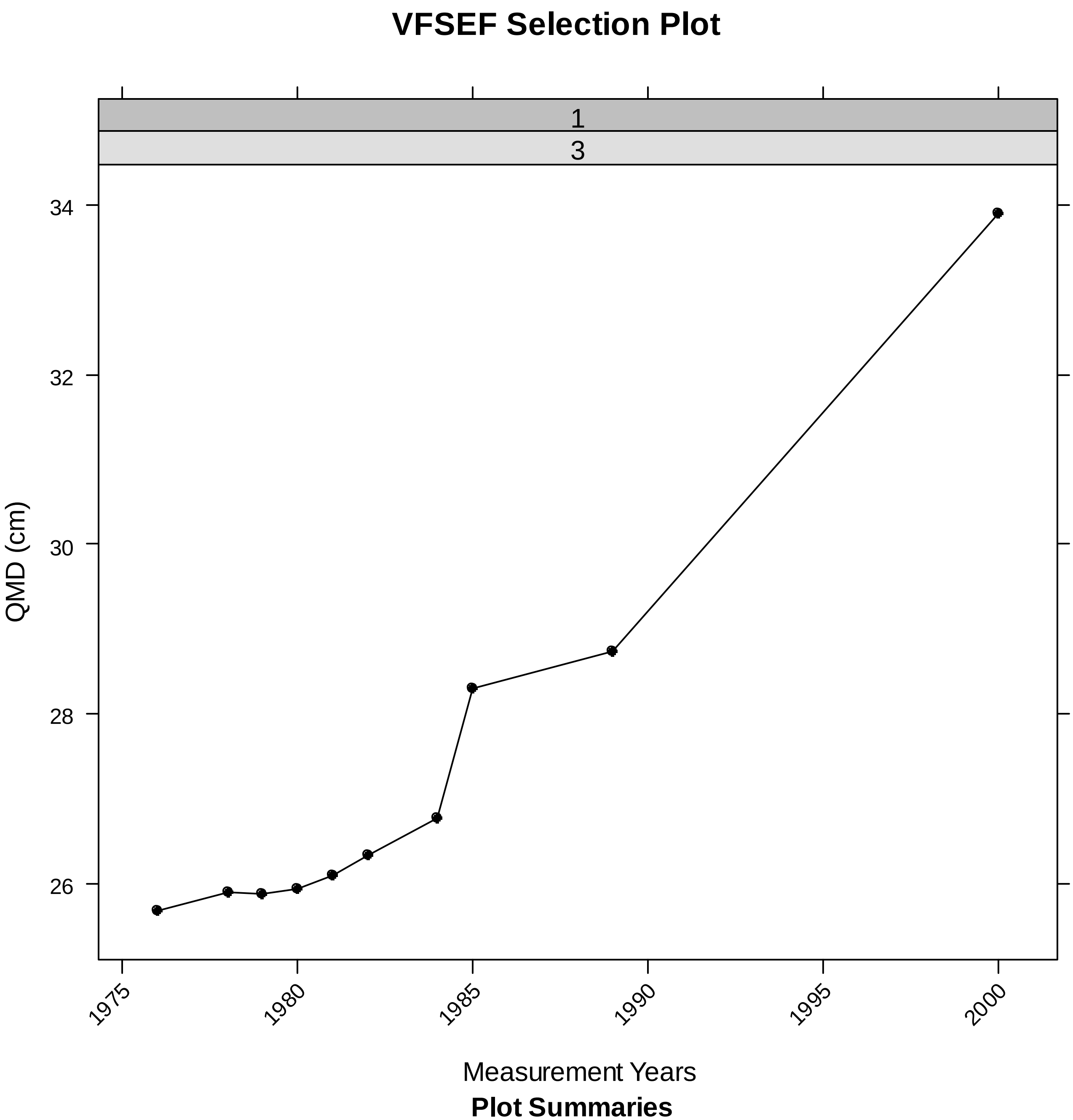


Figure A55. Quadratic mean diameter (cm) through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

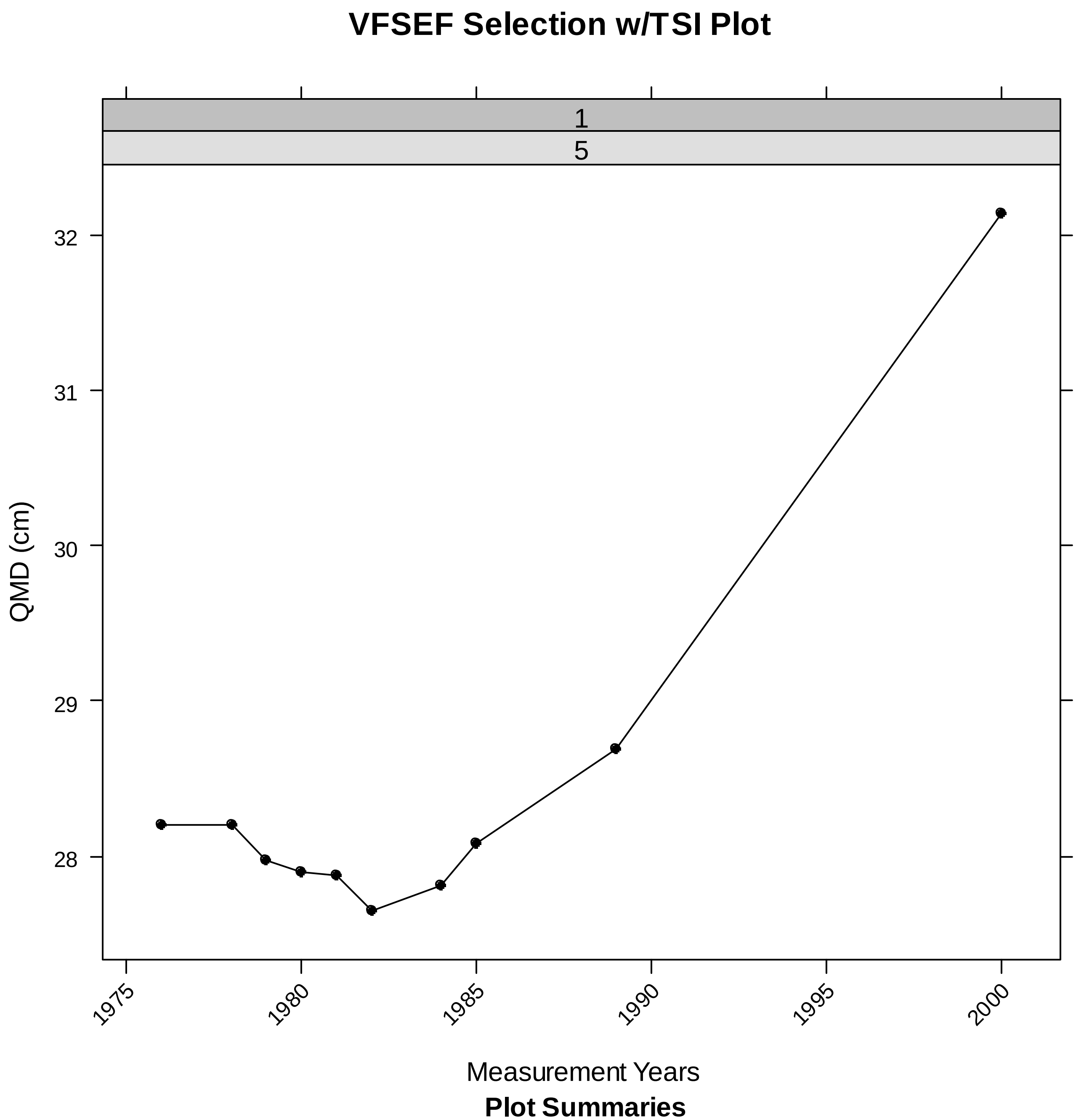


Figure A56. Quadratic mean diameter (cm) through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection with timber stand improvement plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

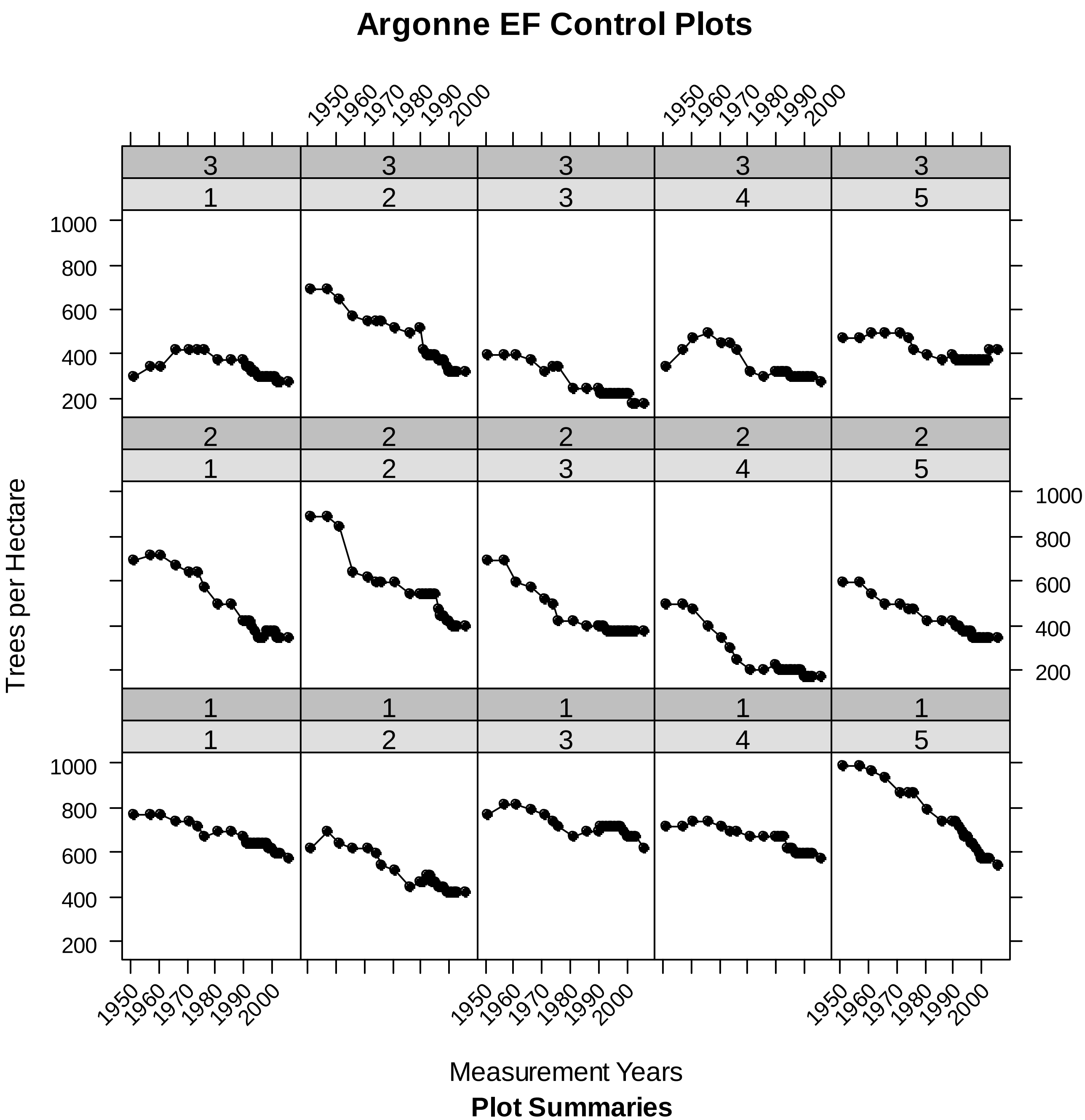


Figure A57. Trees per hectare through time on the Argonne Experimental Forest (AEF) control plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

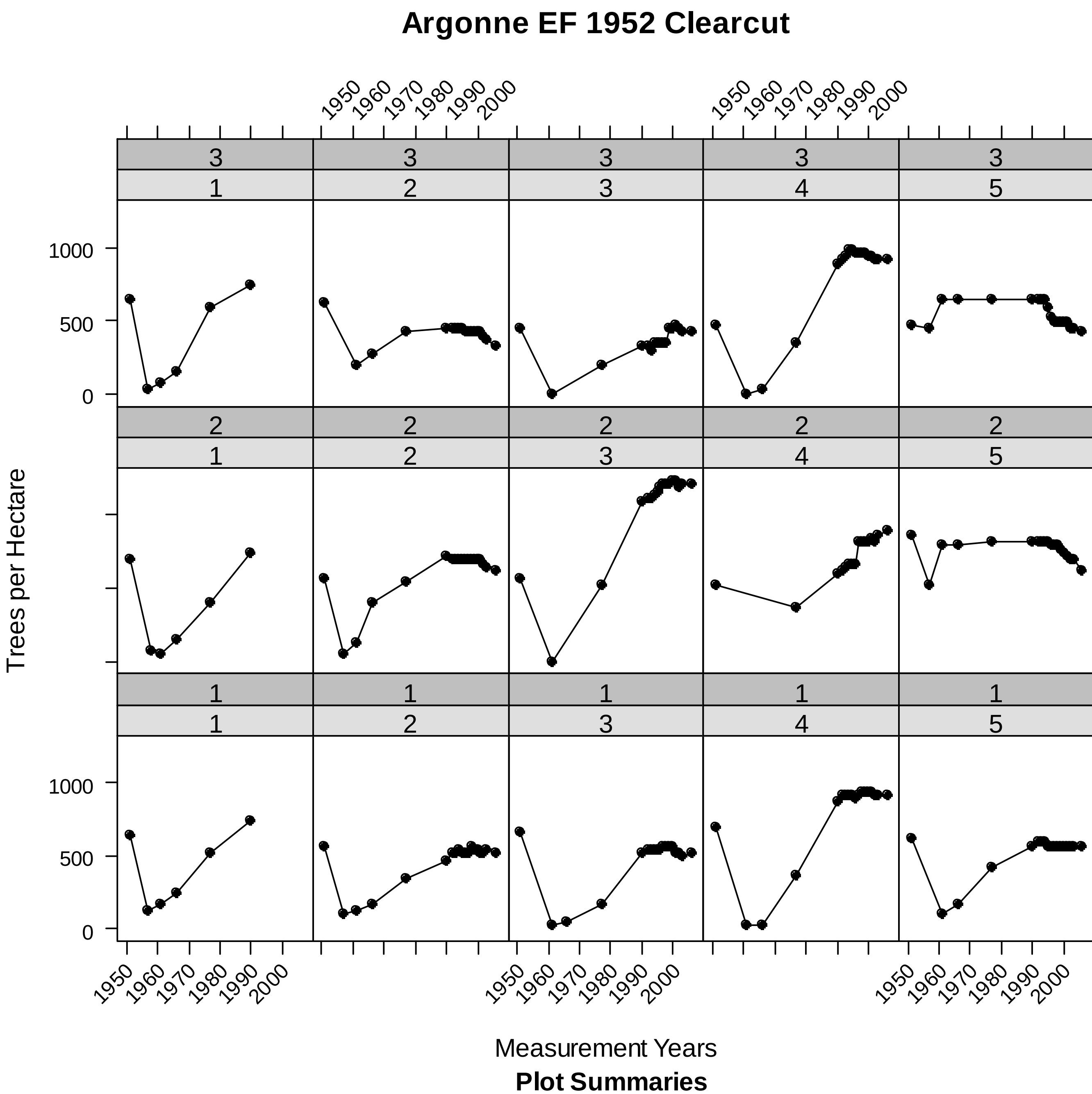


Figure A58. Trees per hectare through time on the Argonne Experimental Forest (AEF) clearcut (ca. 1951) plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

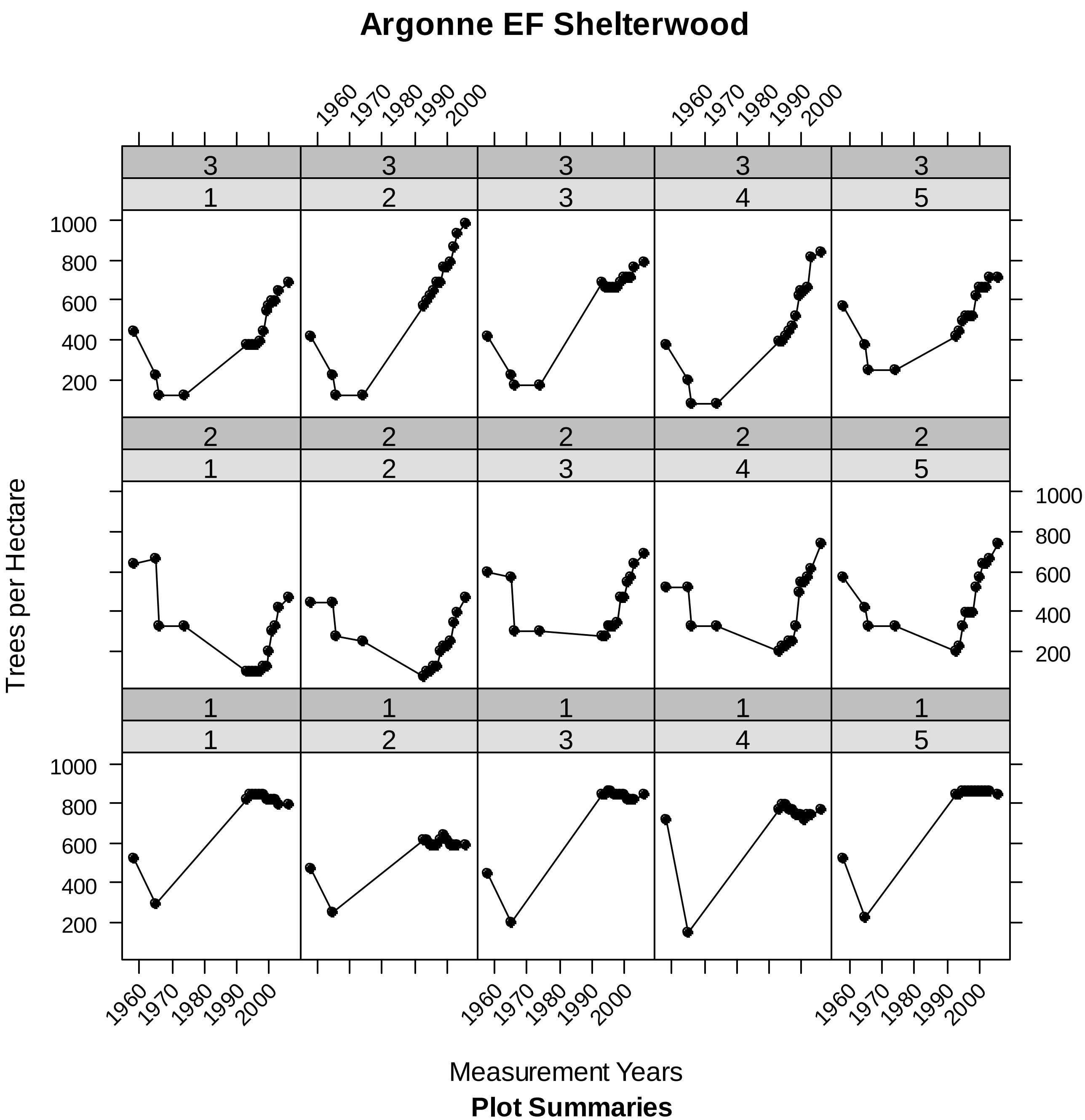


Figure A59. Trees per hectare through time on the Argonne Experimental Forest (AEF) two-stage shelterwood plots. The value in darker grey section is standardized block or treatment replicate, while the value is in light grey section is actual plot number.

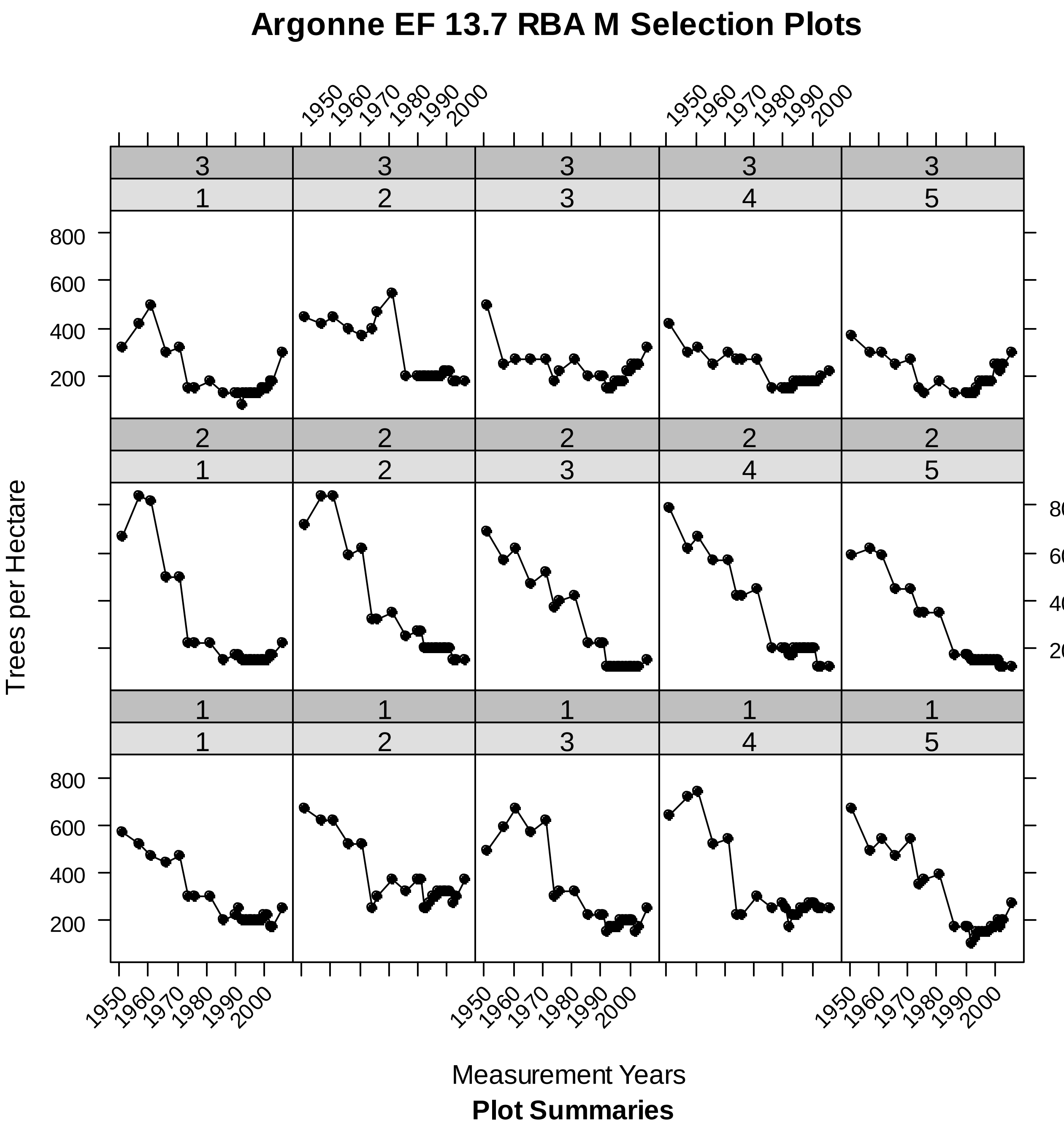


Figure A60. Trees per hectare through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

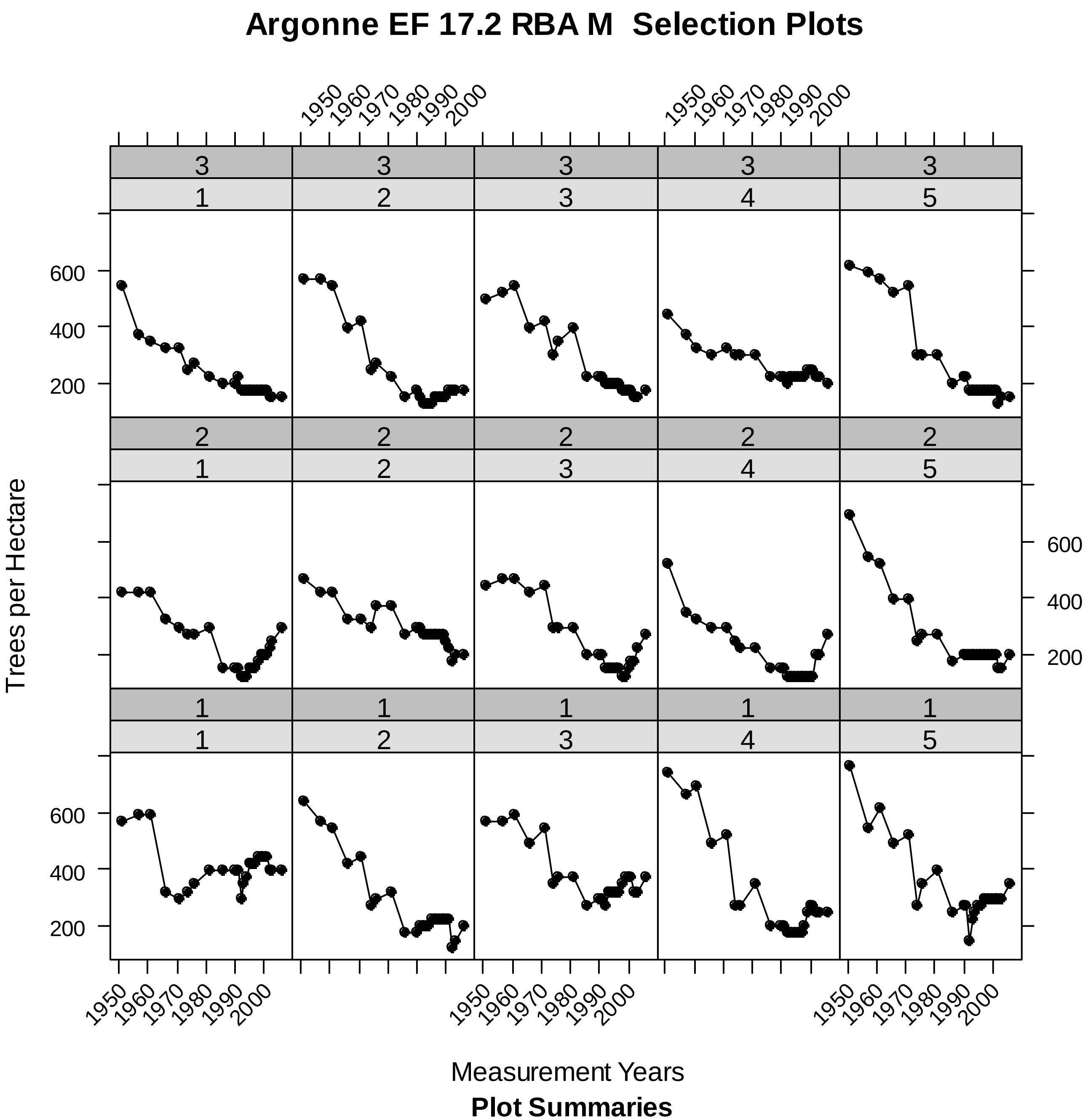


Figure A61. Trees per hectare through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

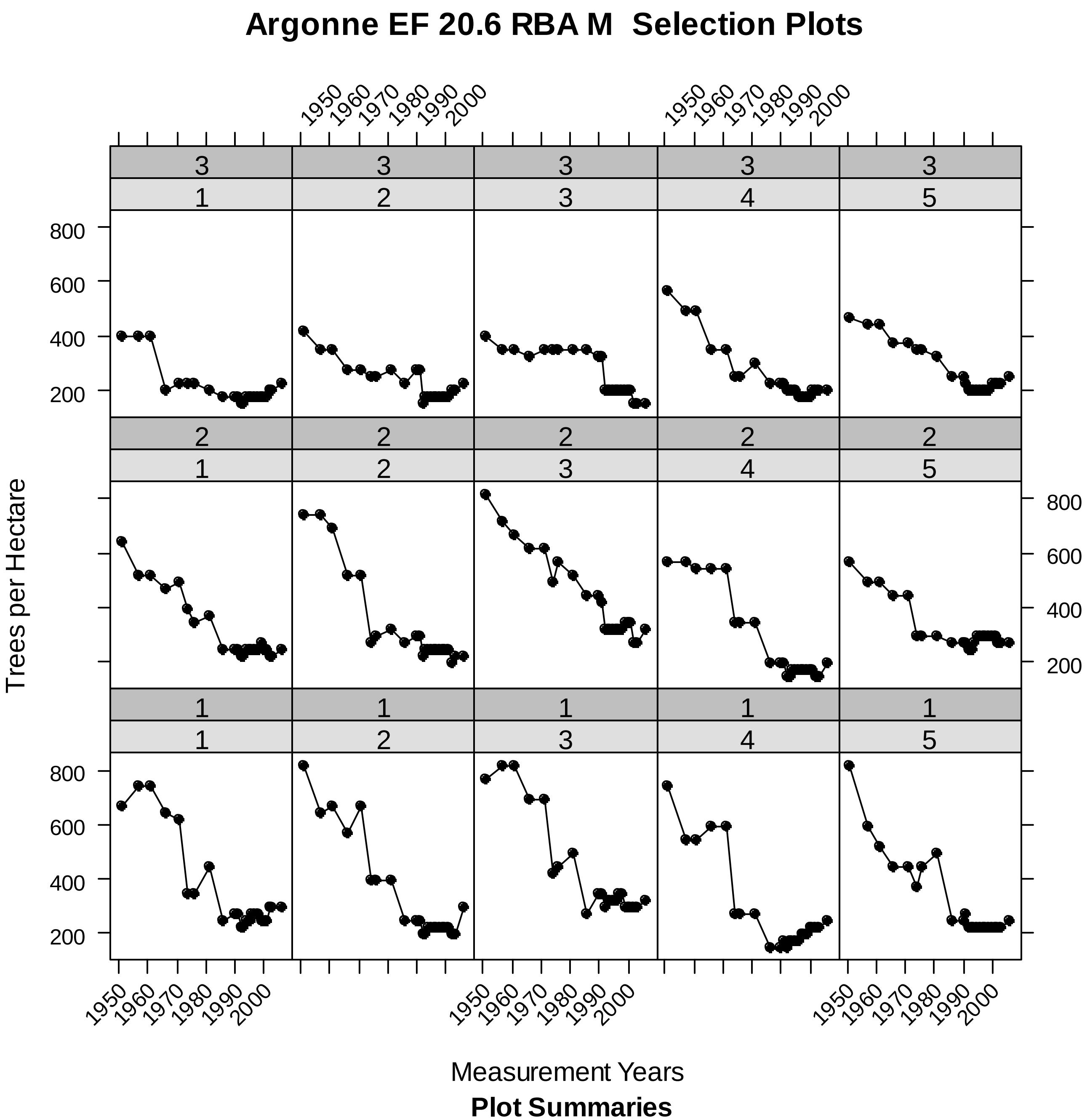


Figure A62. Trees per hectare through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in darker grey section is actual treatment replicate, while the value is in light grey section is actual plot number.

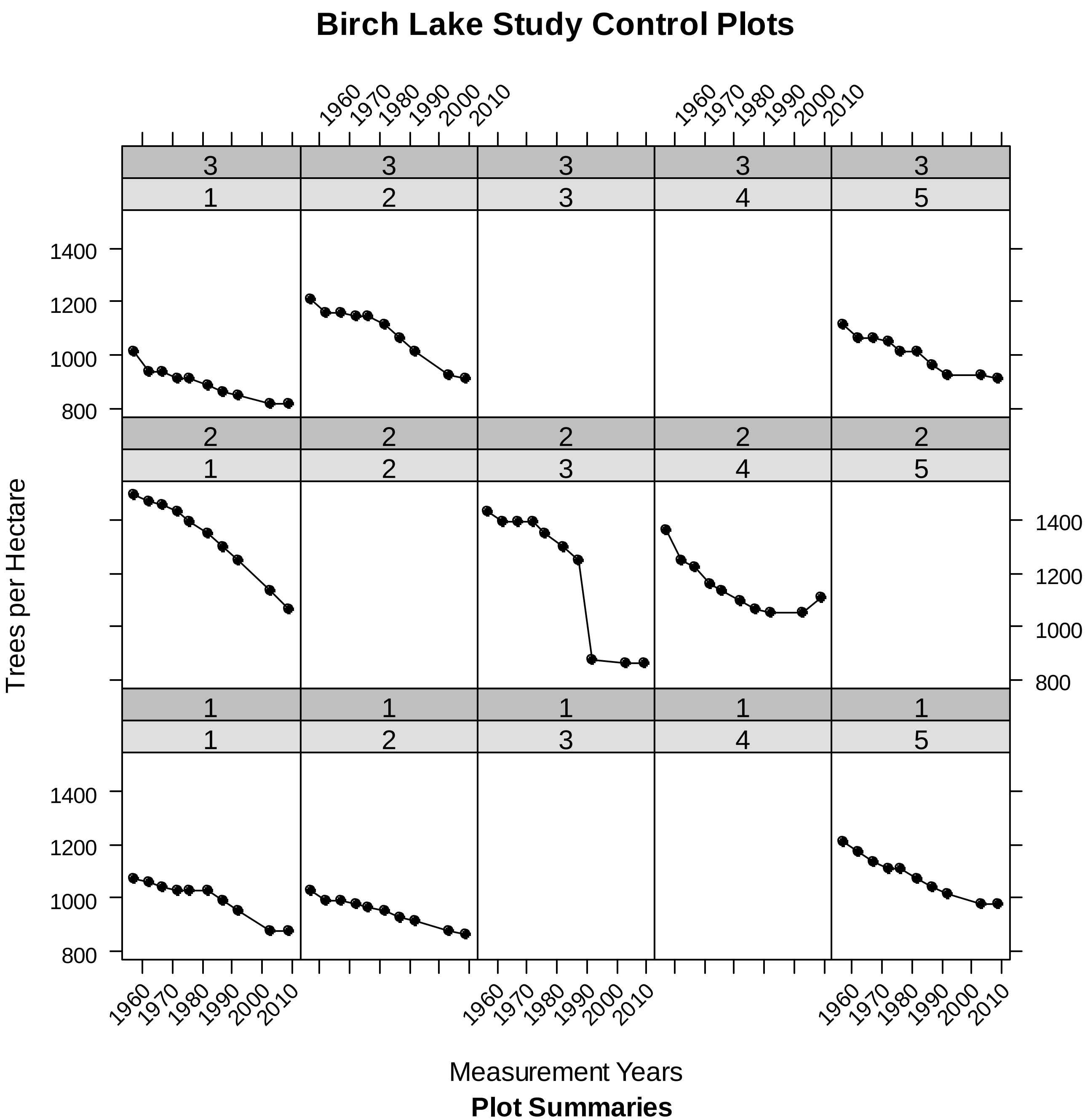


Figure A63. Trees per hectare through time on the Birch Lake Study (BLS) control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is standardized plot number. Standardized replicates 1-3 are BLS blocks 5,9,16 respectively while standardized plots1-5 are Center, East, North East, Southwest, and West BLS plots respectively.

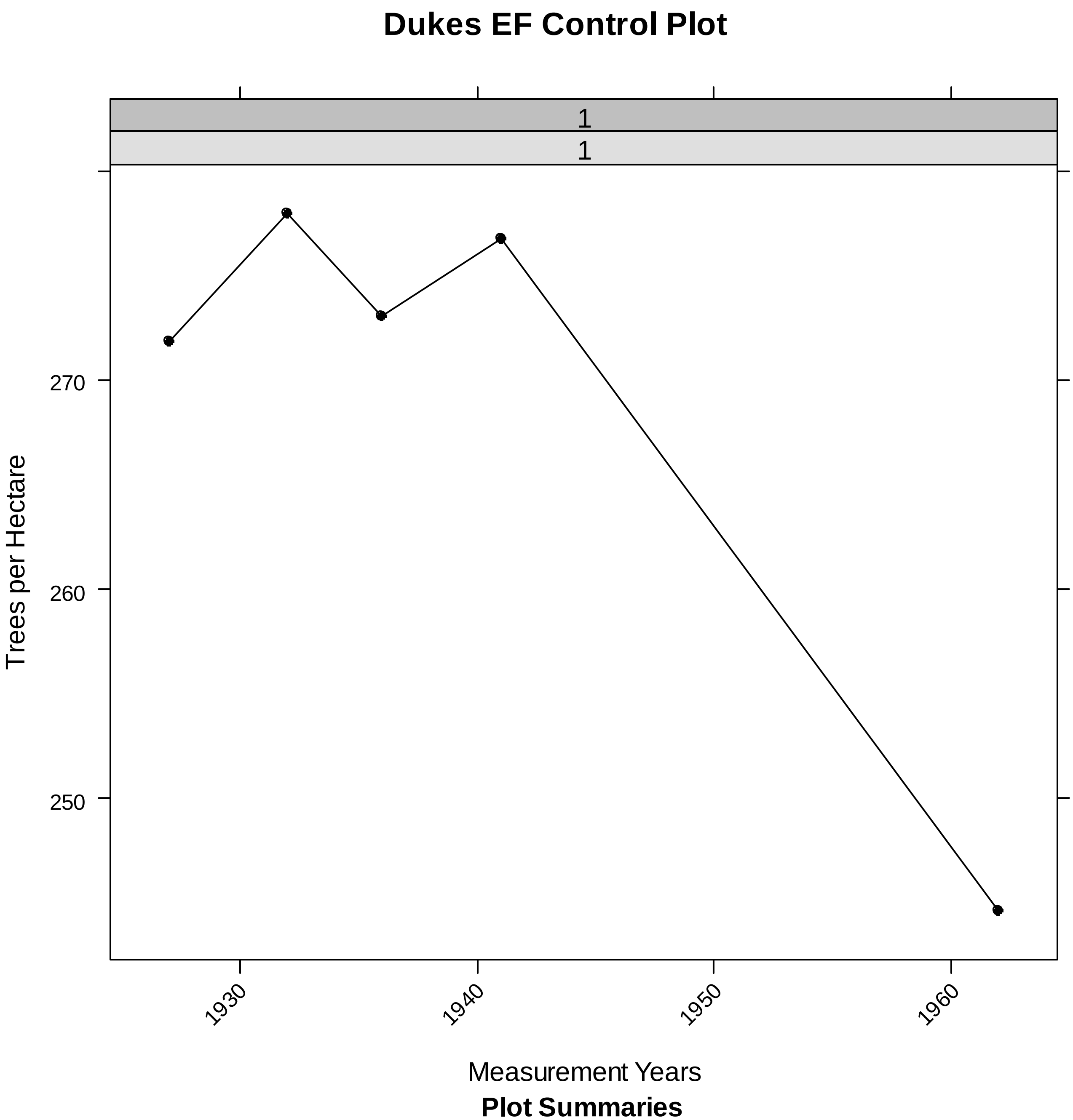


Figure A64. Trees per hectare through time on the Dukes Experimental Forest (DEF) control plot. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

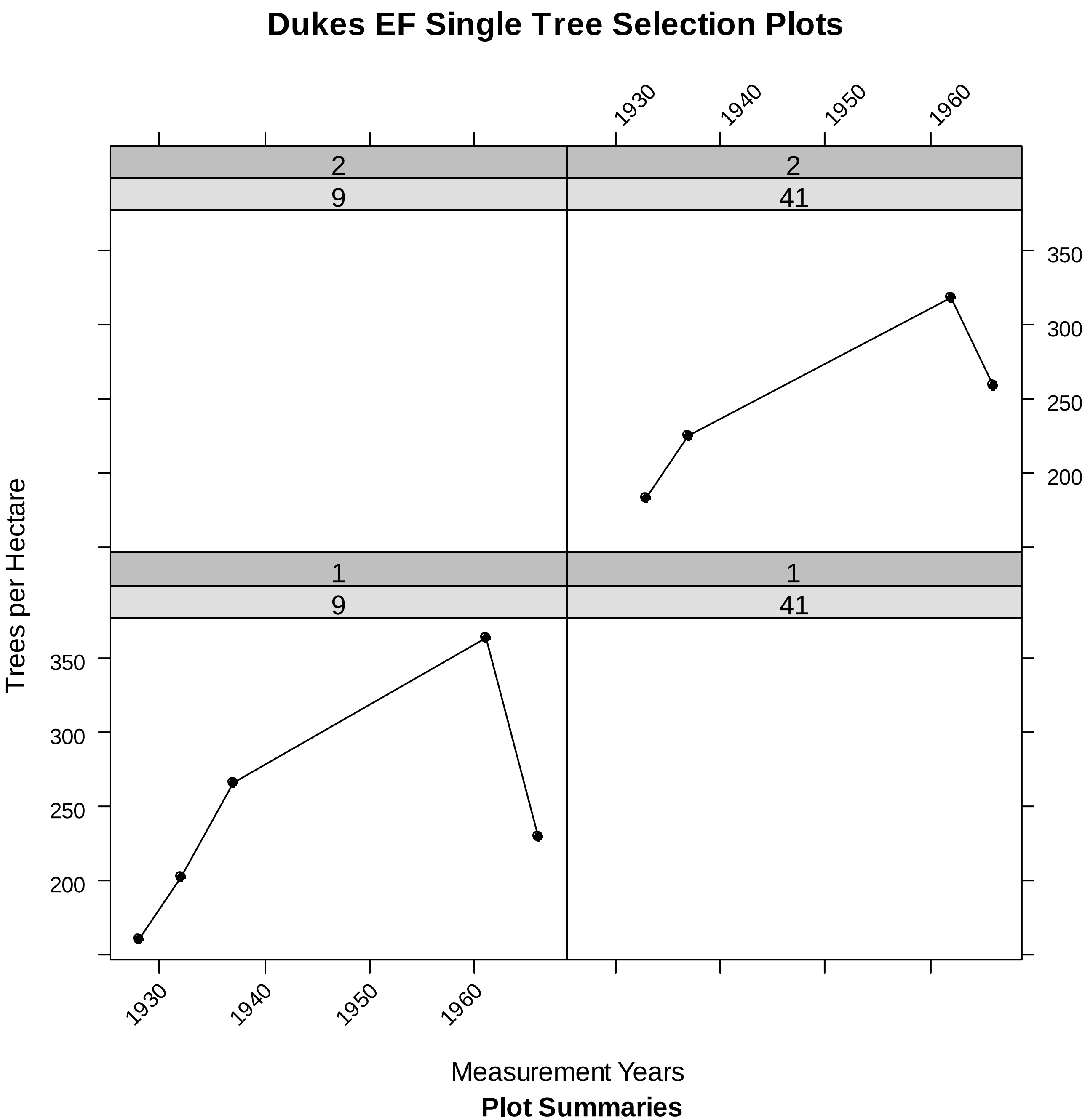


Figure A65. Trees per hectare through time on the Dukes Experimental Forest (DEF) single tree selection plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

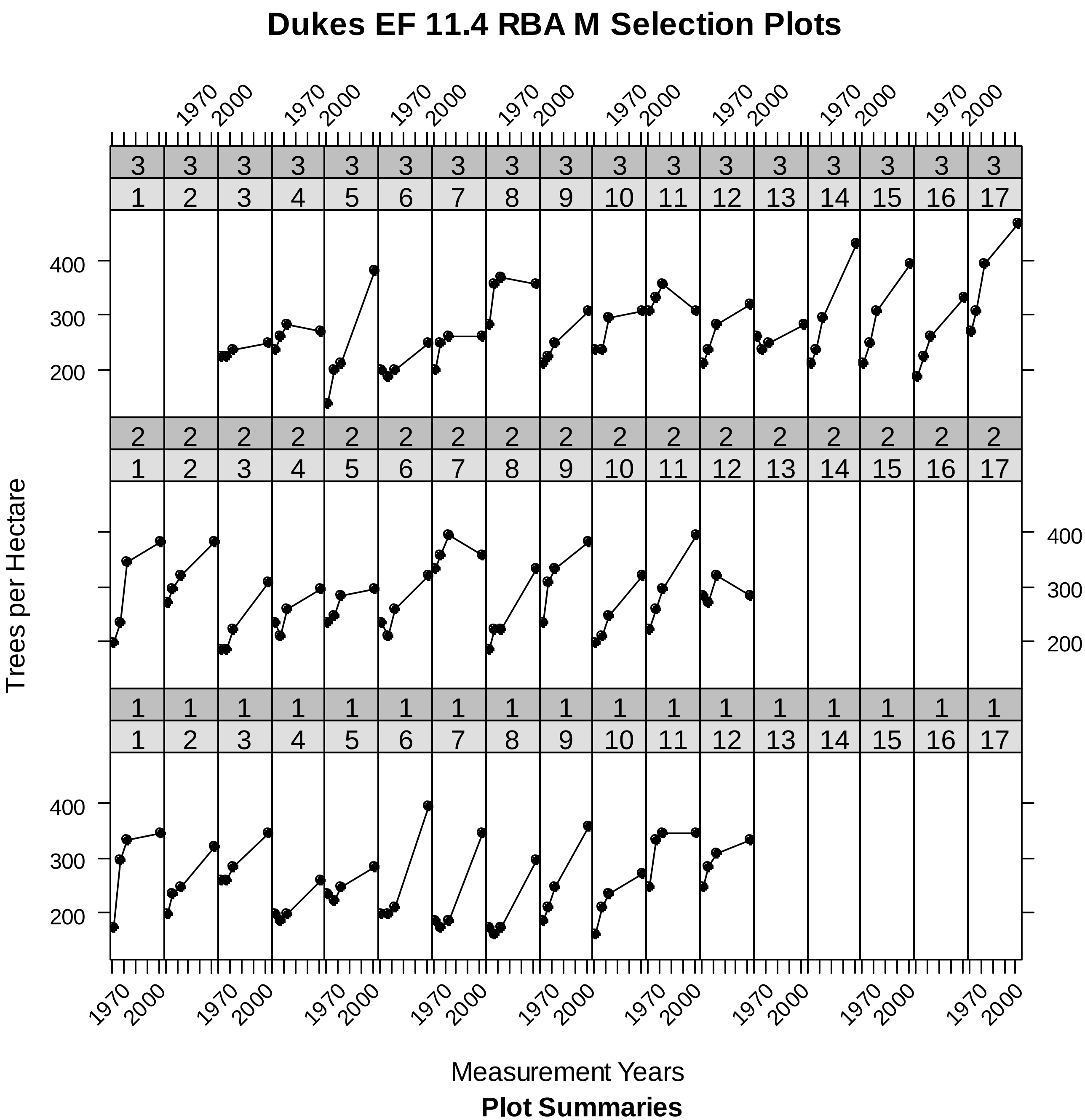


Figure A66. Trees per hectare through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

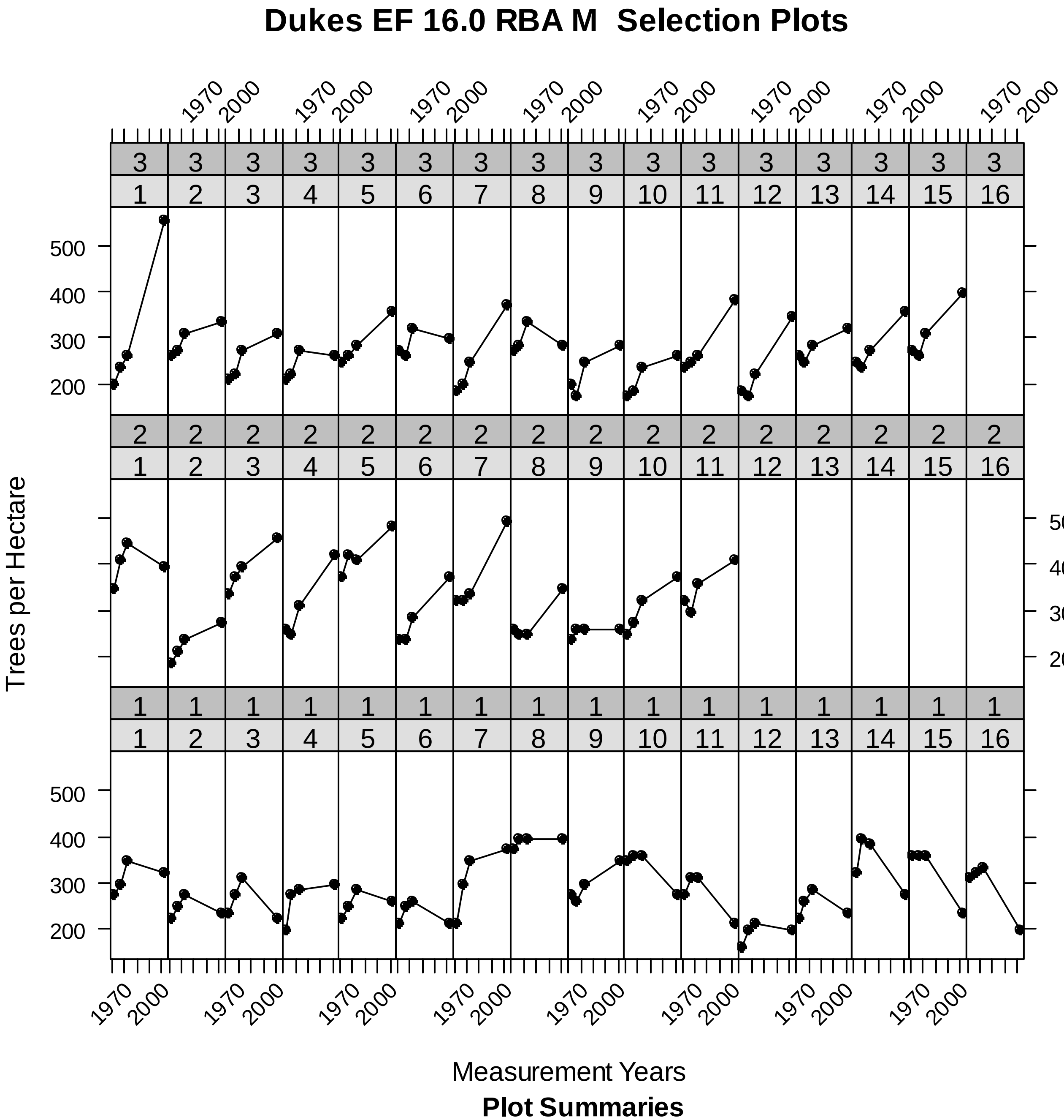


Figure A67. Trees per hectare through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

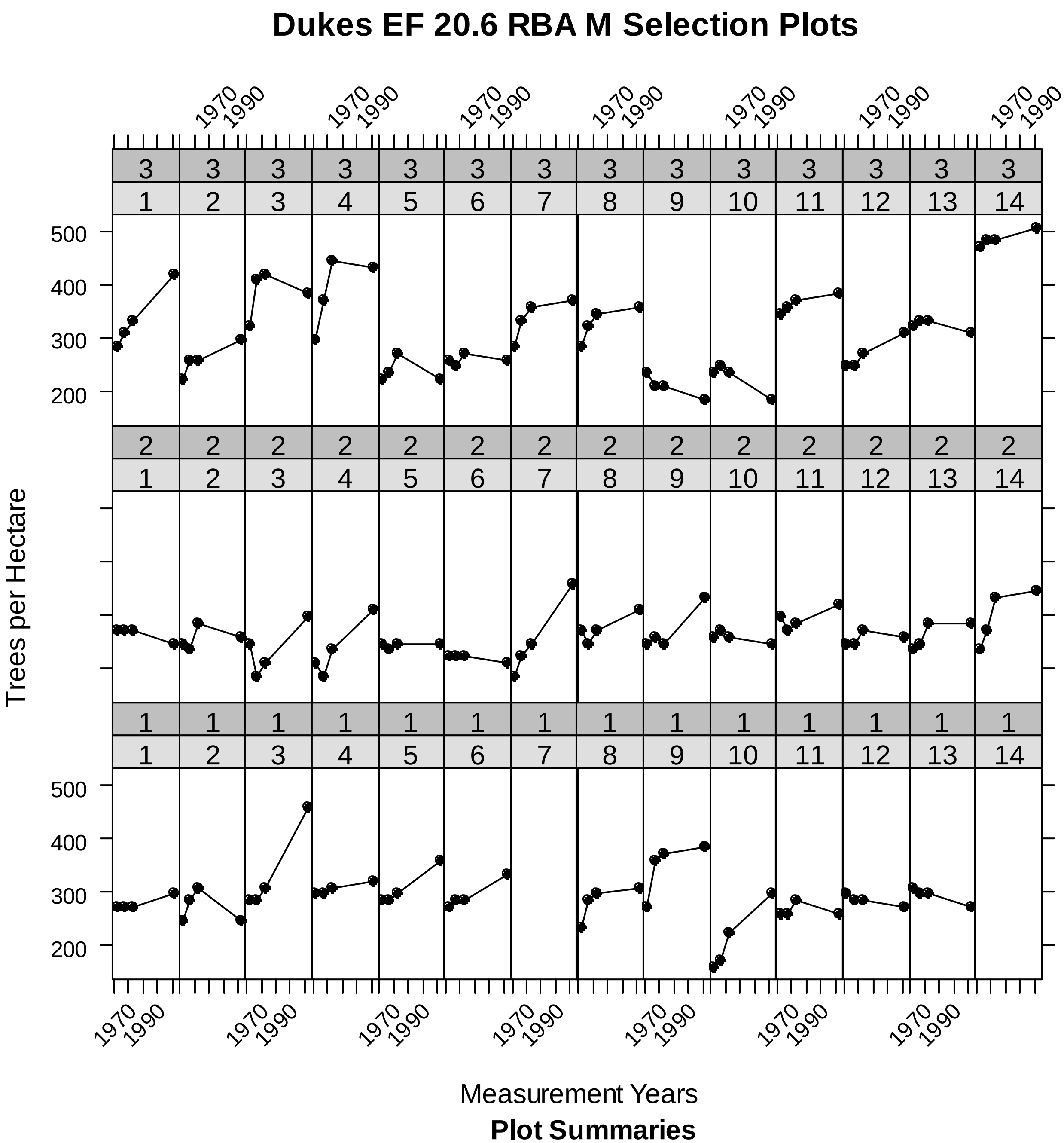


Figure A68. Trees per hectare through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

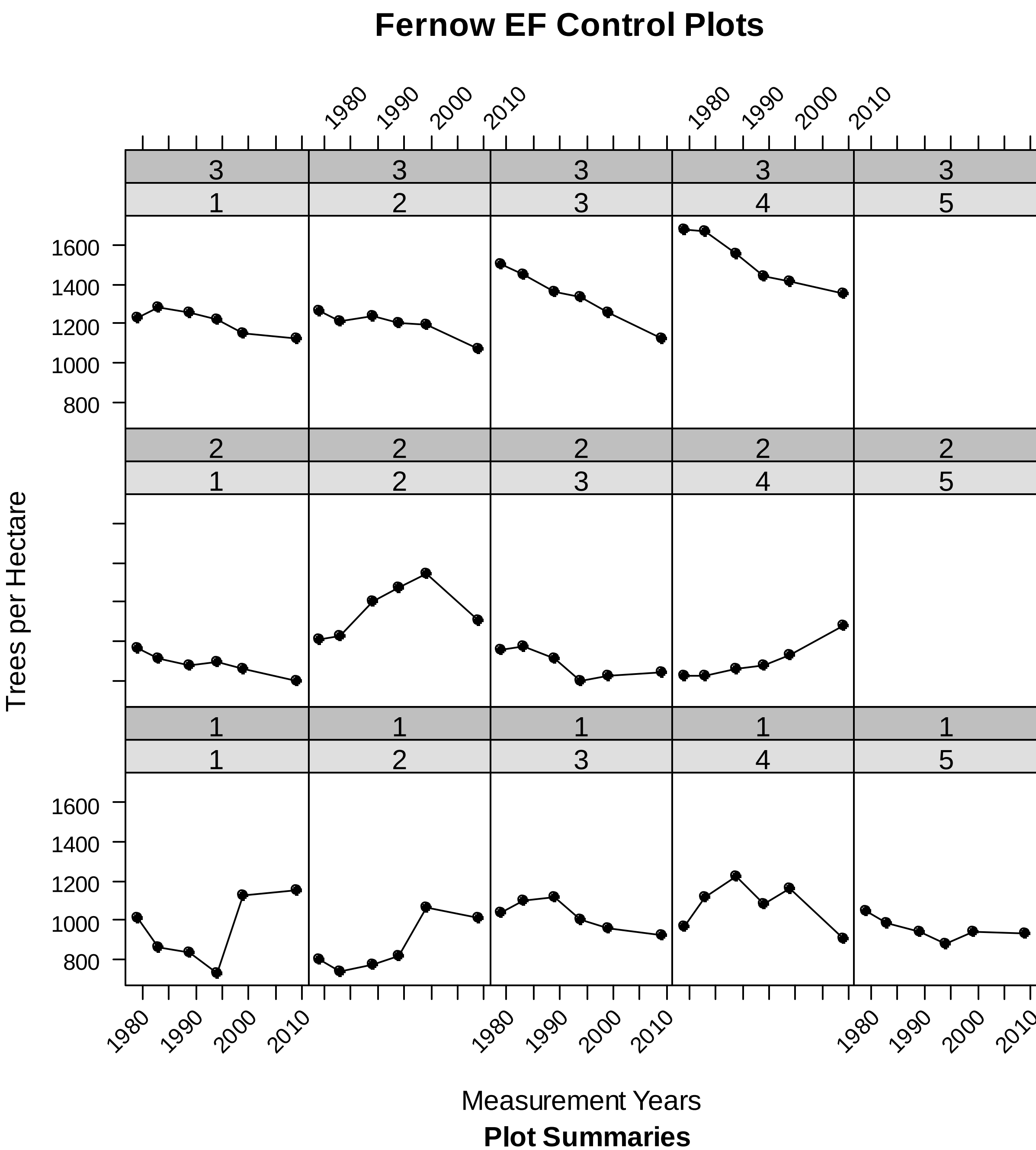


Figure A69. Trees per hectare through time on the Fernow Experimental Forest (FEF) control plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

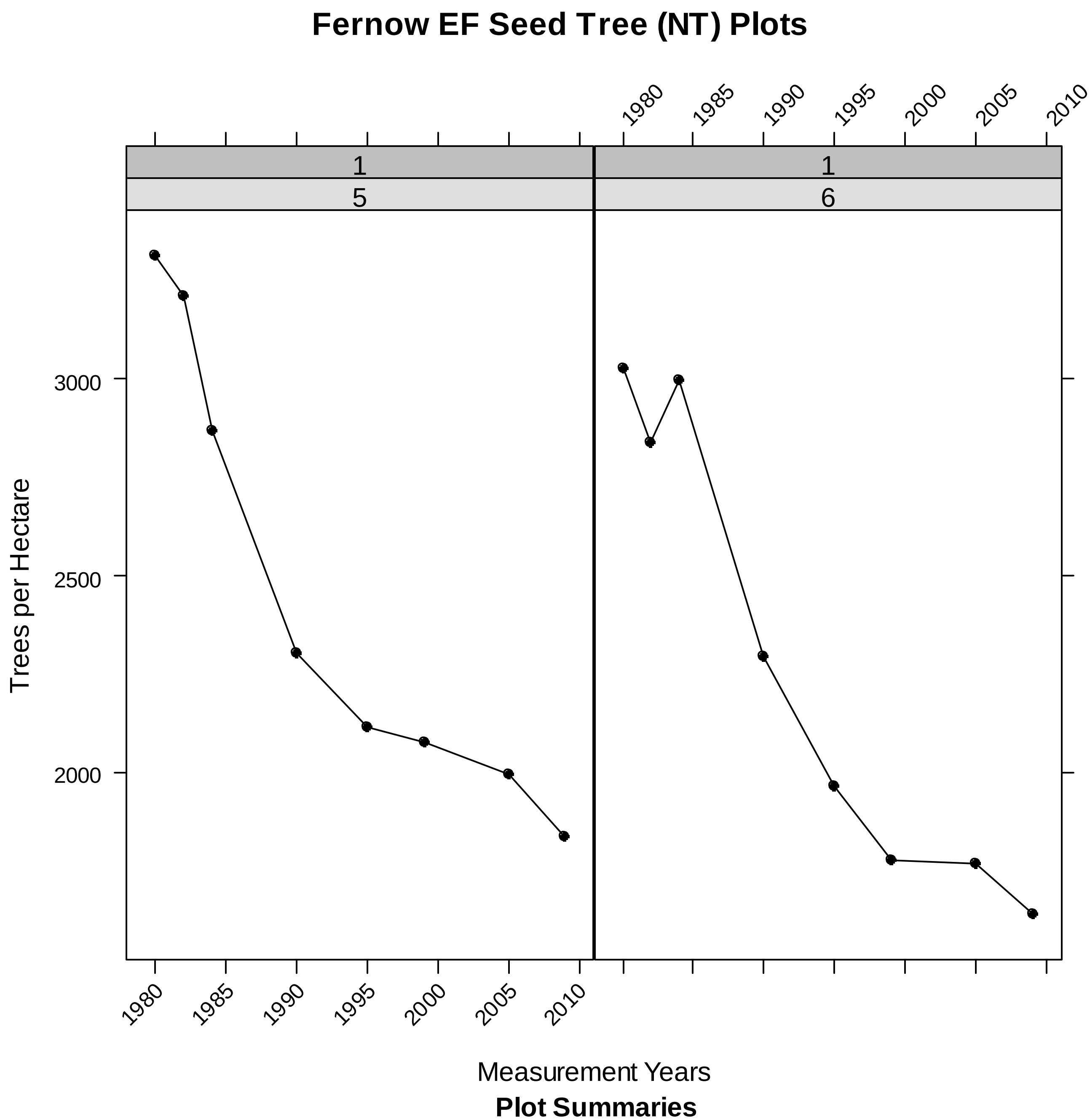


Figure A70. Trees per hectare through time on the Fernow Experimental Forest (FEF) non-thinned seed tree plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

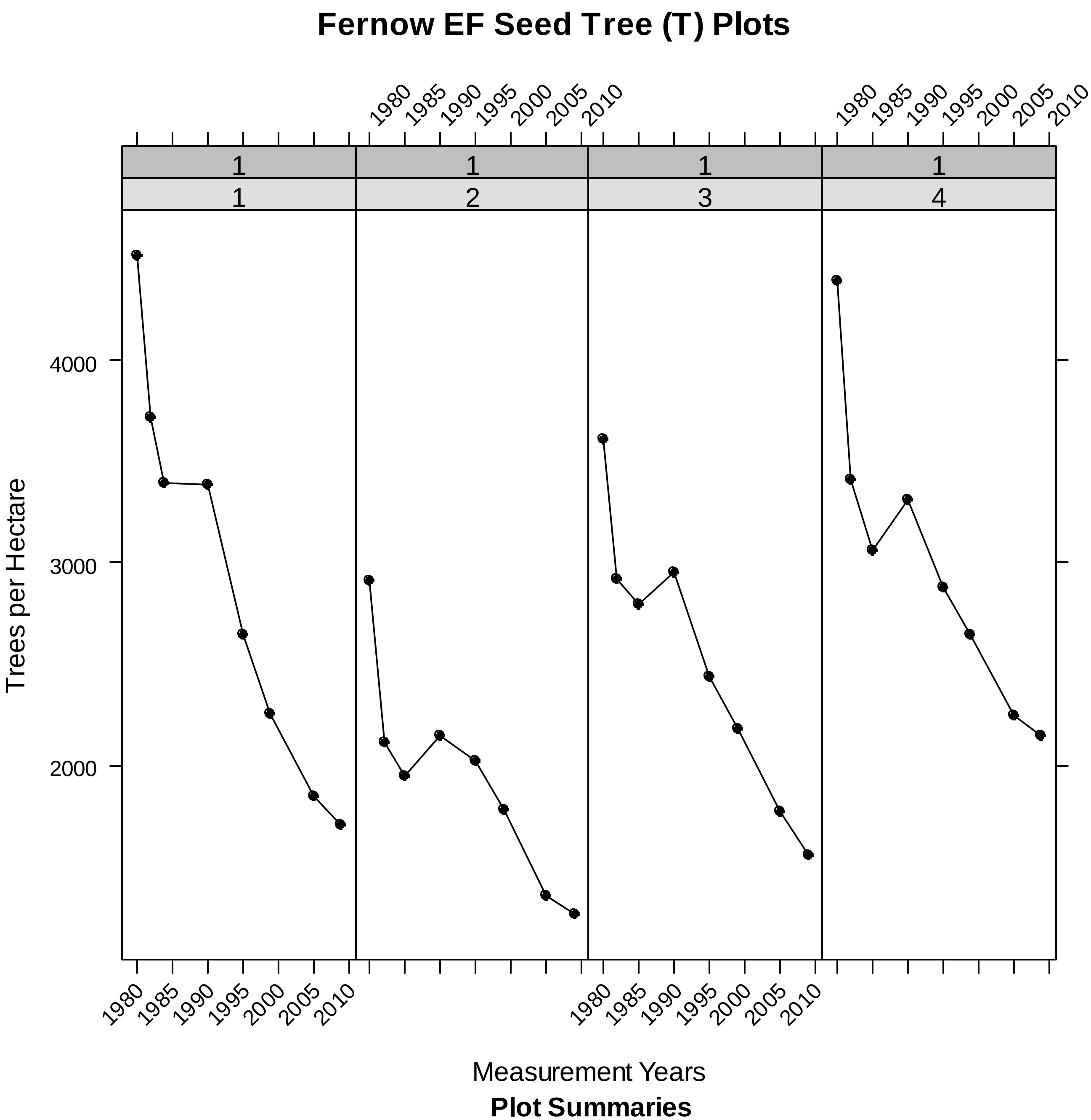


Figure A71. Trees per hectare through time on the Fernow Experimental Forest (FEF) thinned seed tree plots. The value in darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in light grey section is actual plot number.

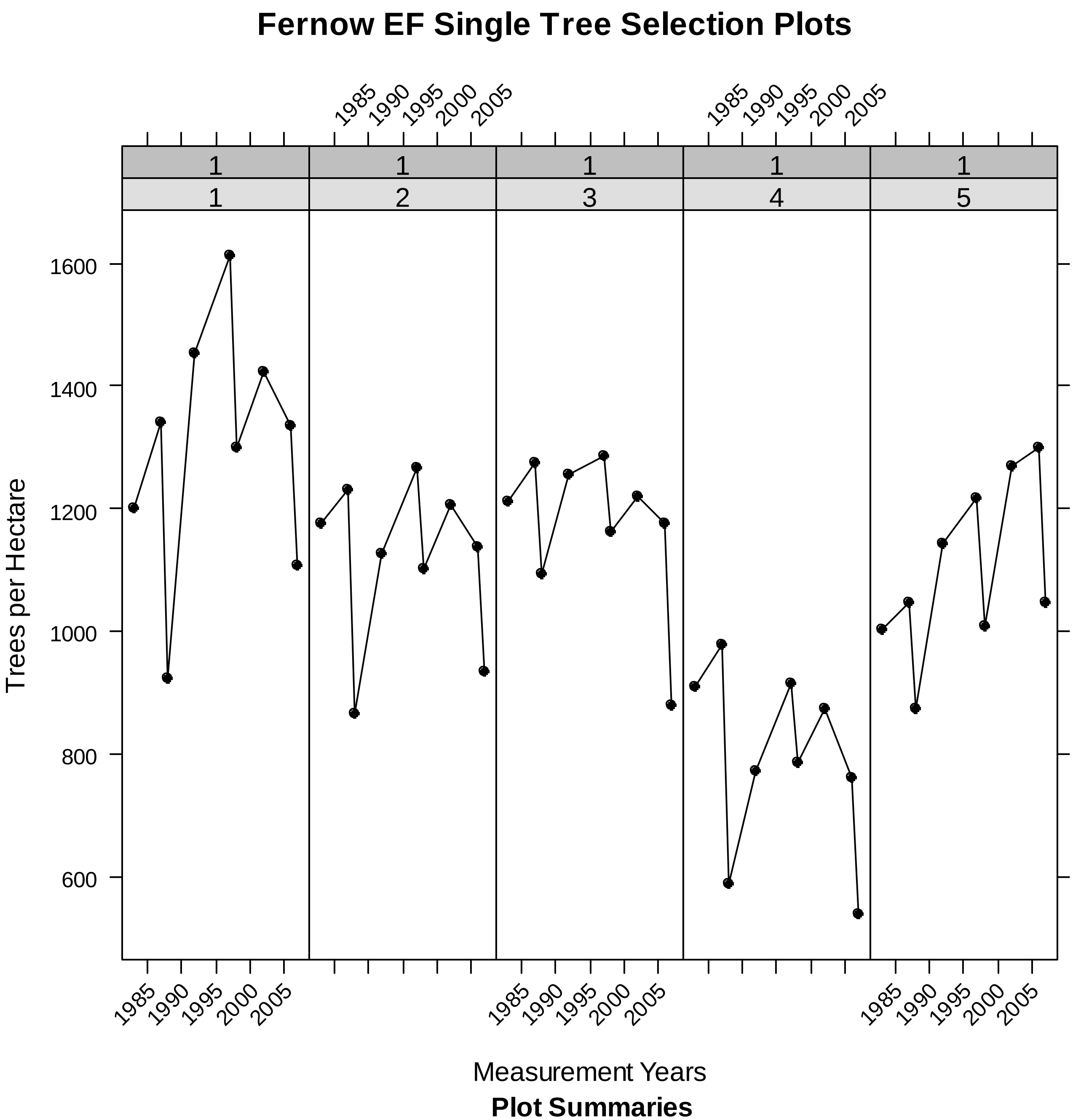


Figure A72. Trees per hectare through time on the Fernow Experimental Forest (FEF) single-tree selection plots. The value in darker grey section is standardized treatment replicate (A:1), while the value is in light grey section is actual plot number.

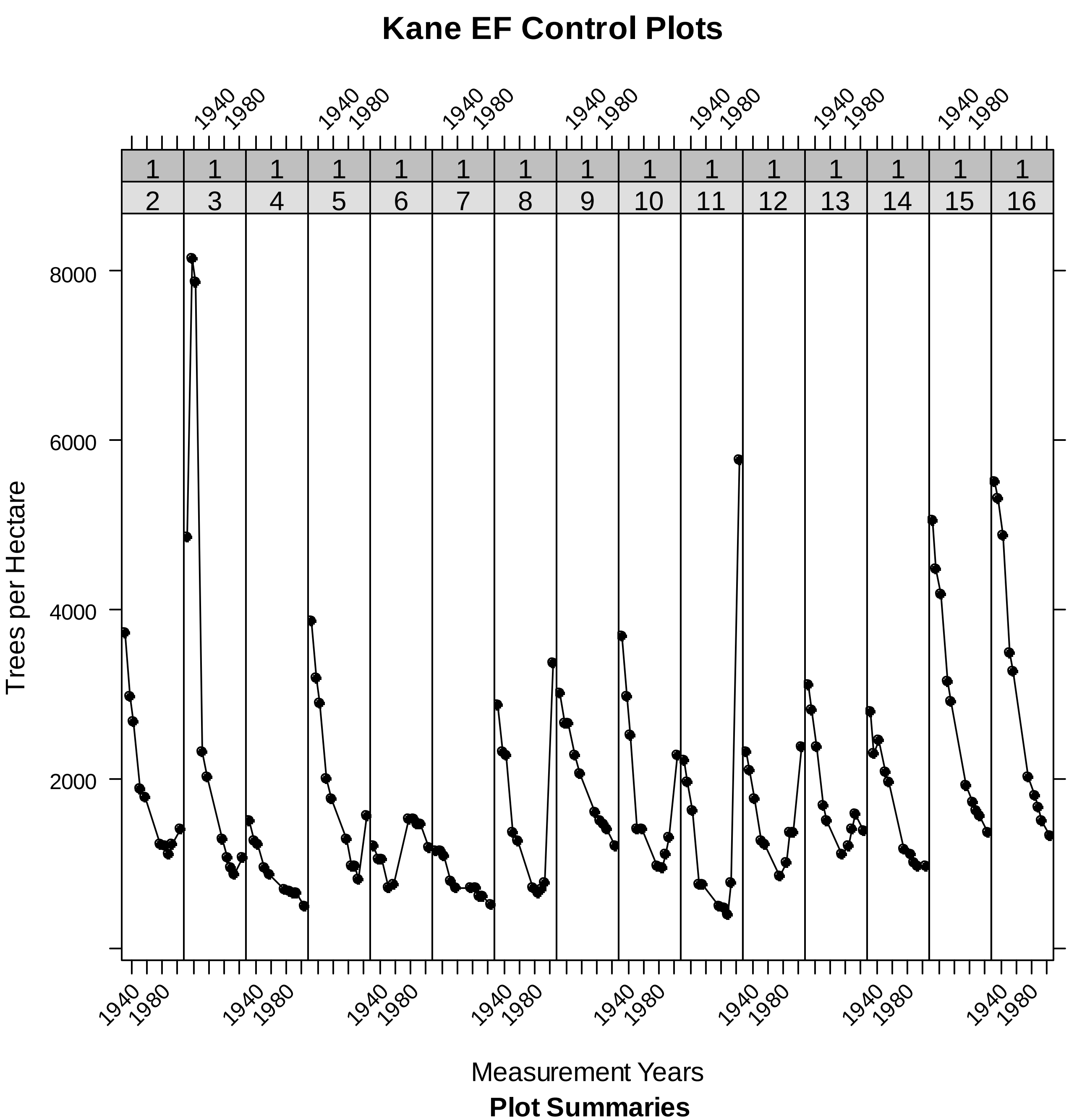


Figure A73. Trees per hectare through time on the Kane Experimental Forest (KEF) control plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

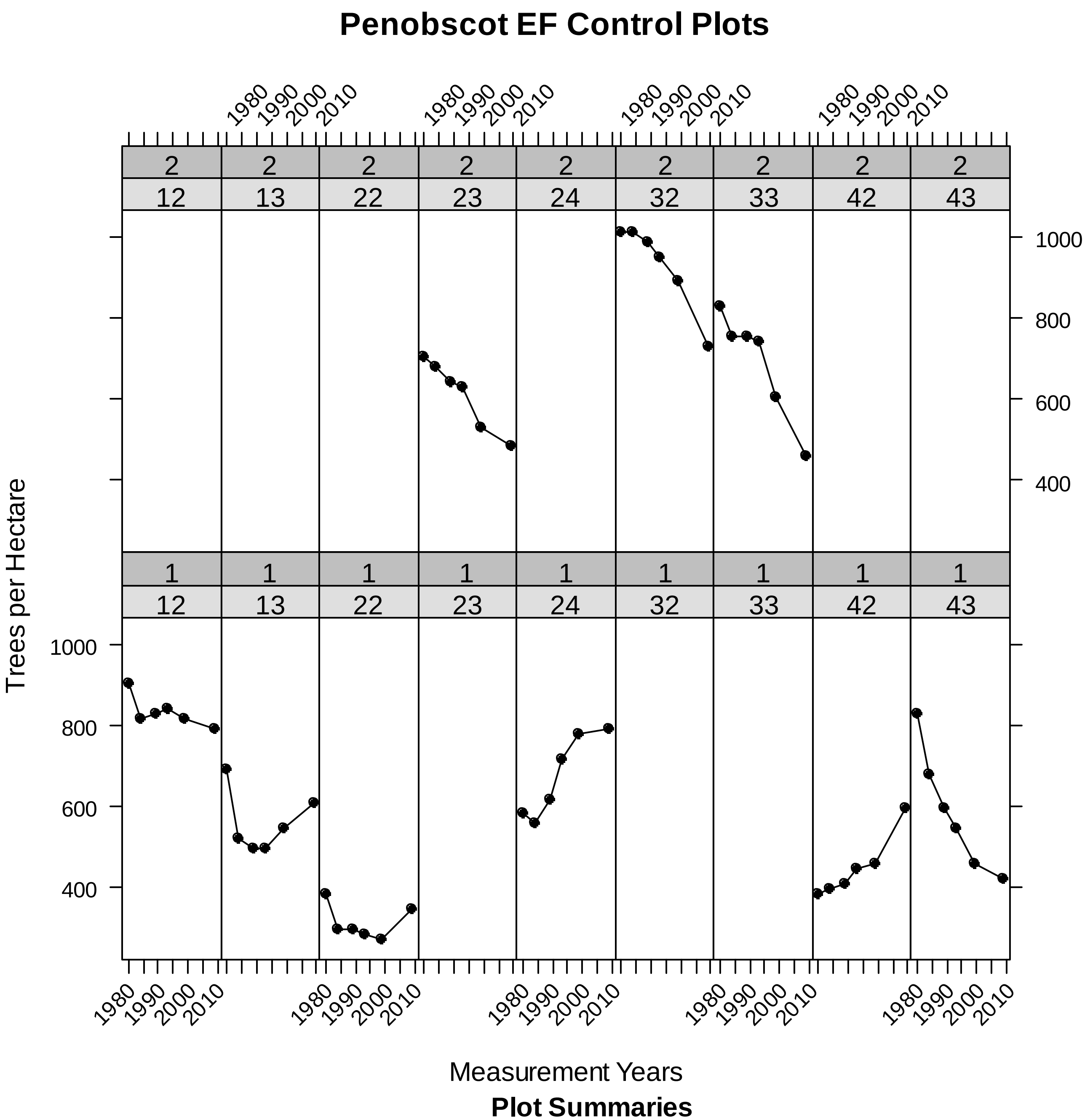


Figure A74. Trees per hectare through time on the Penobscot Experimental Forest (PEF) control plots. The value in darker grey section is standardized treatment replicate (1: MU 32A, 2: MU 32B), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

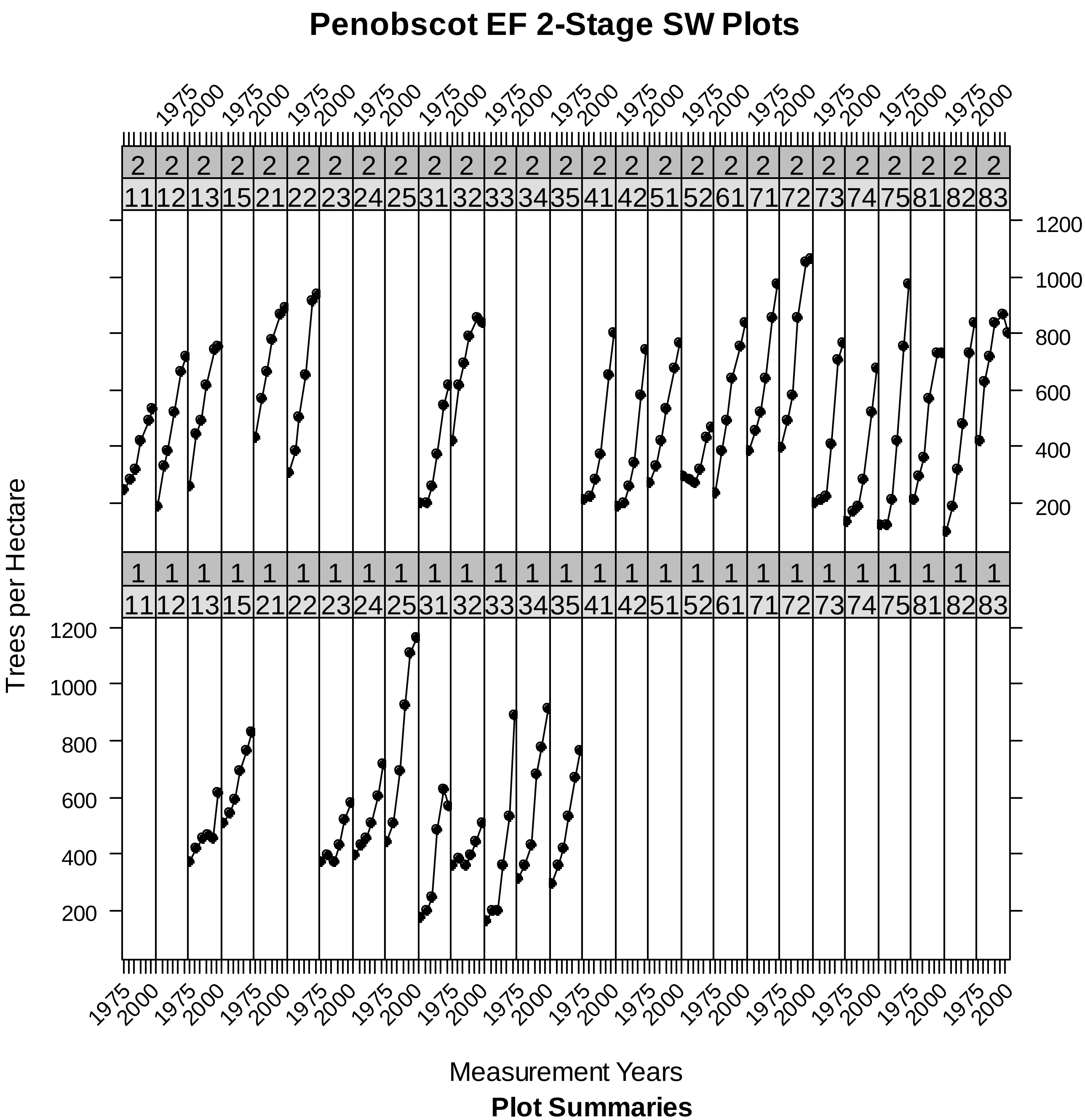


Figure A75. Trees per hectare through time on the Penobscot Experimental Forest (PEF) two-stage shelterwood plots. The value in darker grey section is standardized treatment replicate (1: MU 21, 2: MU 30), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

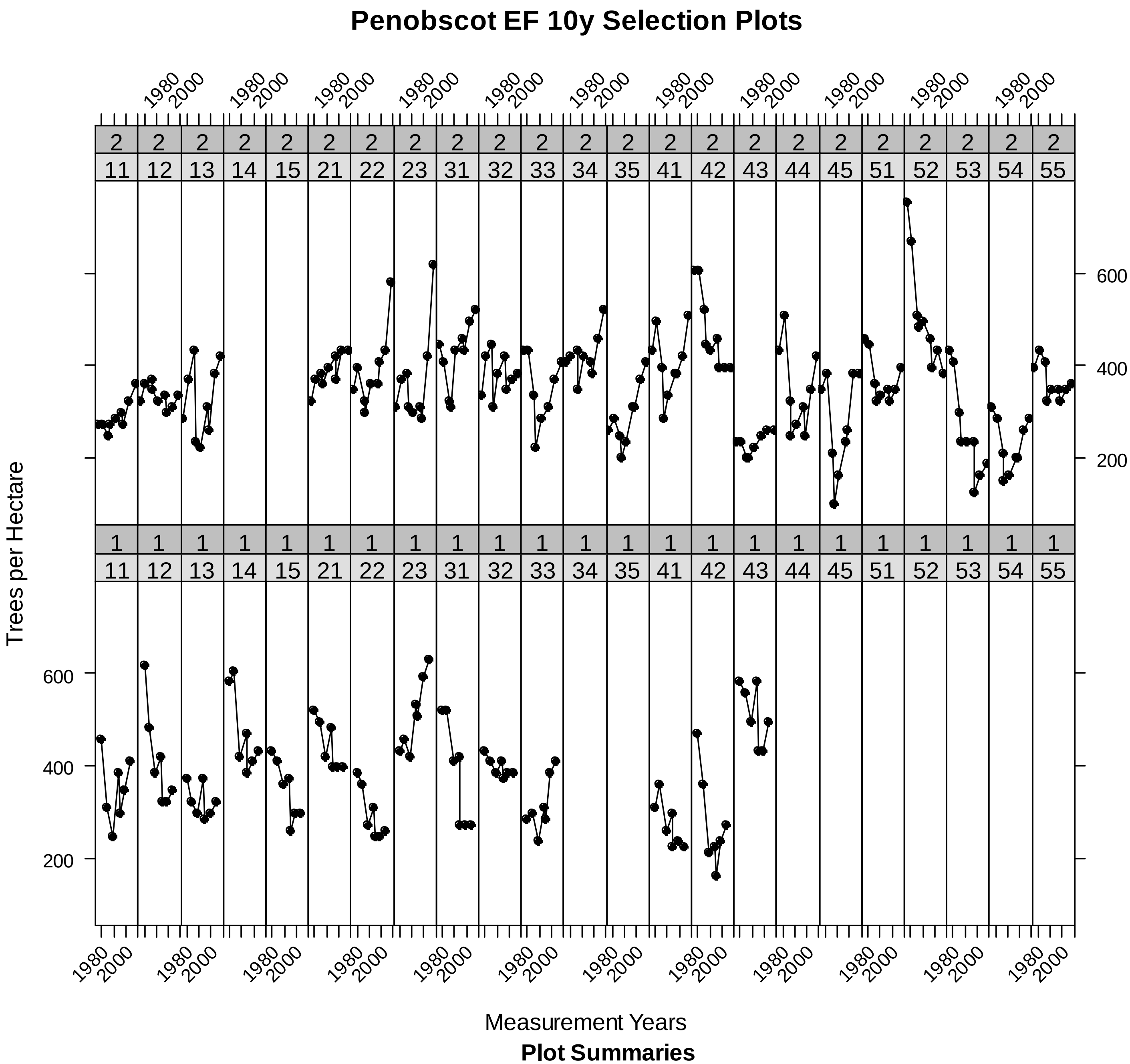


Figure A76. Trees per hectare through time on the Penobscot Experimental Forest (PEF) ten-year selection plots. The value in darker grey section is standardized treatment replicate (1:MU 12, 2: MU 20), while the value is in light grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

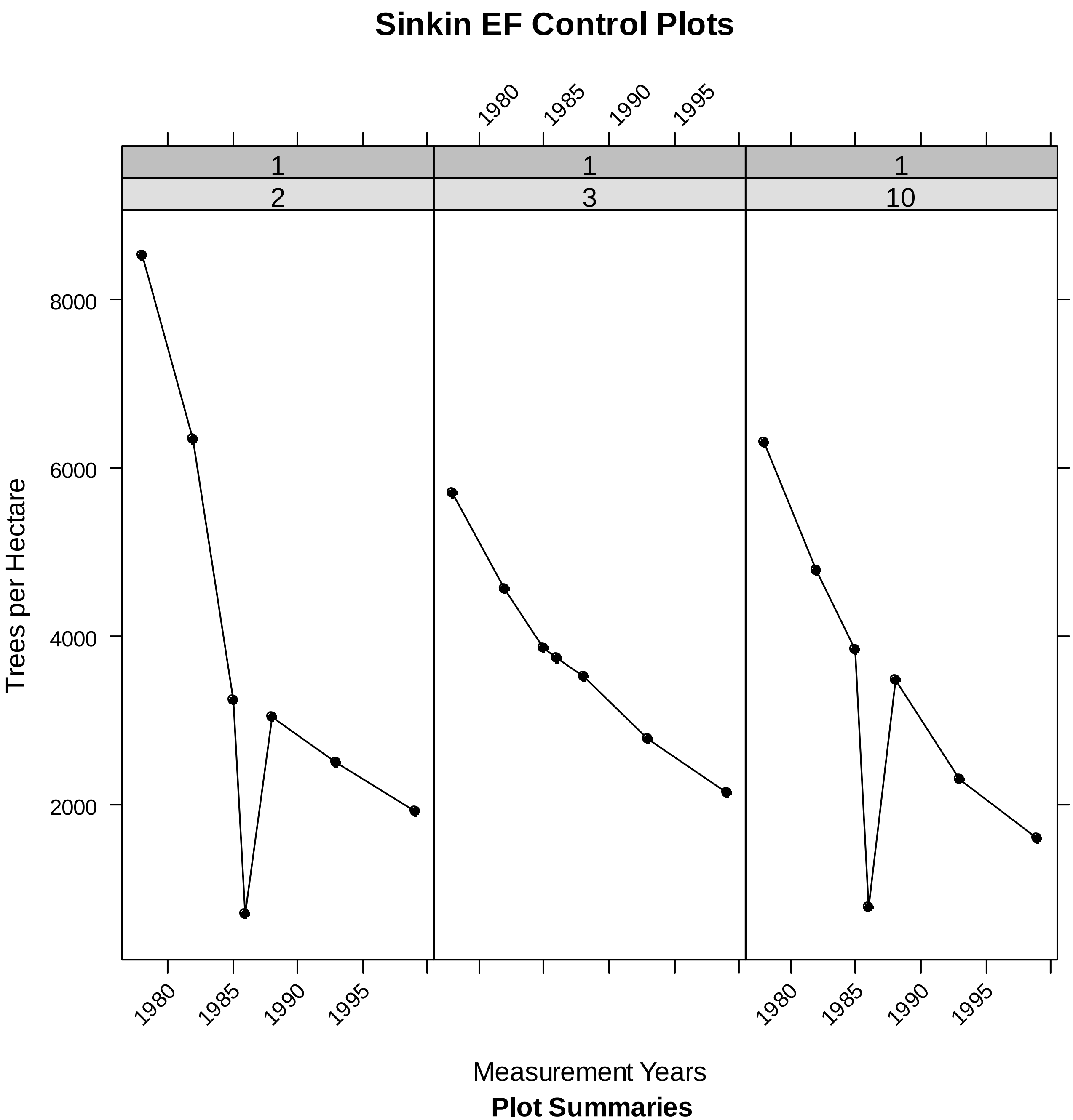


Figure A77. Trees per hectare through time on the Sinkin Experimental Forest (SEF) spatial distribution control plots. The value in darker grey section is standardized treatment replicate , while the value is in light grey section is actual plot number.

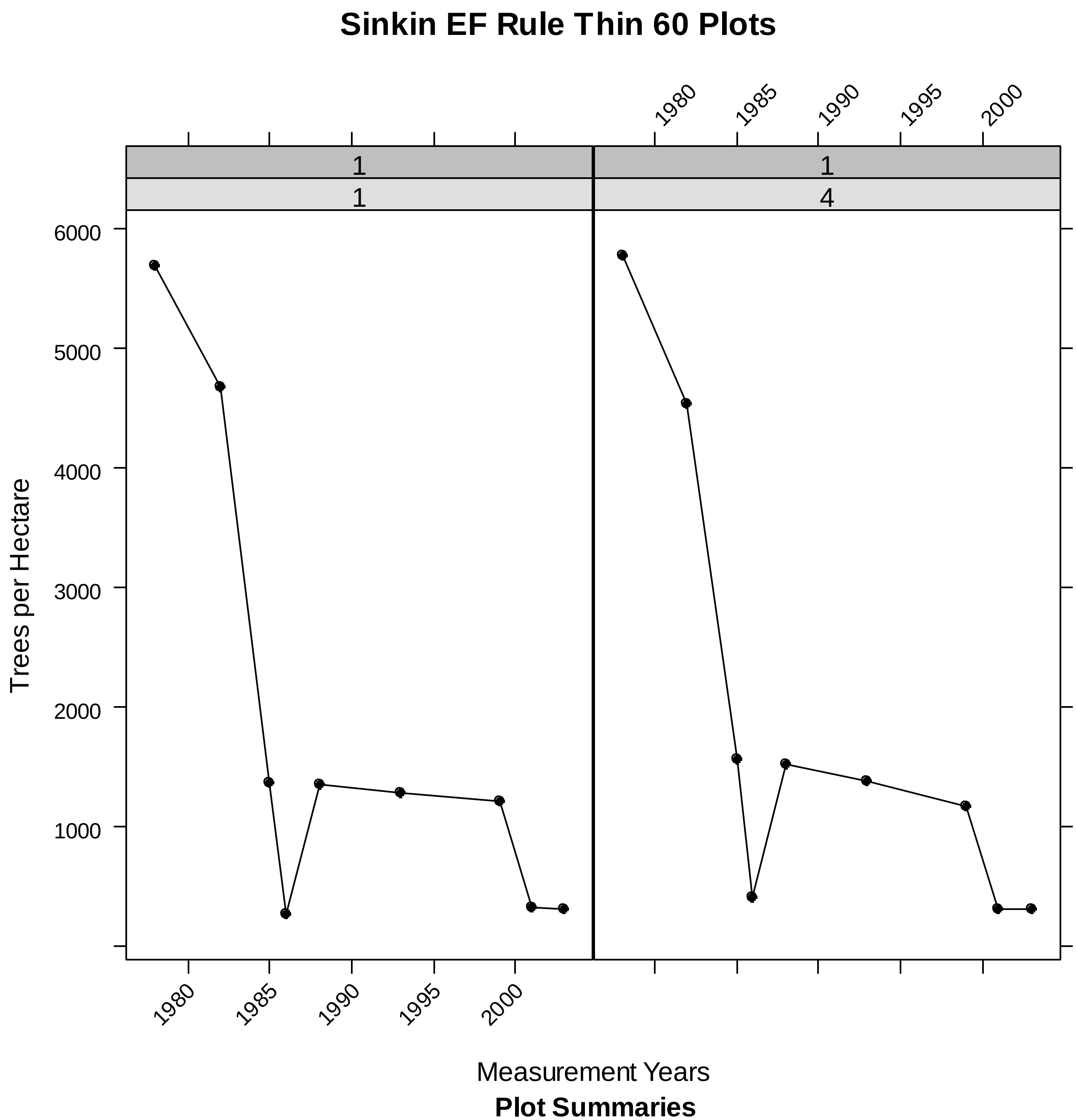


Figure A78. Trees per hectare through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (60%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

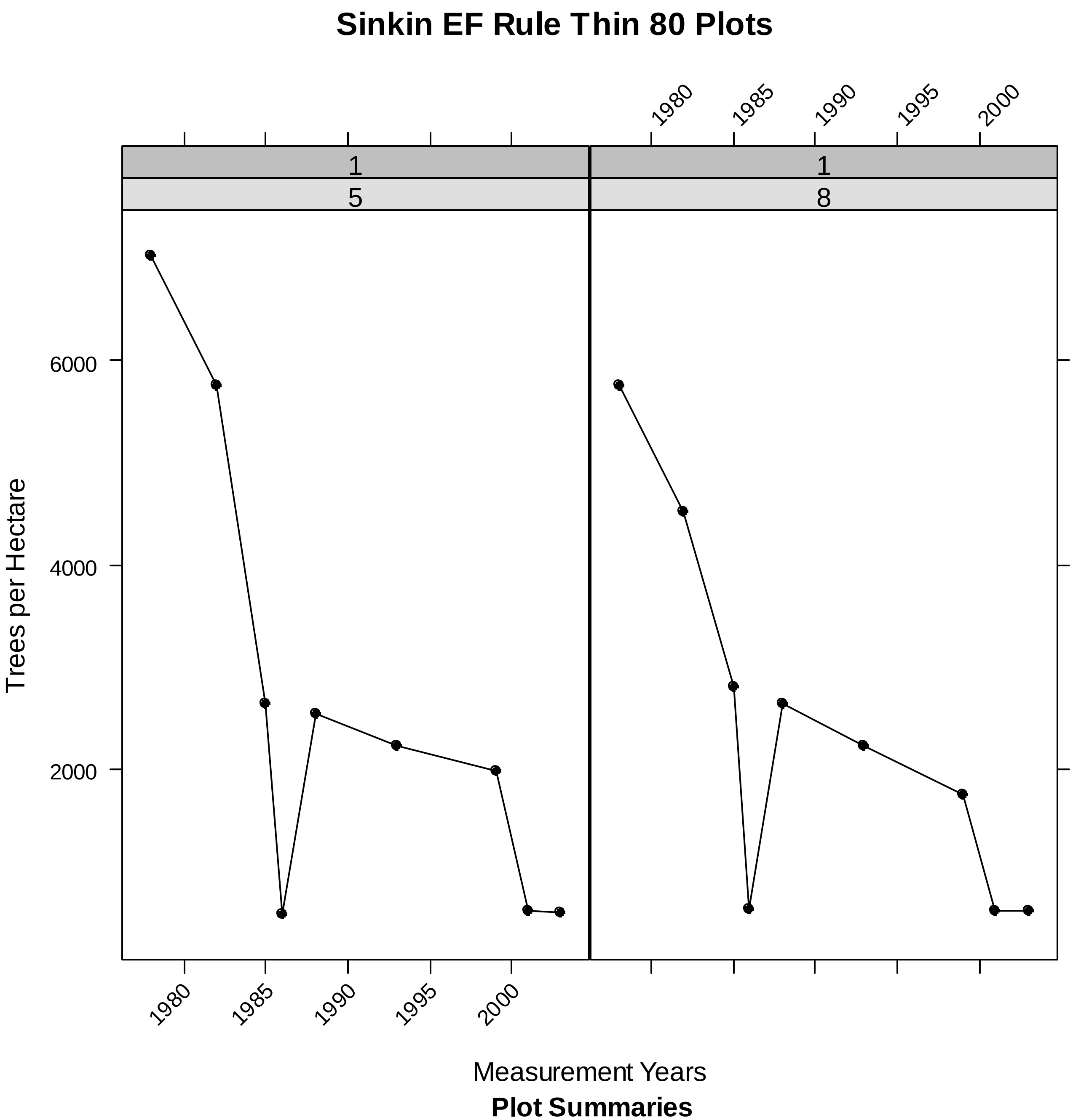


Figure A80. Trees per hectare through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (80%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

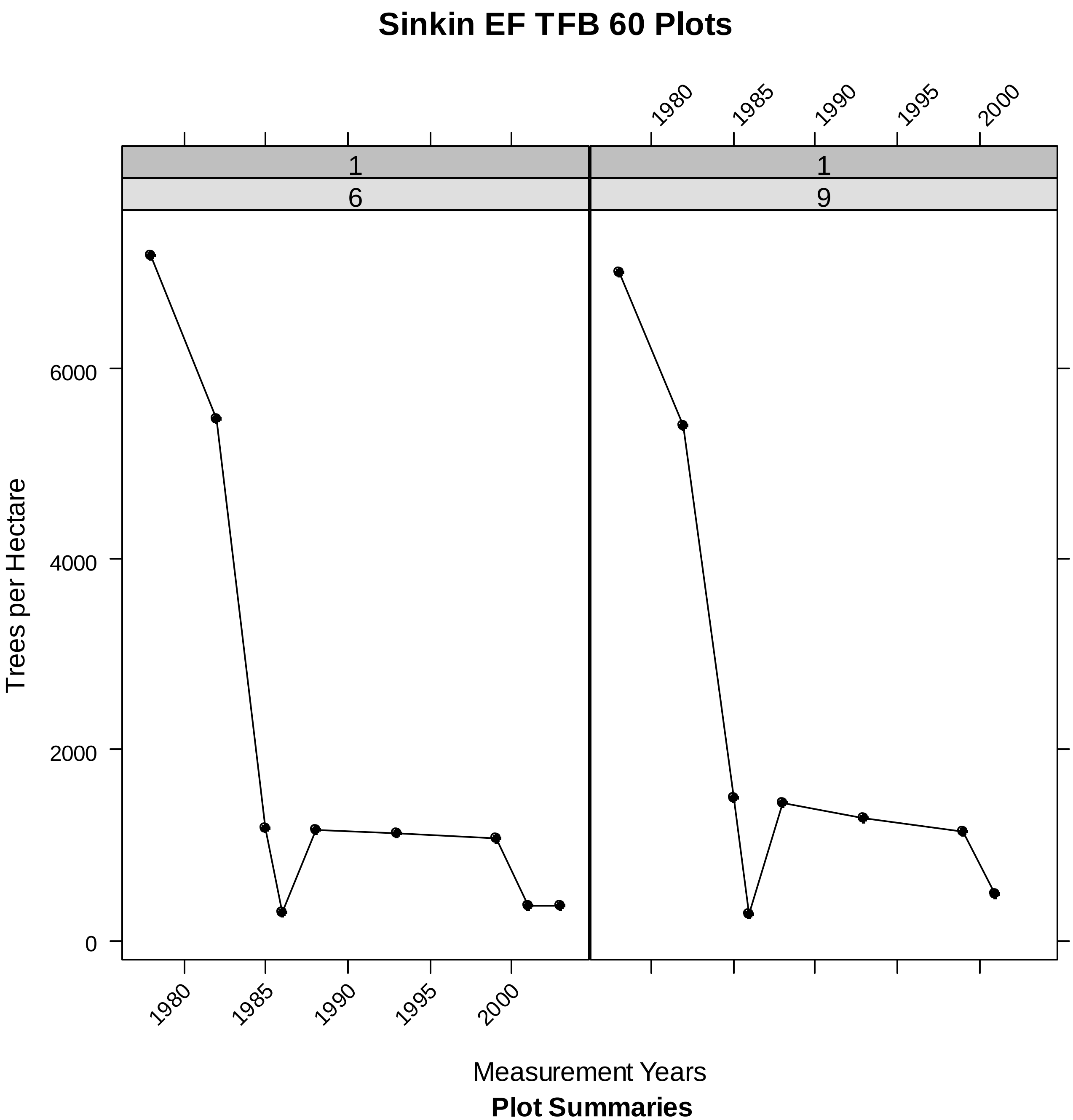


Figure A81. Trees per hectare through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (60%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

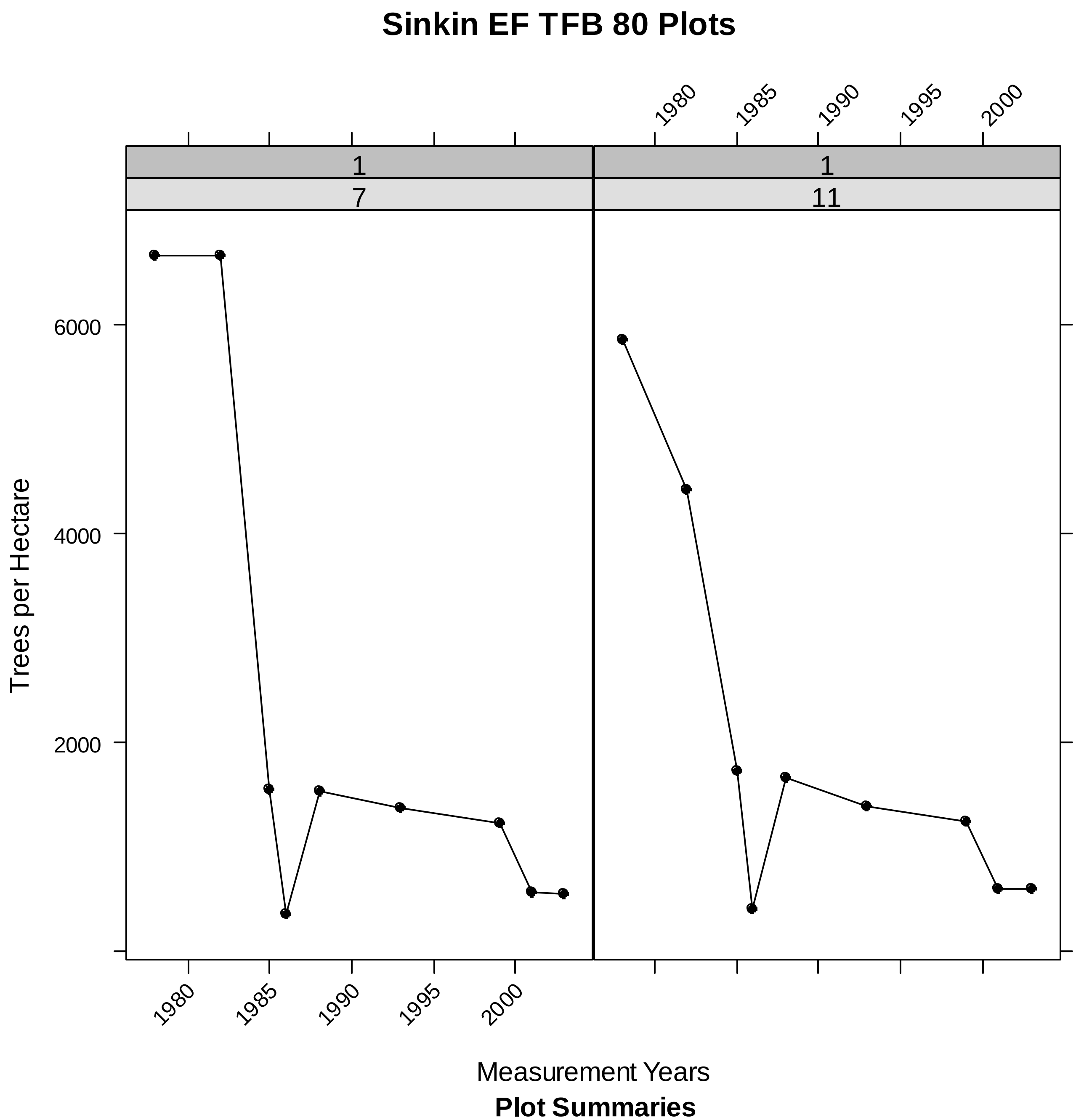


Figure A81. Trees per hectare through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (80%) plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

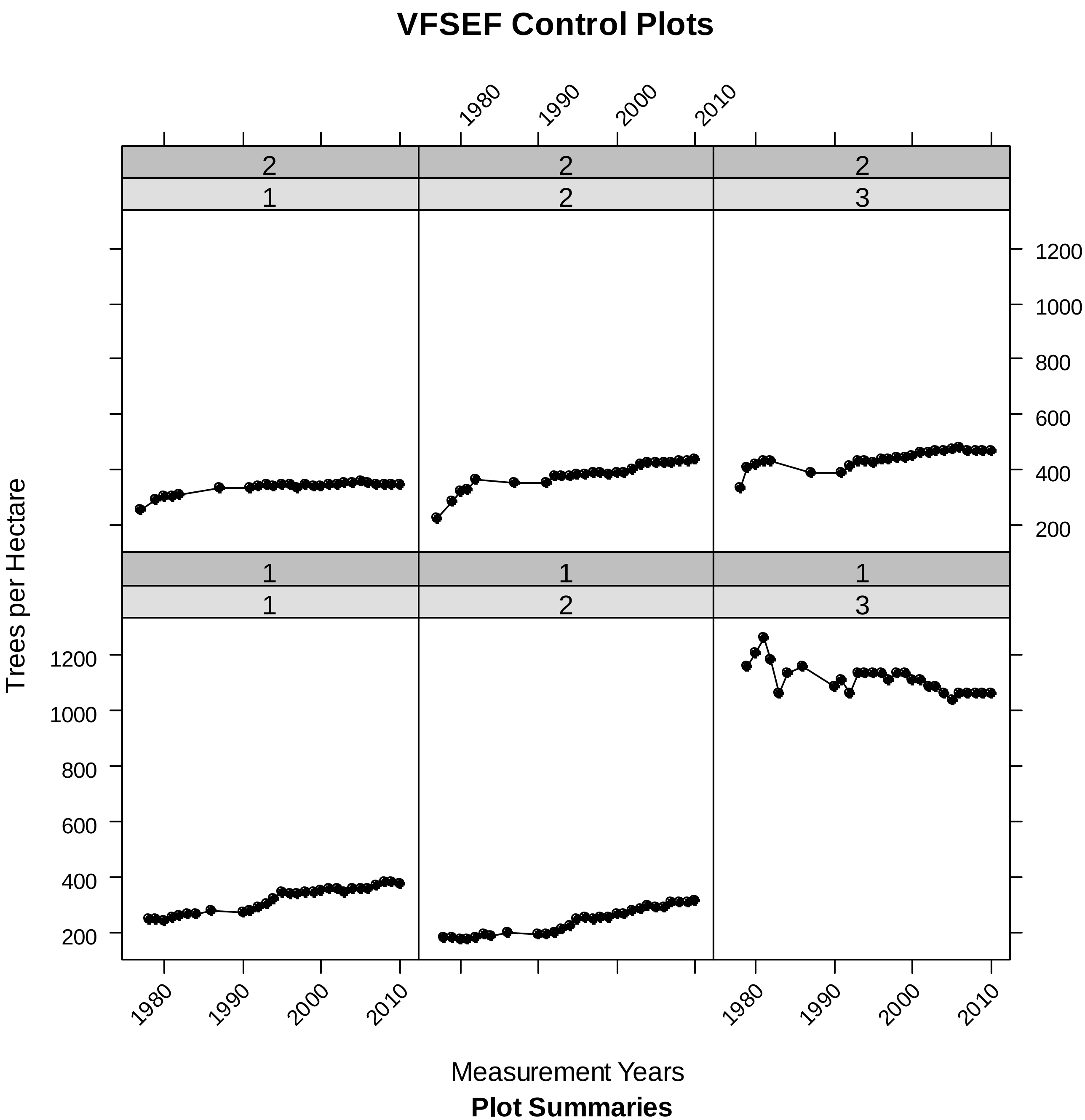


Figure A82. Trees per hectare through time on the Vinton-Furnace State Experimental Forest (VFSEF) control plots. The value in darker grey section is standardized treatment replicate (1-2, Study 25, 27 respectively) , while the value is in light grey section is actual plot number.

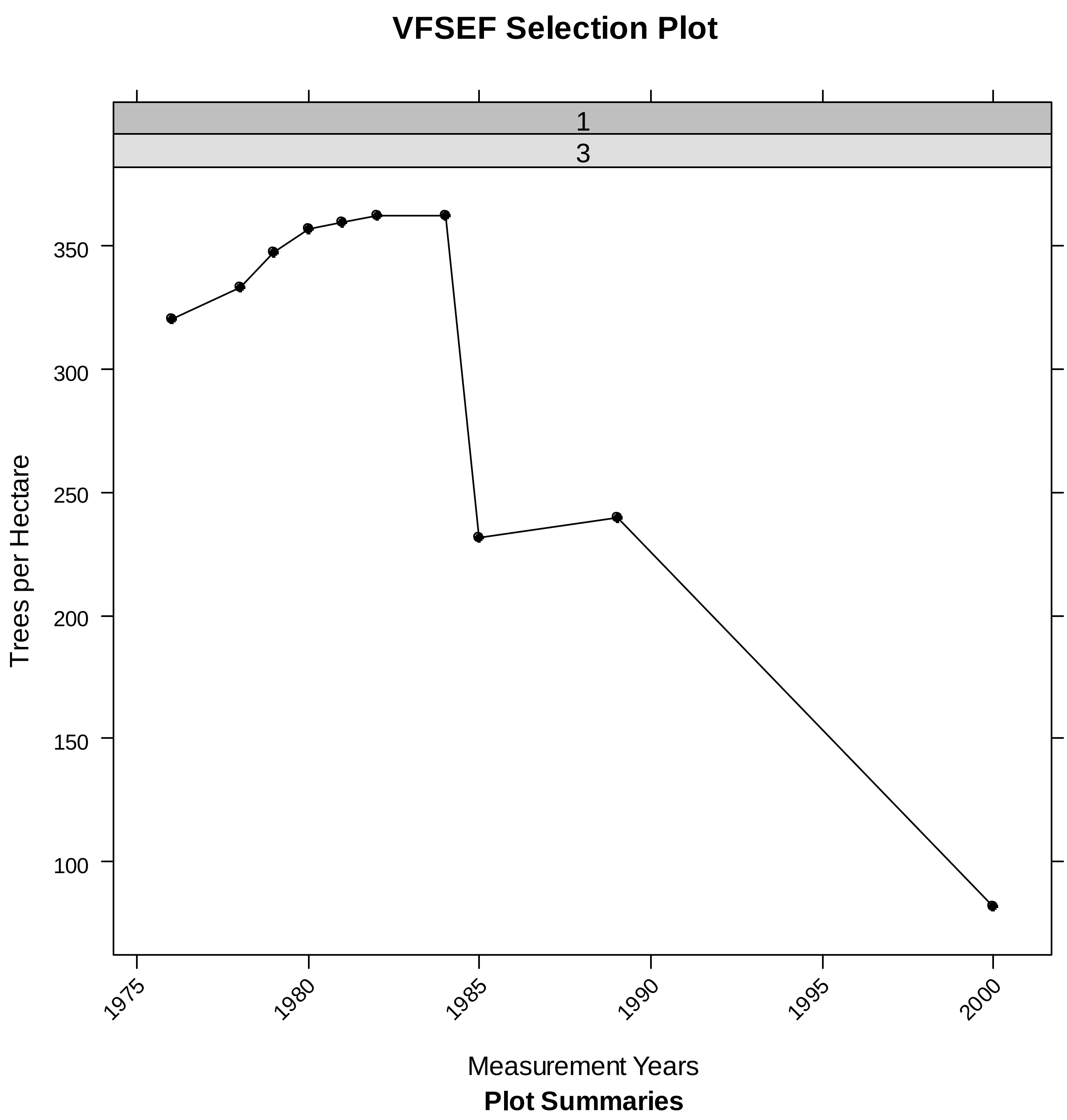


Figure A83. Trees per hectare through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

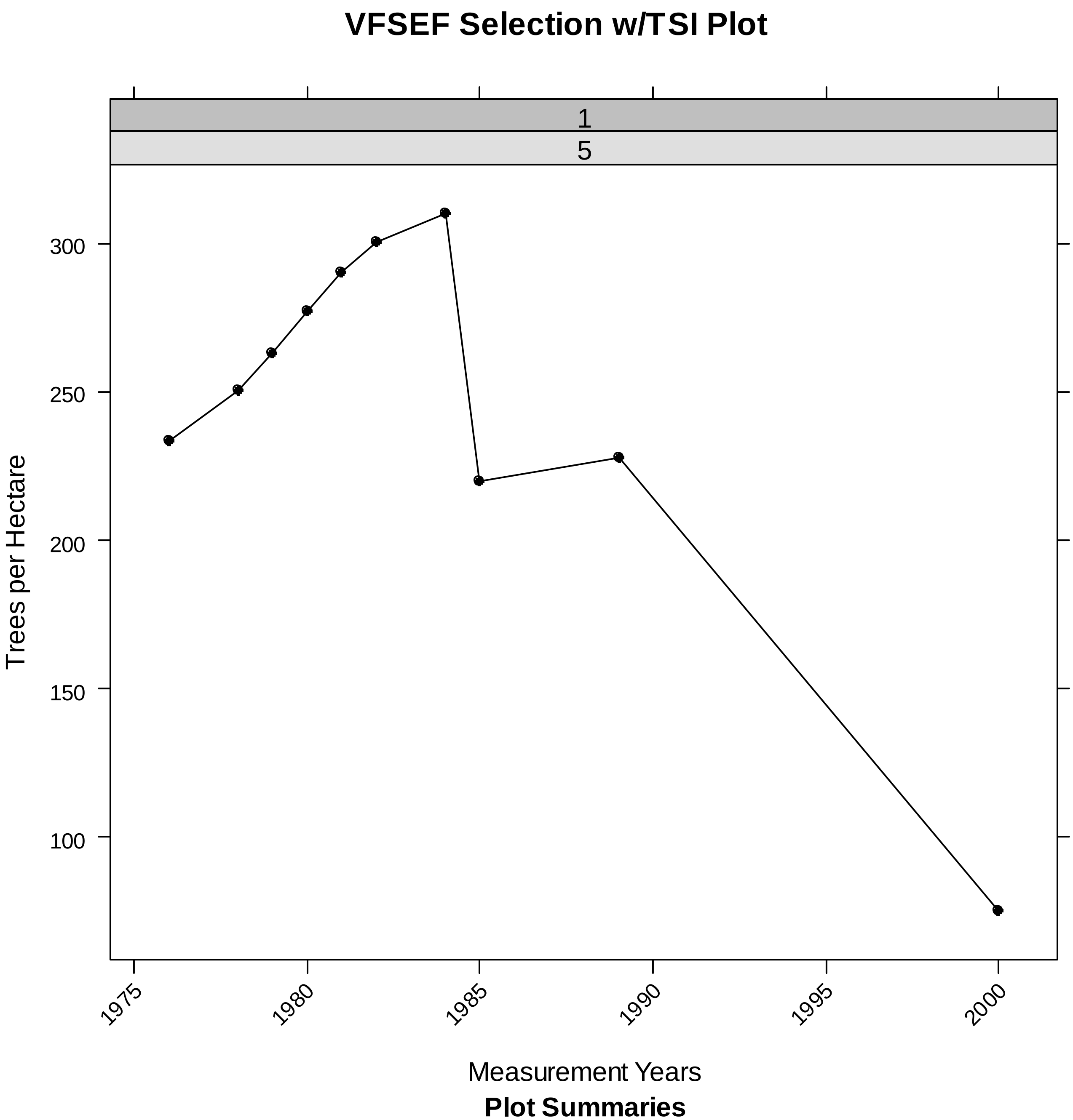


Figure A84. Trees per hectare through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection with timber stand improvement plots. The value in darker grey section is standardized treatment replicate, while the value is in light grey section is actual plot number.

APPENDIX B. Truncation effects by unique treatment type across USFS Silvicultural trials

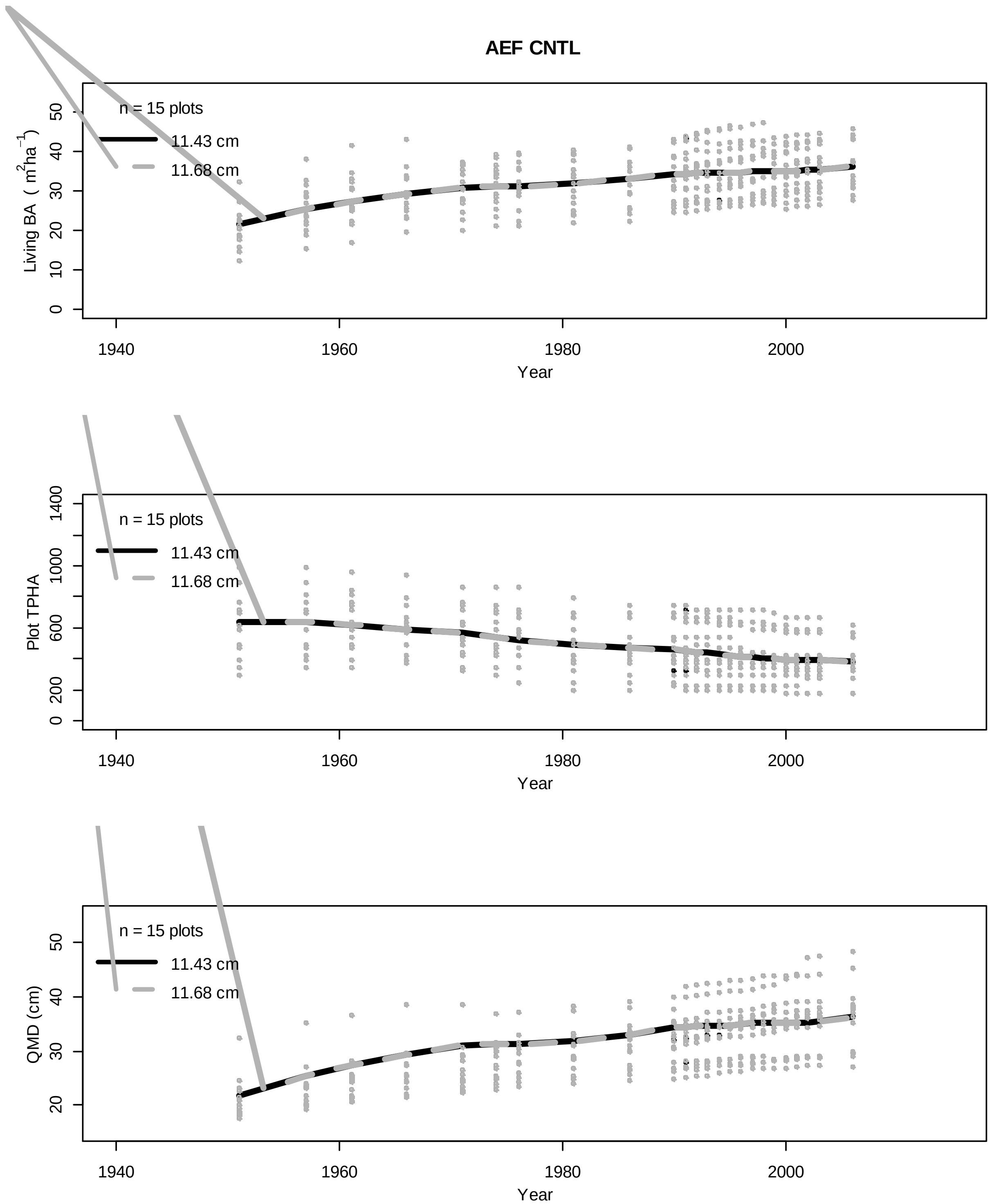
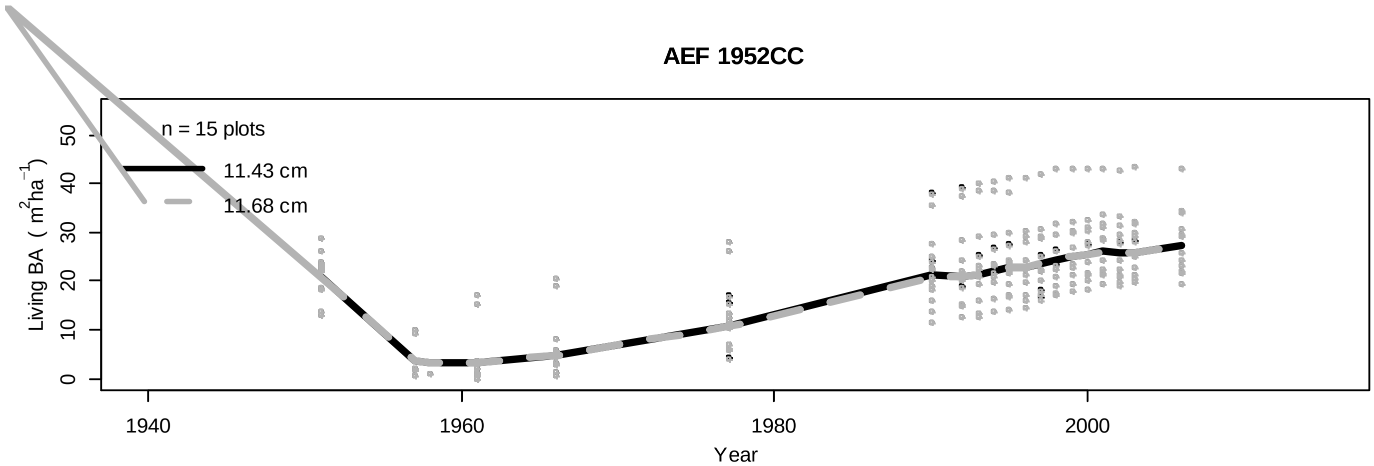
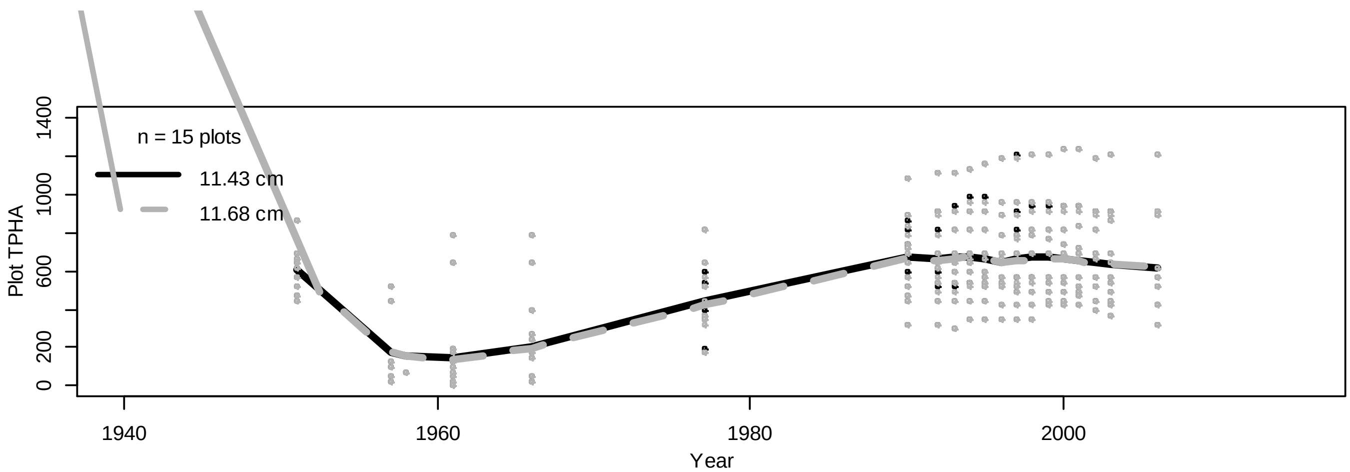


Figure B1. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Argonne Experimental Forest (AEF) control plots. Additional experiment level diameter re-measures may be available.

AEF 1952CC





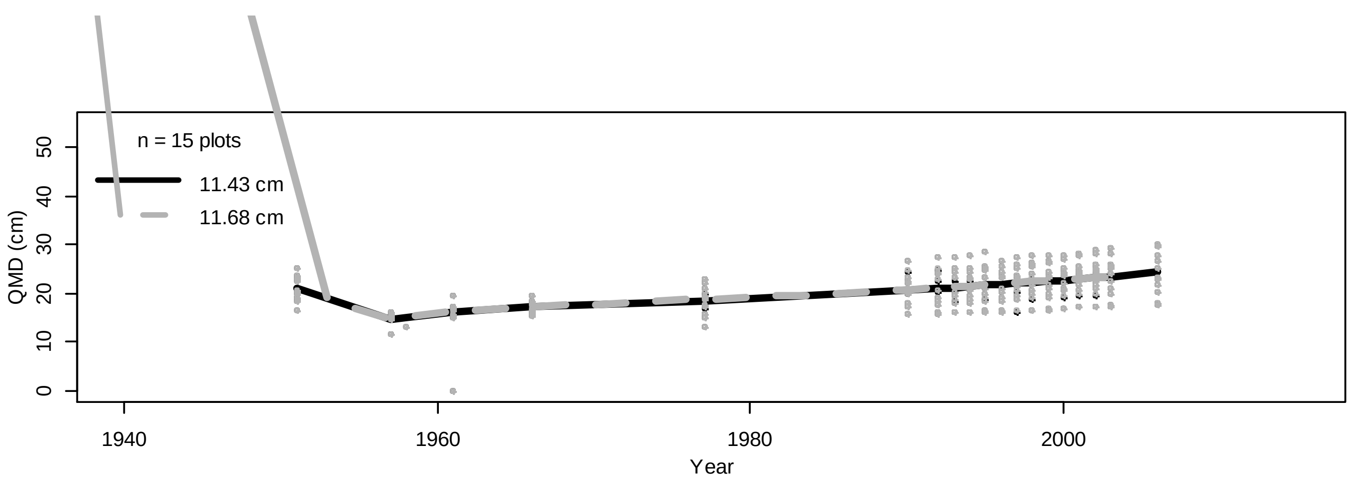


Figure B2. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Argonne Experimental Forest (AEF) clearcut (ca. 1951) plots. Additional experiment level diameter re-measures may be available.

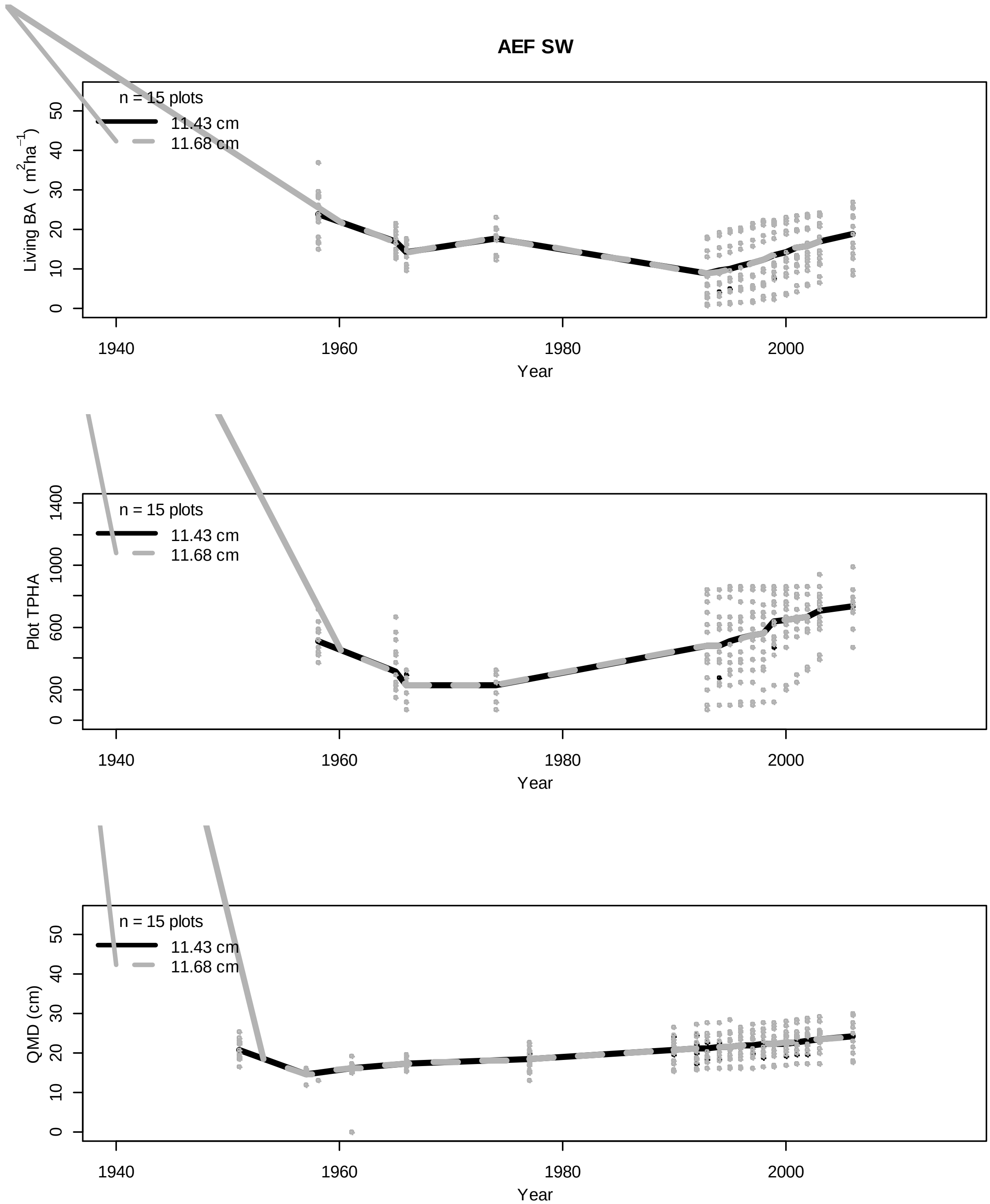


Figure B3. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Argonne Experimental Forest (AEF) two-stage shelterwood plots. Additional experiment level diameter re-measures may be available.

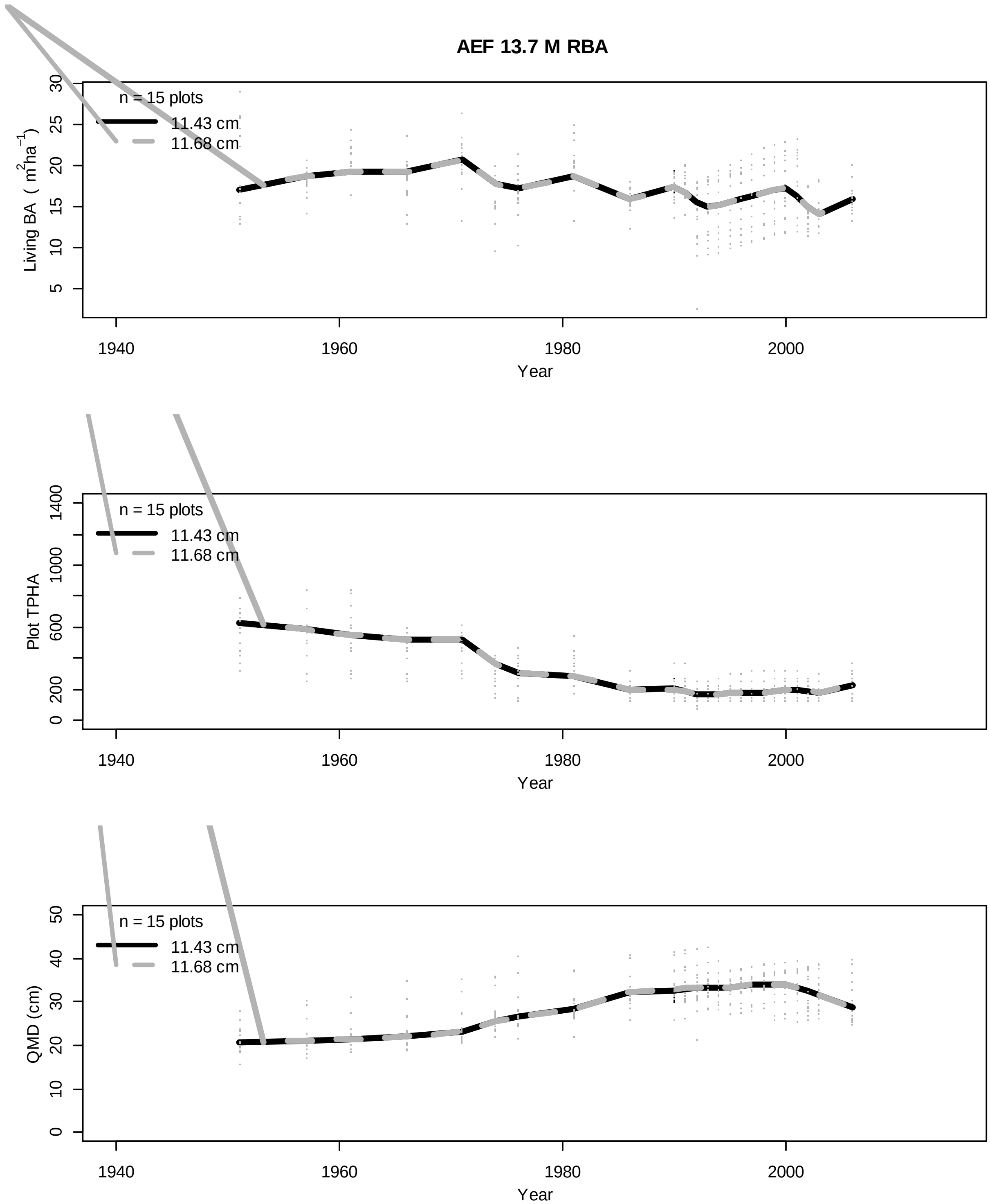


Figure B4. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Argonne Experimental Forest (AEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

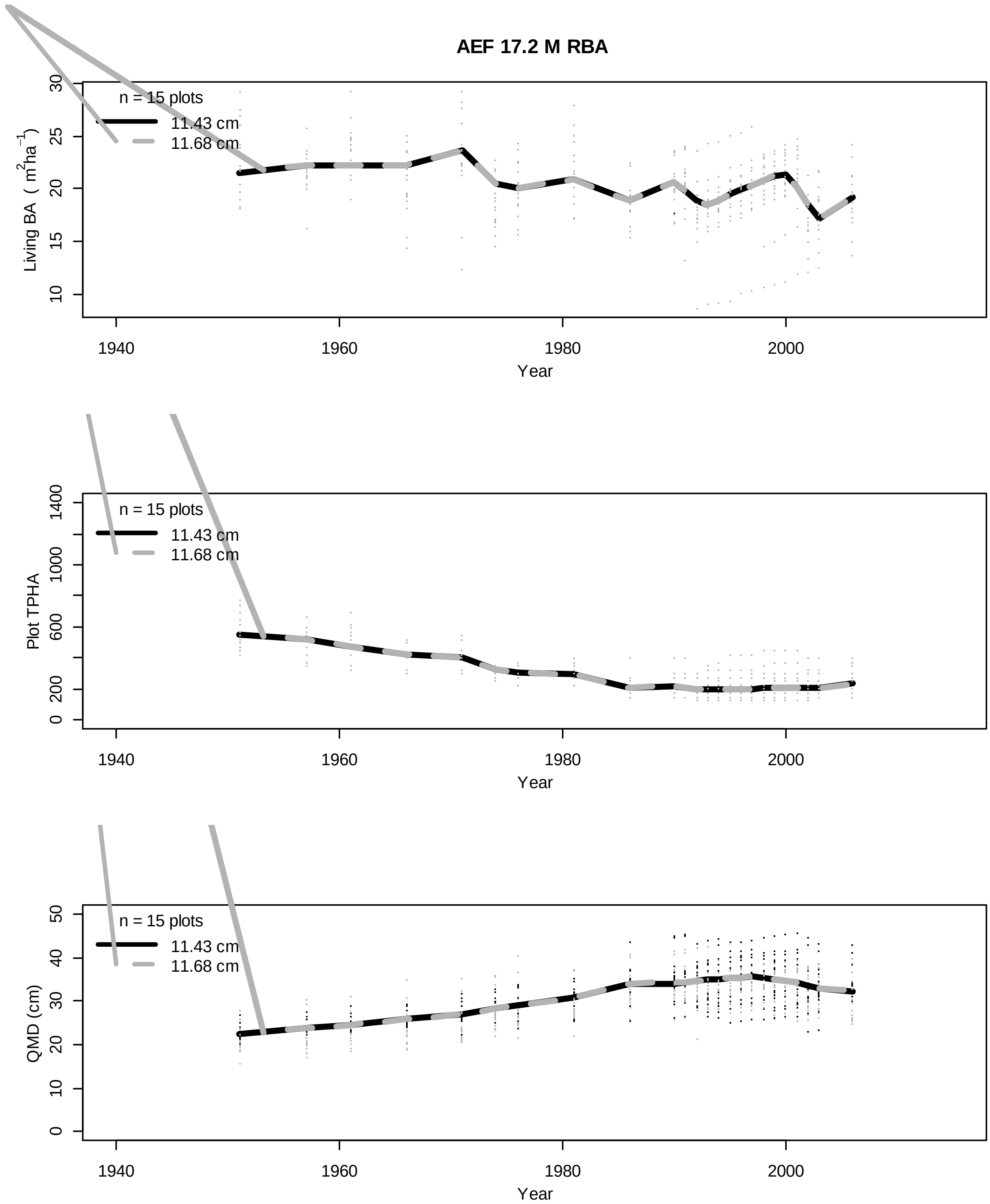


Figure B5. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Argonne Experimental Forest (AEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

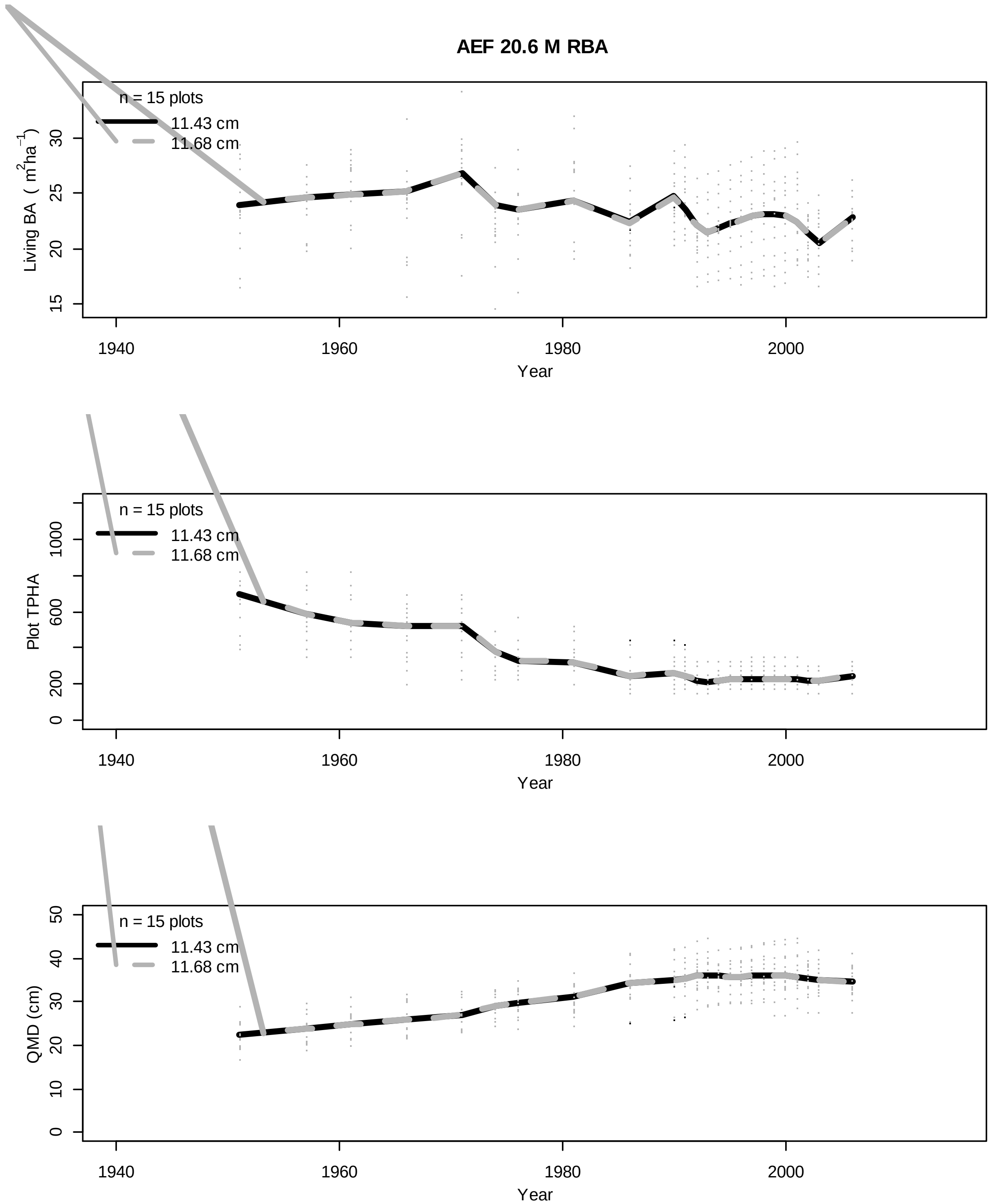


Figure B6. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Argonne Experimental Forest (AEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

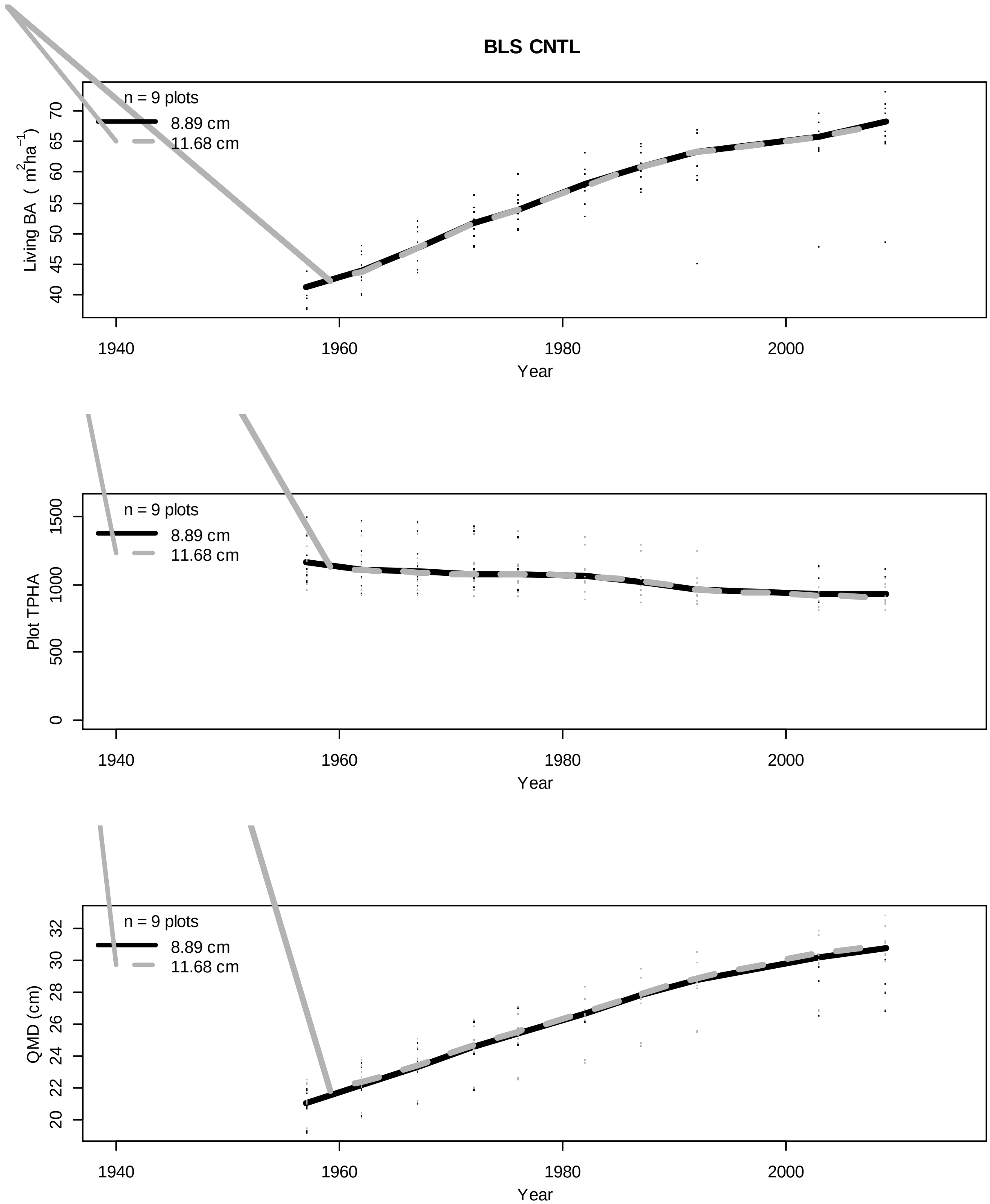


Figure B7. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Birch Lake Study (BLS) control plots.

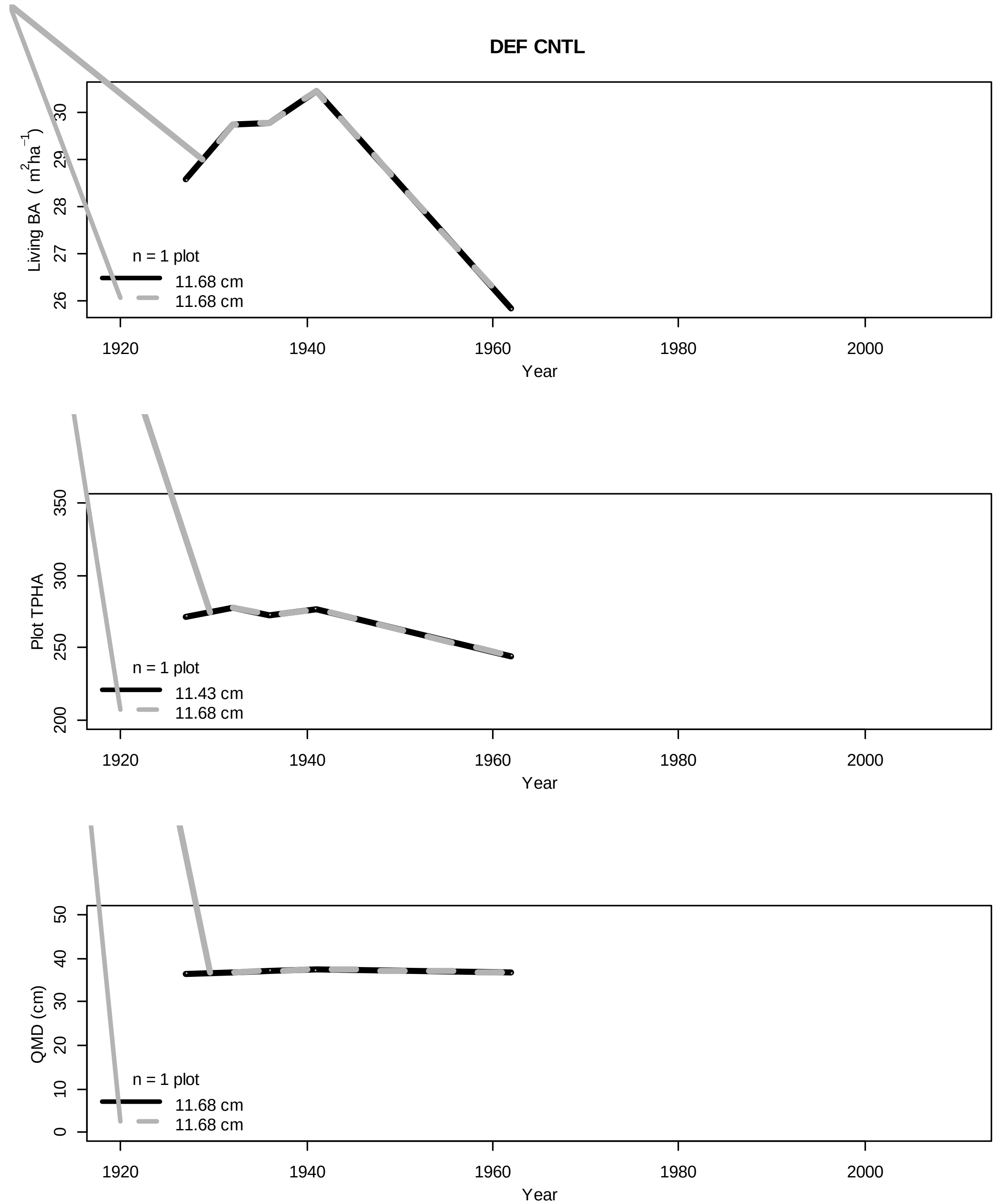


Figure B8. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Dukes Experimental Forest (DEF) control plot. Additional experiment level diameter re-measures may be available.

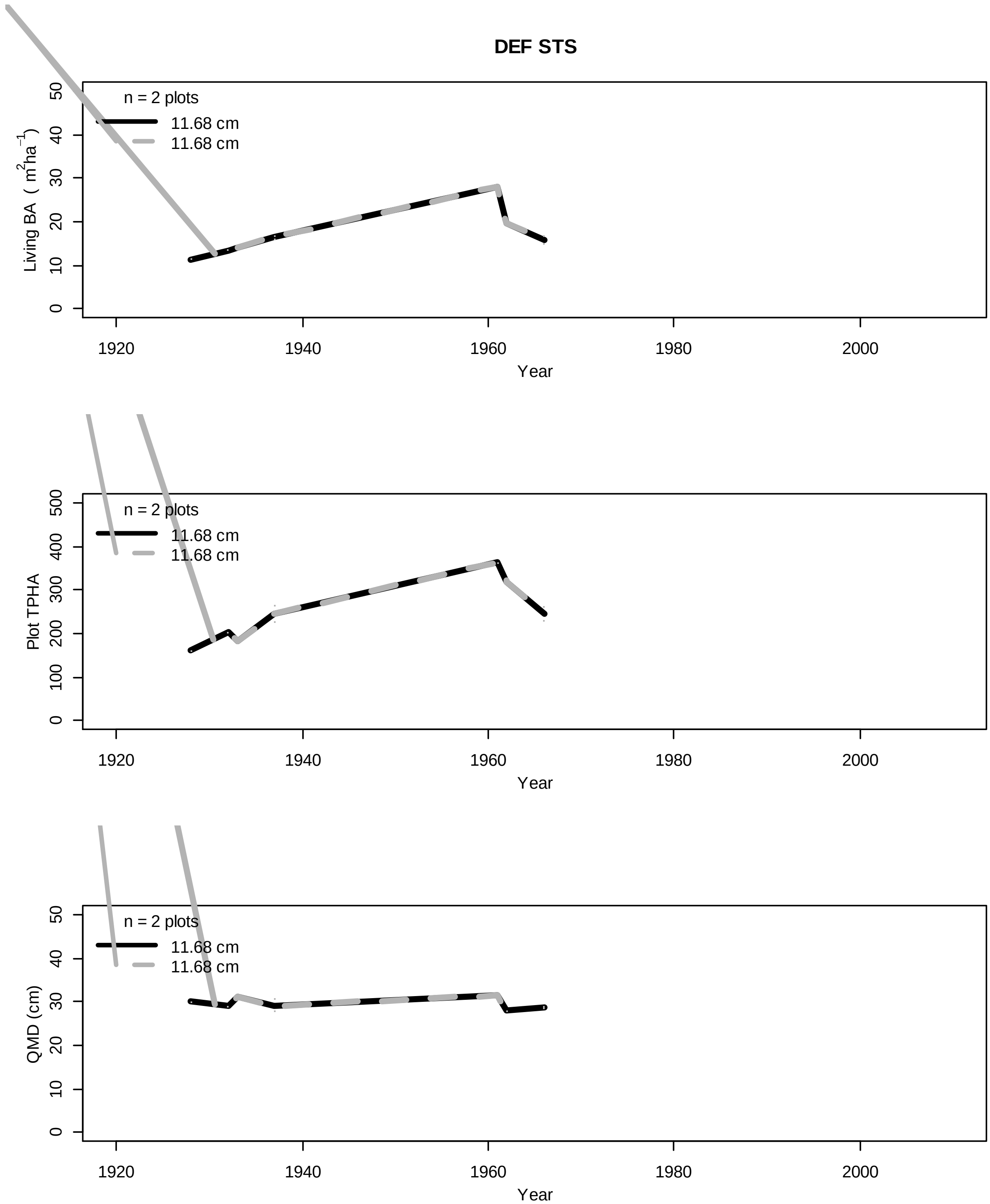


Figure B9. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Dukes Experimental Forest (DEF) single tree selection plots. Additional experiment level diameter re-measures may be available.

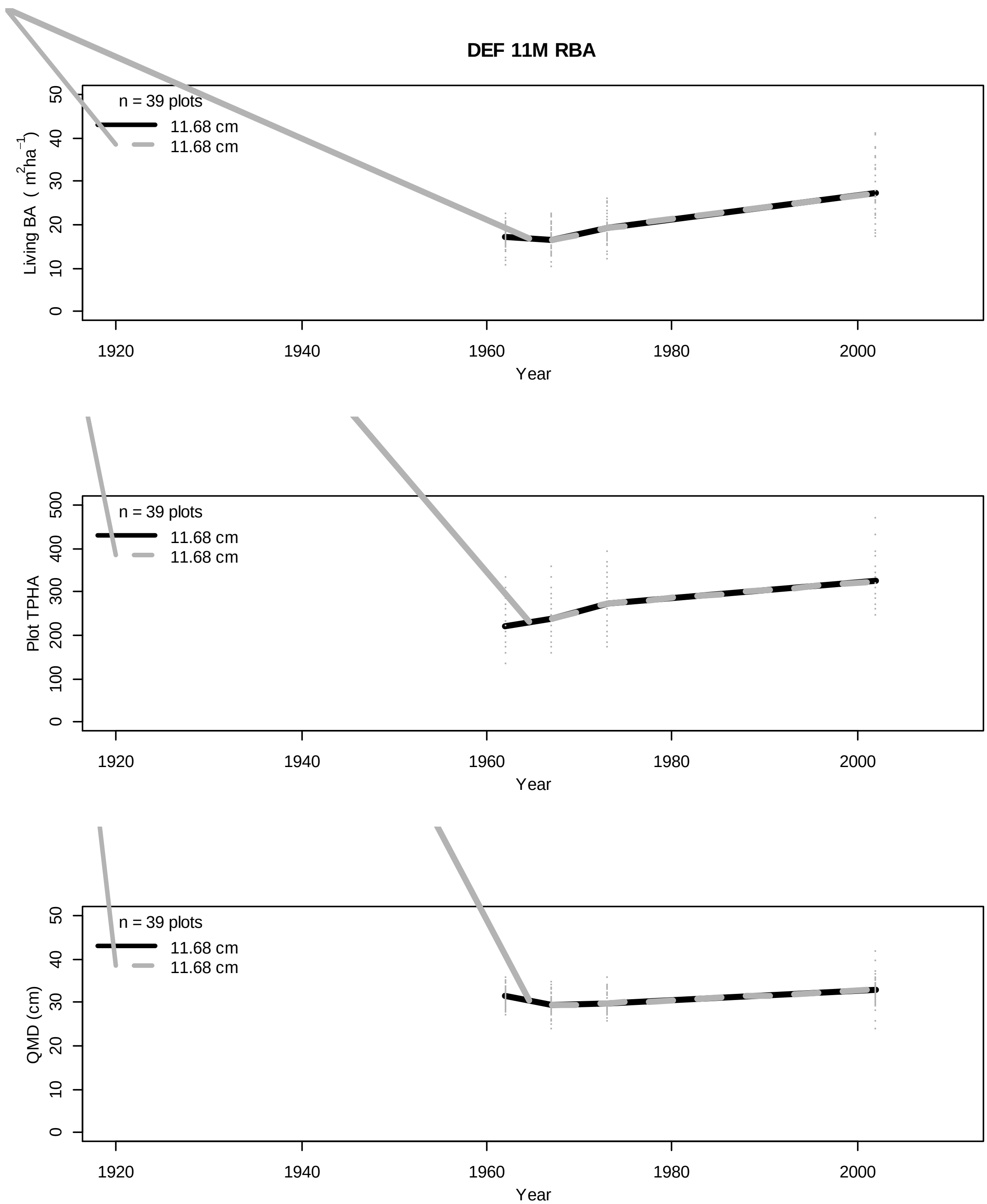


Figure B10. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Dukes Experimental Forest (DEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

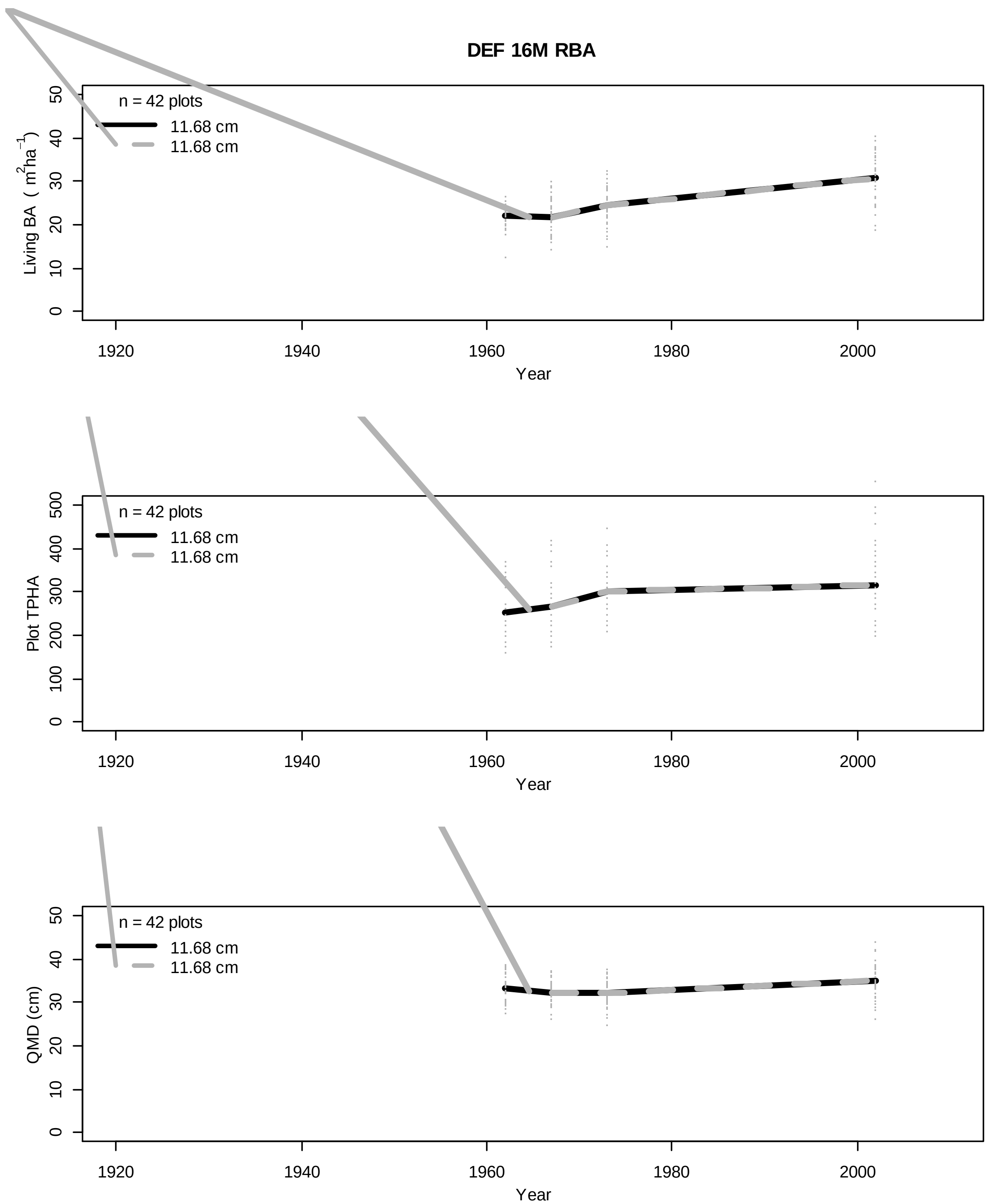


Figure B11. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Dukes Experimental Forest (DEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

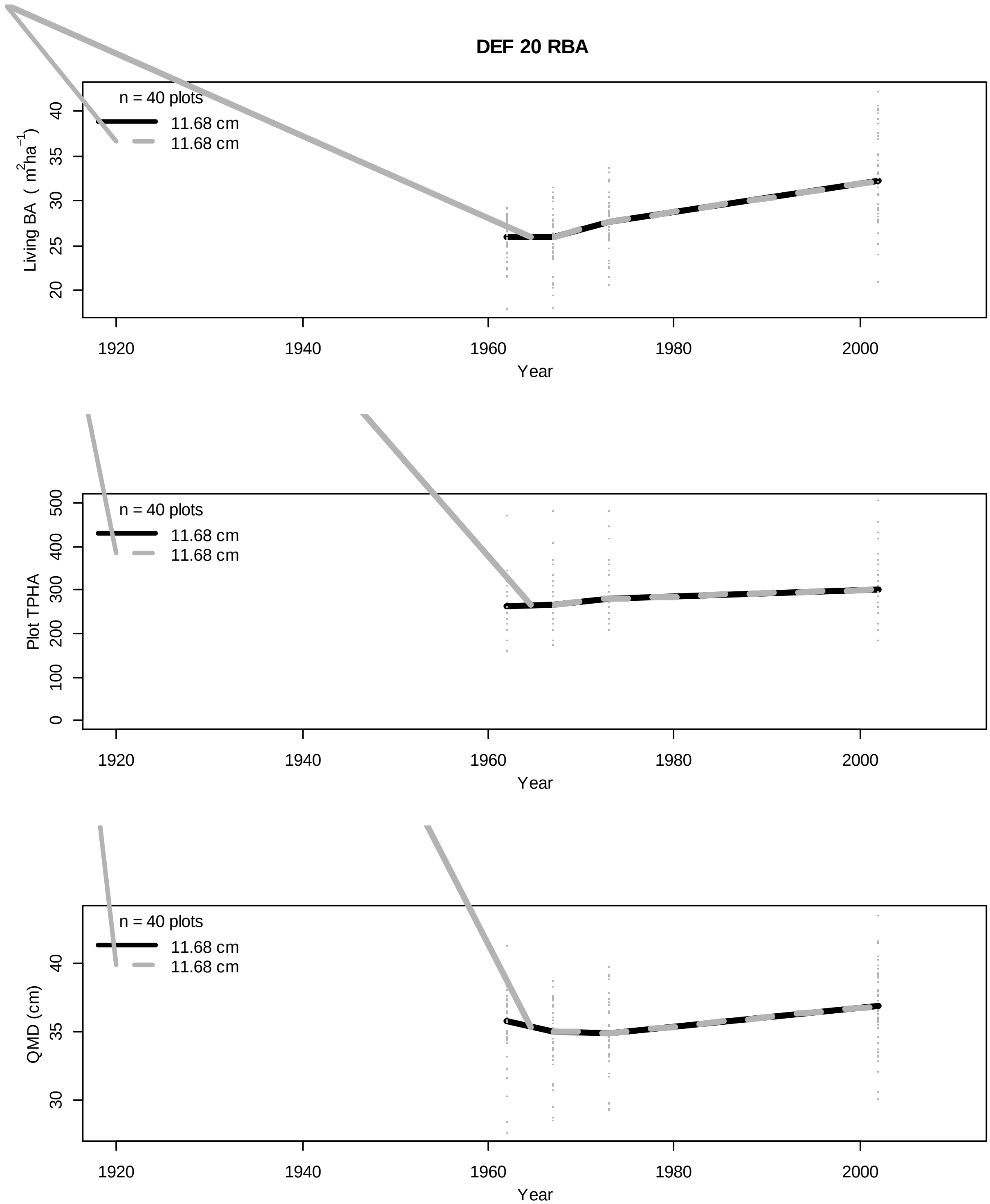


Figure B12. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Dukes Experimental Forest (DEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

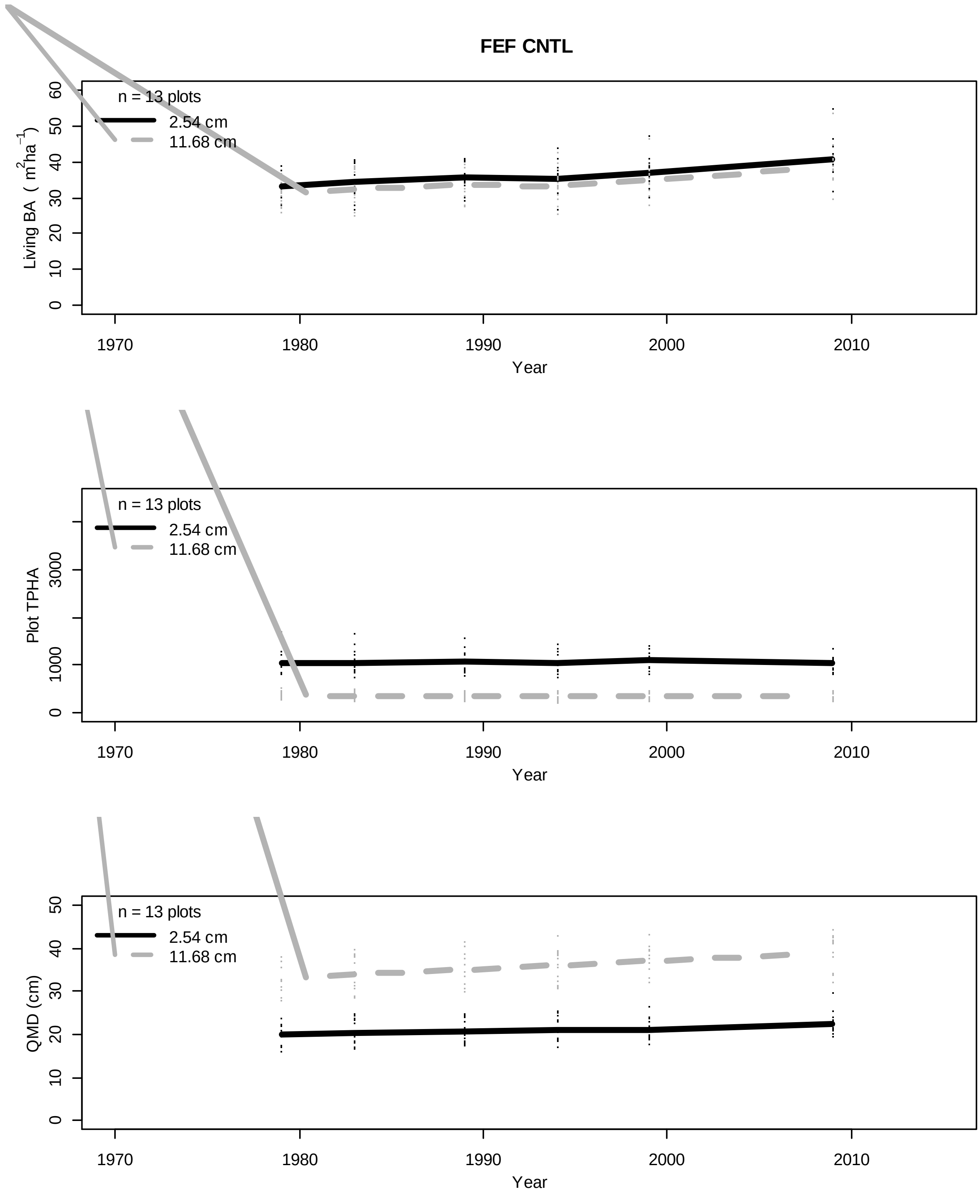


Figure B13. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Fernow Experimental Forest (FEF) control plots. Additional experiment level diameter re-measures may be available.

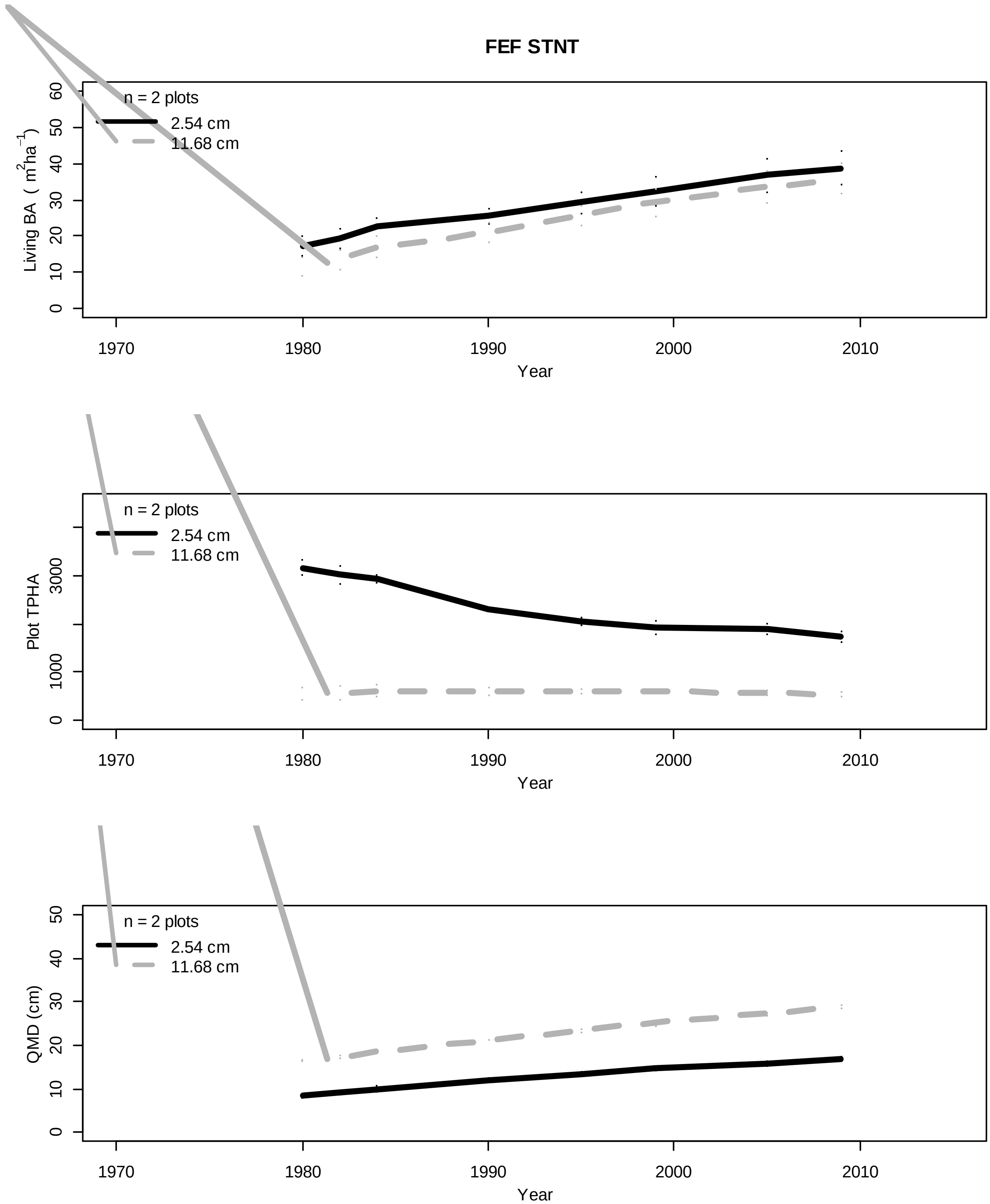


Figure B14. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Fernow Experimental Forest (FEF) non-thinned seed tree plots. Additional experiment level diameter re-measures may be available.

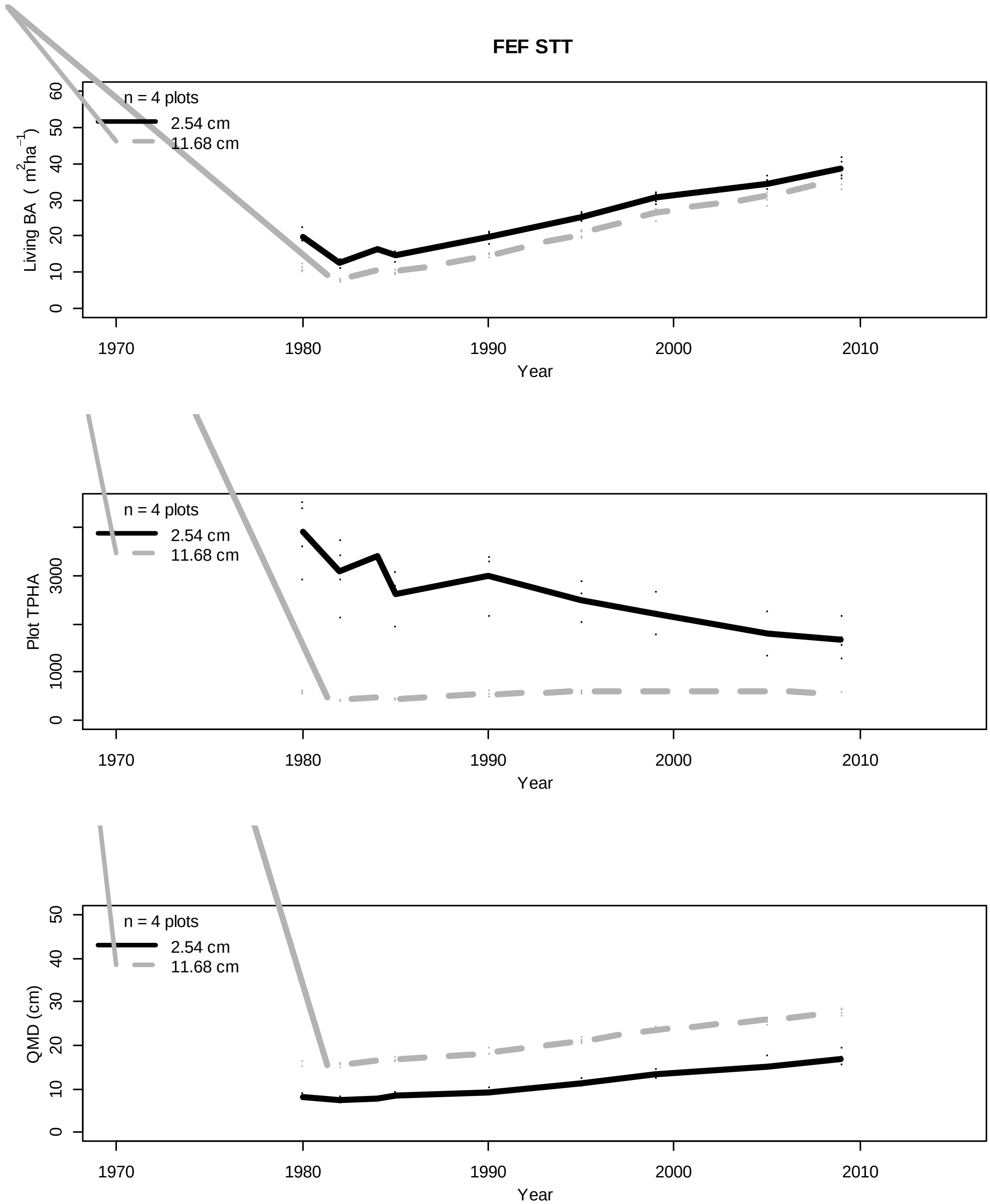


Figure B15. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Fernow Experimental Forest (FEF) thinned seed tree plots. Additional experiment level diameter re-measures may be available.

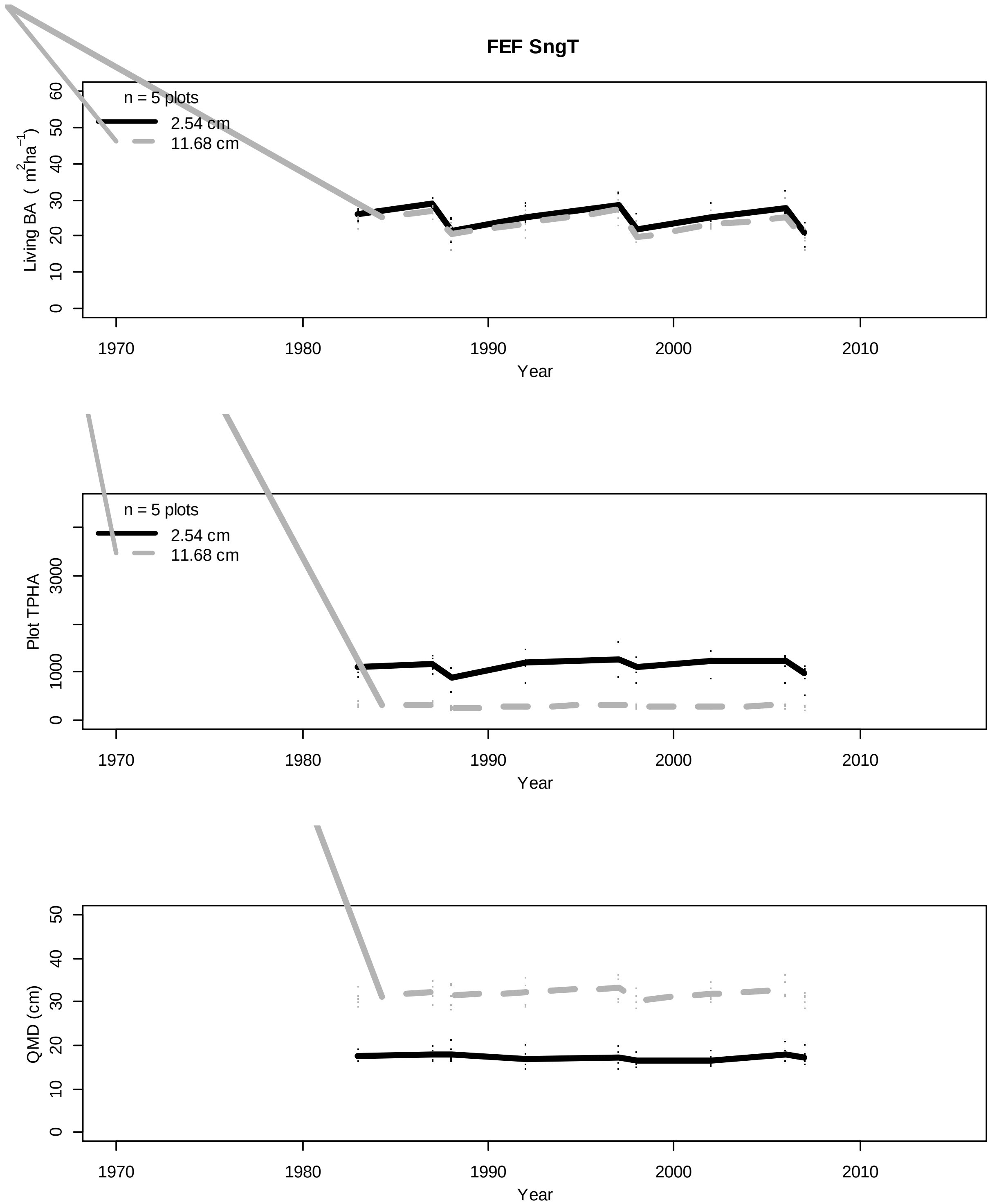


Figure B16. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Fernow Experimental Forest (FEF) single-tree selection plots. Additional experiment level diameter re-measures may be available.

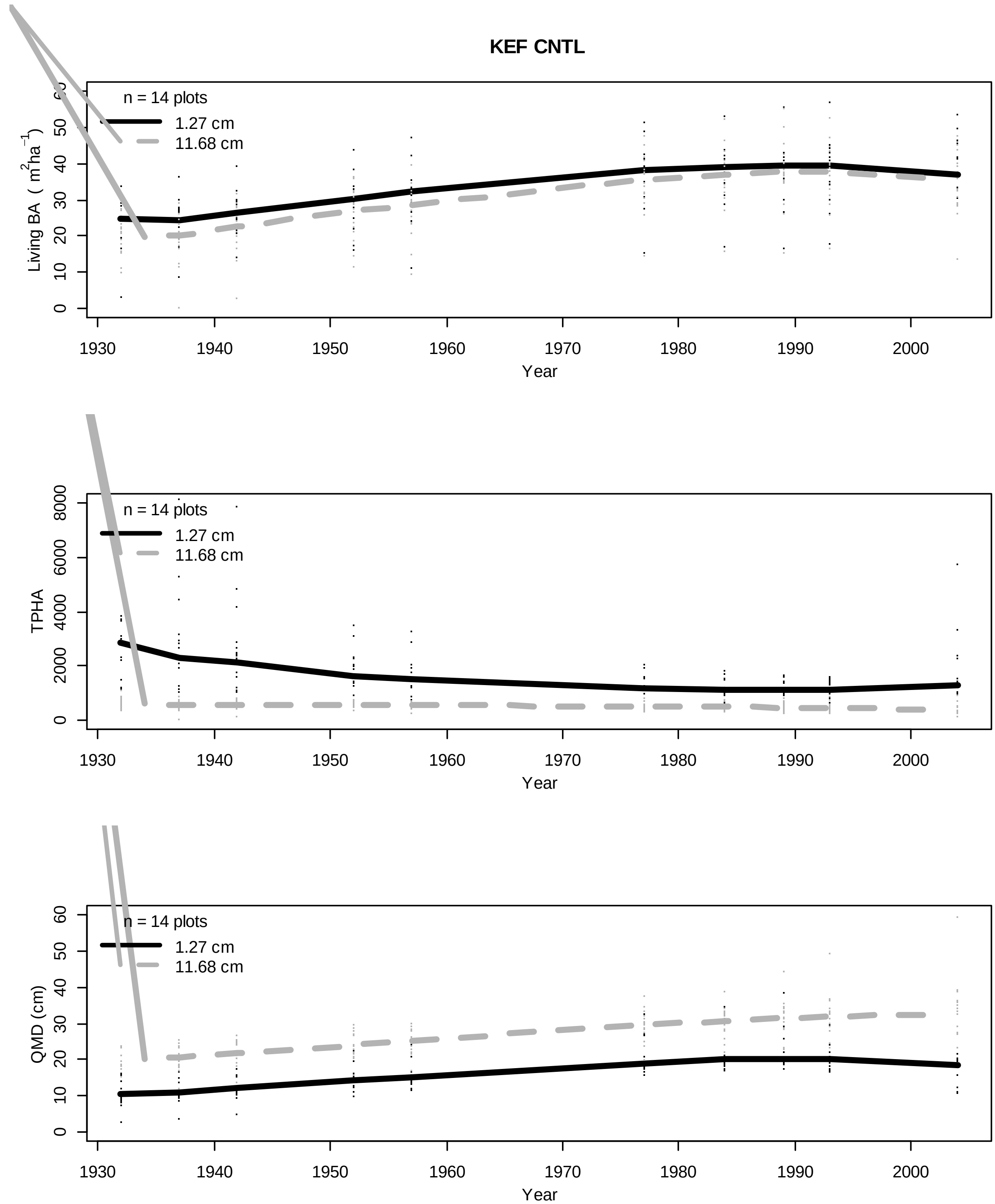


Figure B17. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Kane Experimental Forest (KEF) control plots.

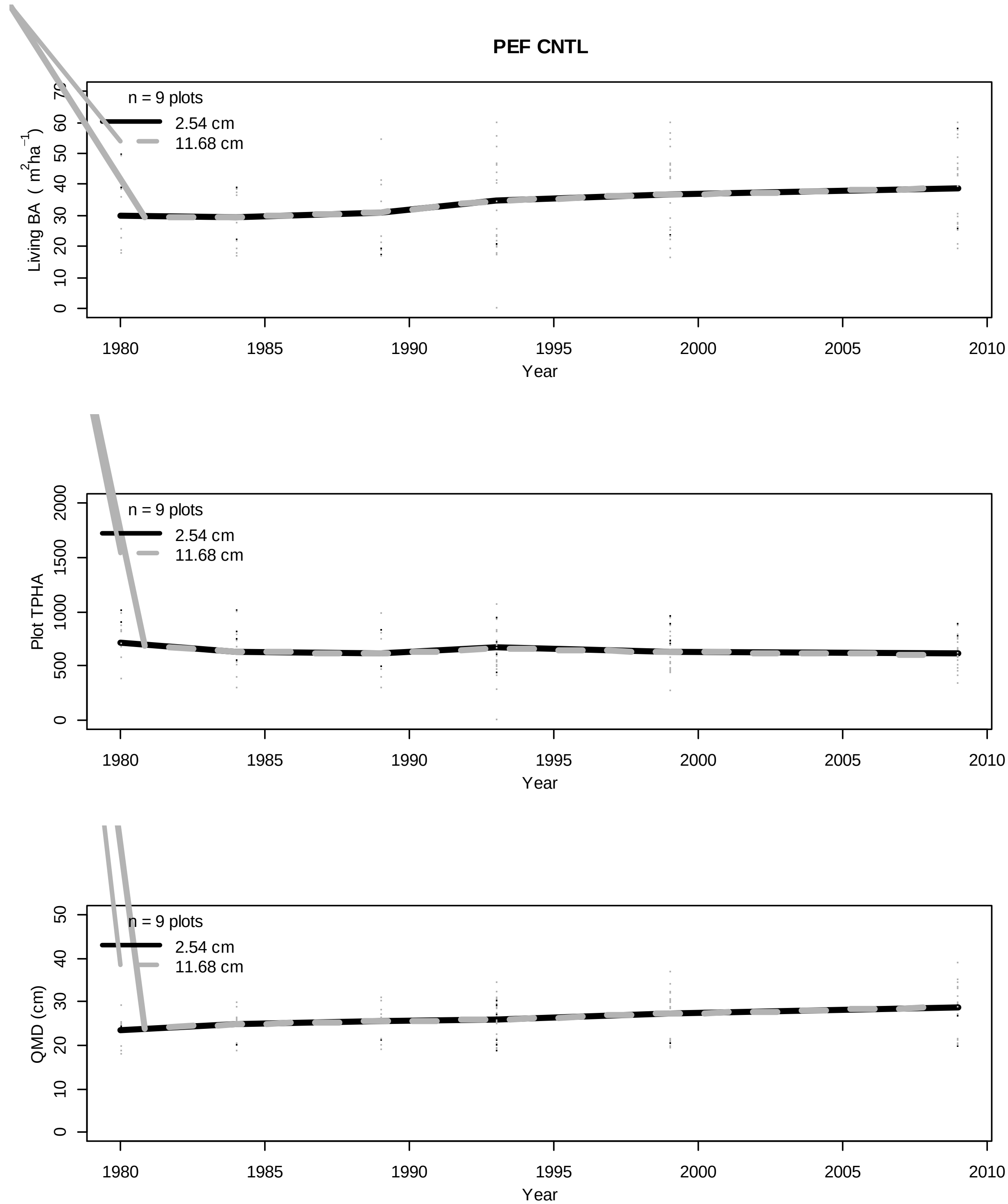


Figure B18. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Penobscot Experimental Forest (PEF) control plots. Additional experiment level diameter re-measures may be available.

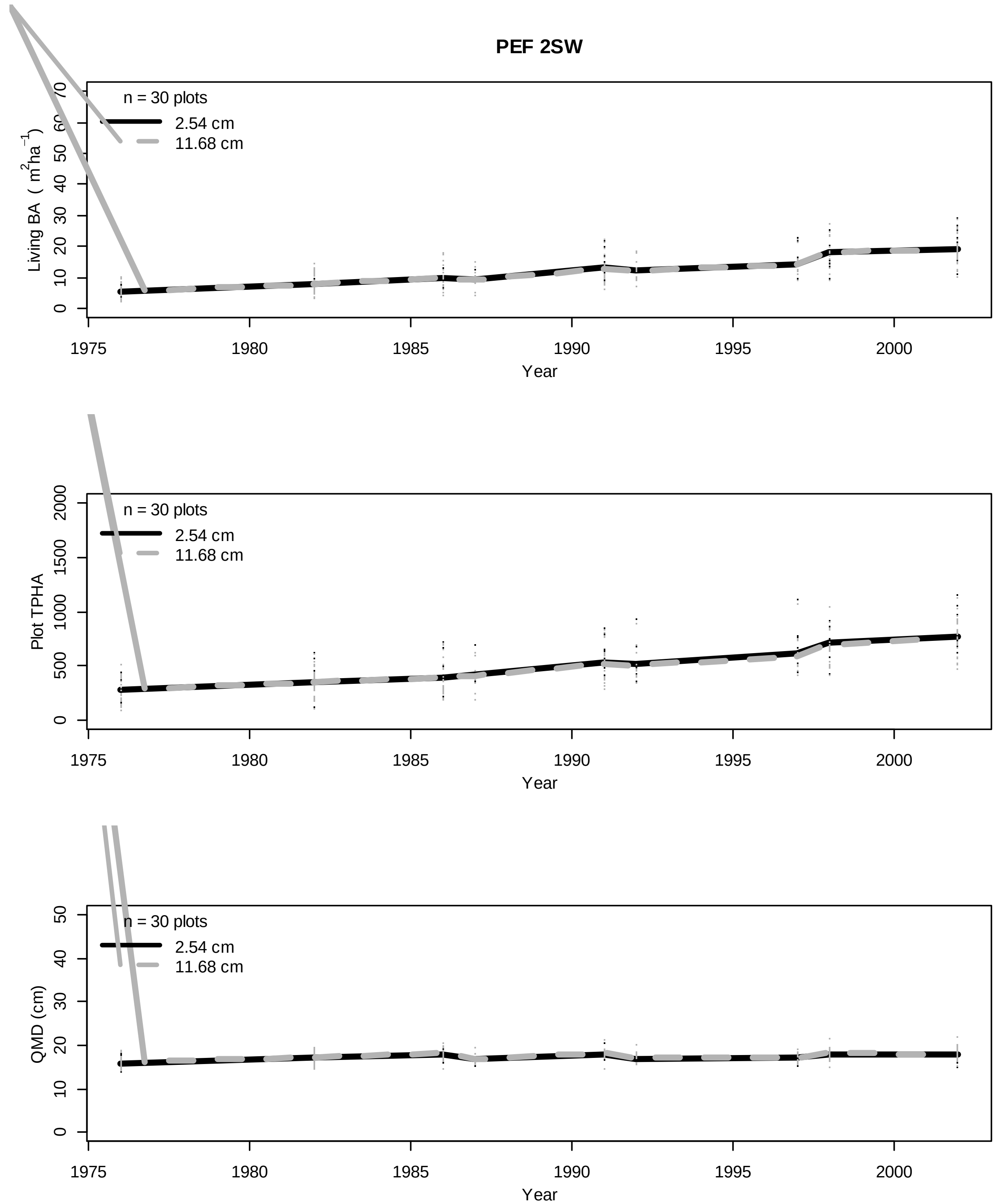


Figure B19. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Penobscot Experimental Forest (PEF) two-stage shelterwood plots. Additional experiment level diameter re-measures may be available.

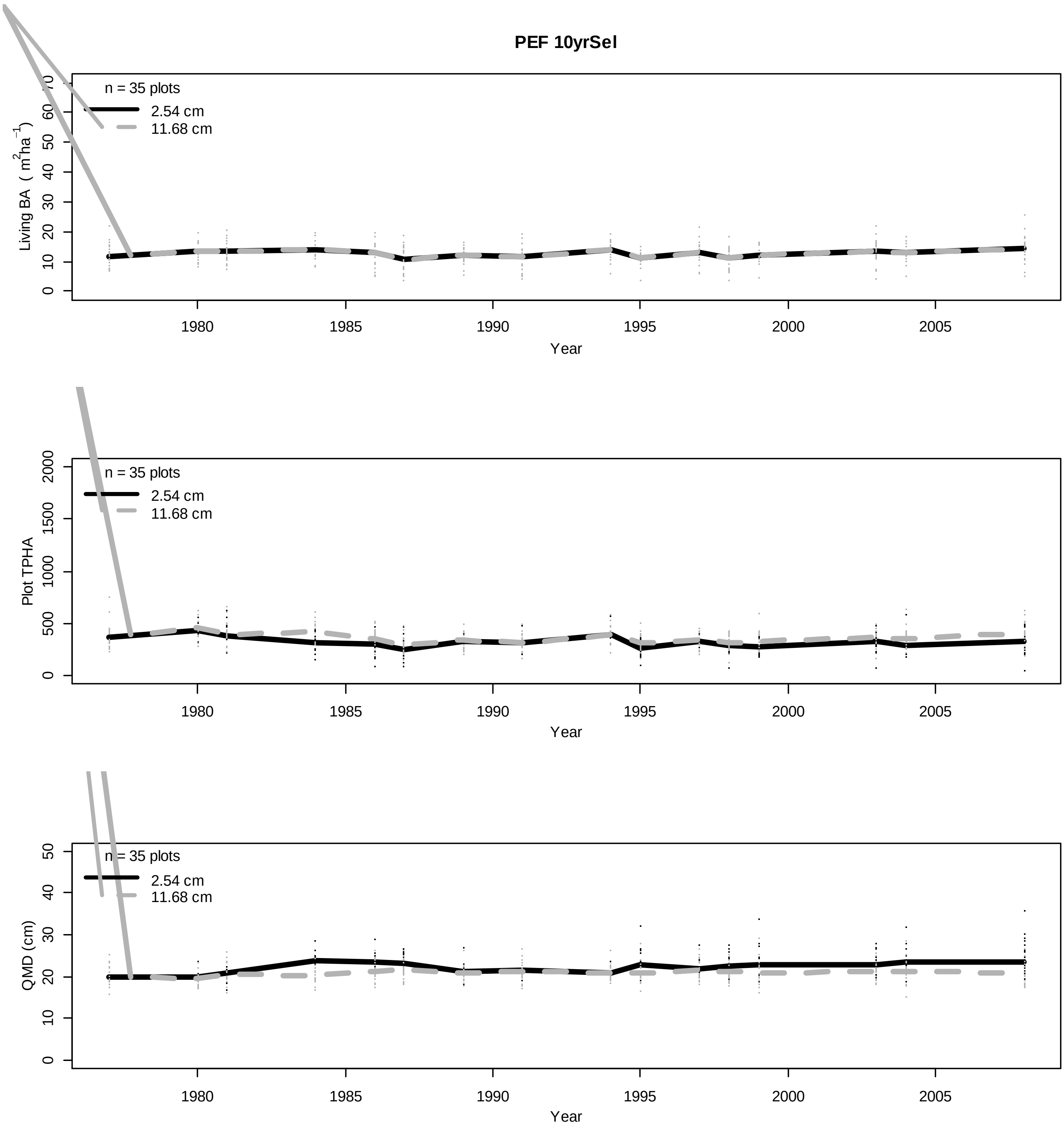


Figure B20. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Penobscot Experimental Forest (PEF) ten-year selection plots. Additional experiment level diameter re-measures may be available.

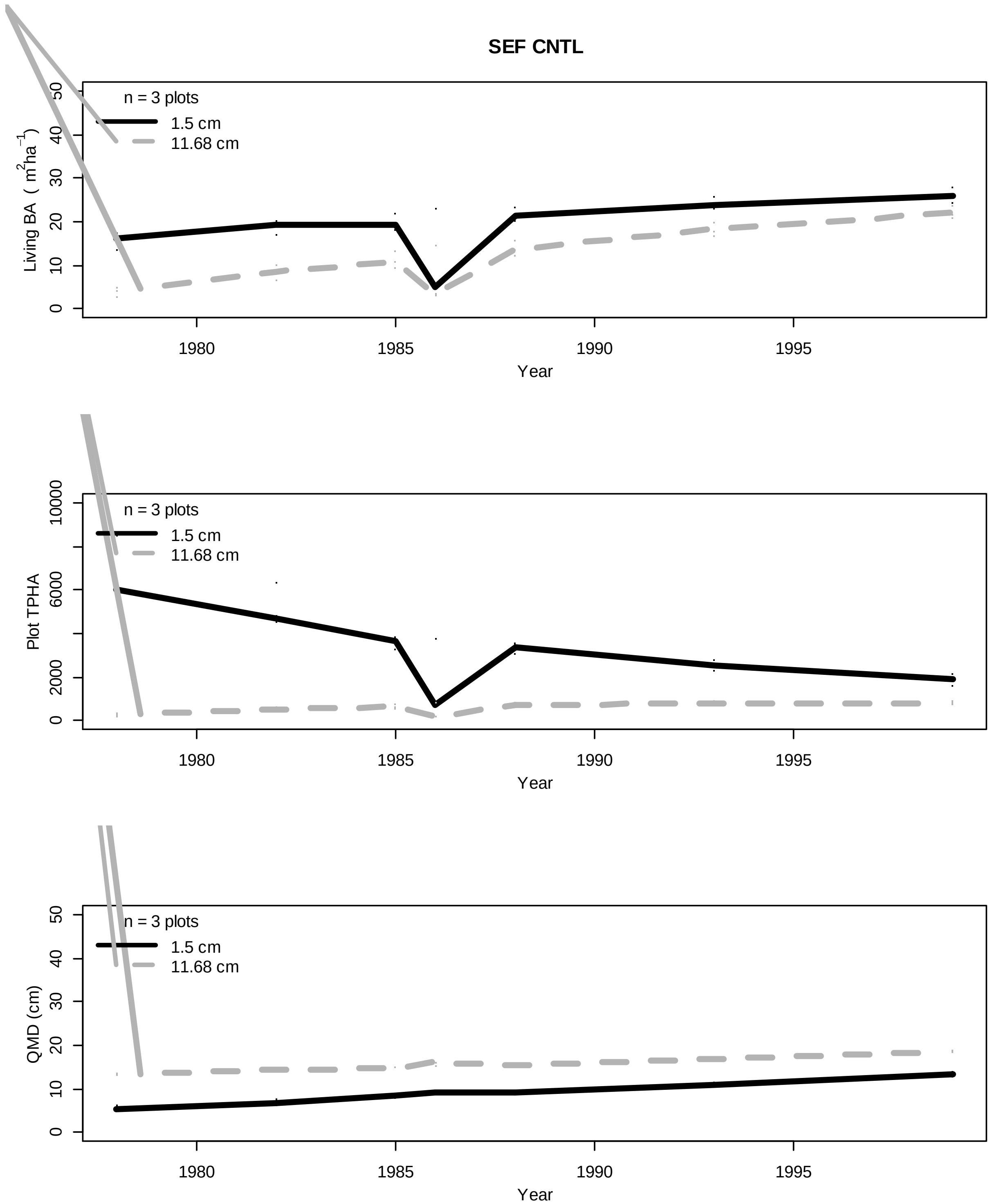


Figure B21. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Sinkin Experimental Forest (SEF) control plots. Additional experiment level diameter re-measures may be available.

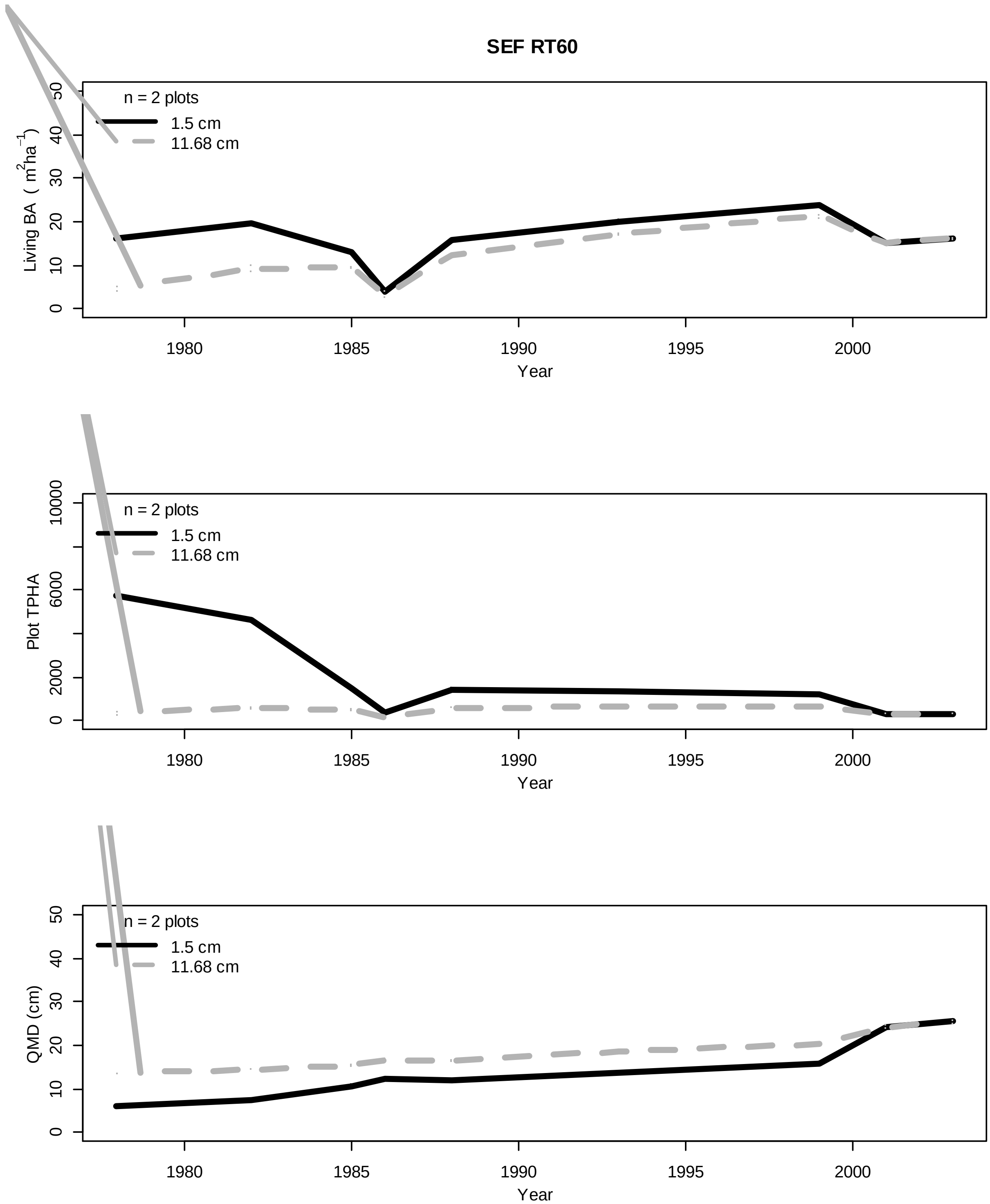


Figure B22. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Sinkin Experimental Forest (SEF) 60% rule thinned plots. Additional experiment level diameter re-measures may be available.

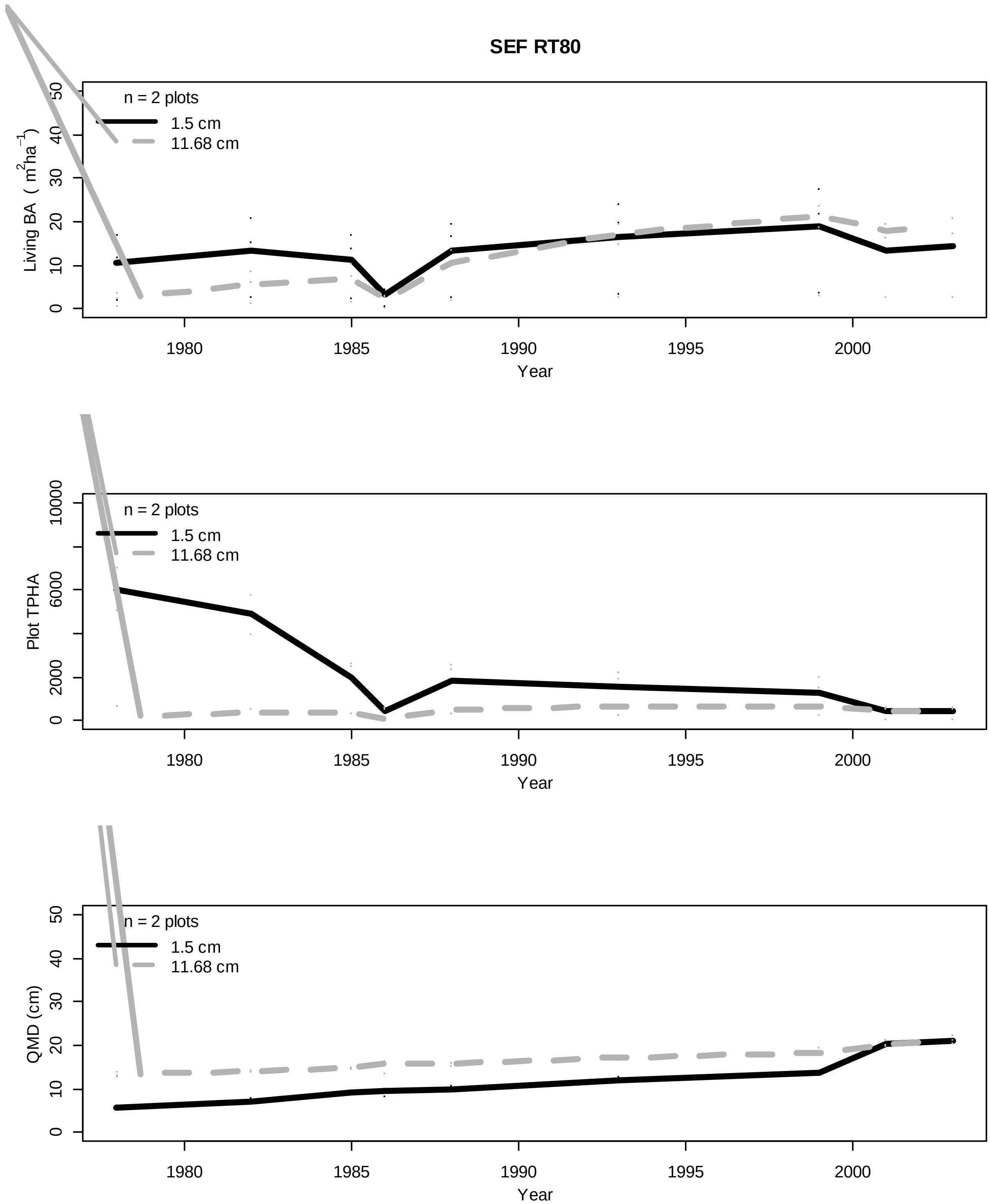


Figure B23. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Sinkin Experimental Forest (SEF) 80% rule thinned plots. Additional experiment level diameter re-measures may be available.

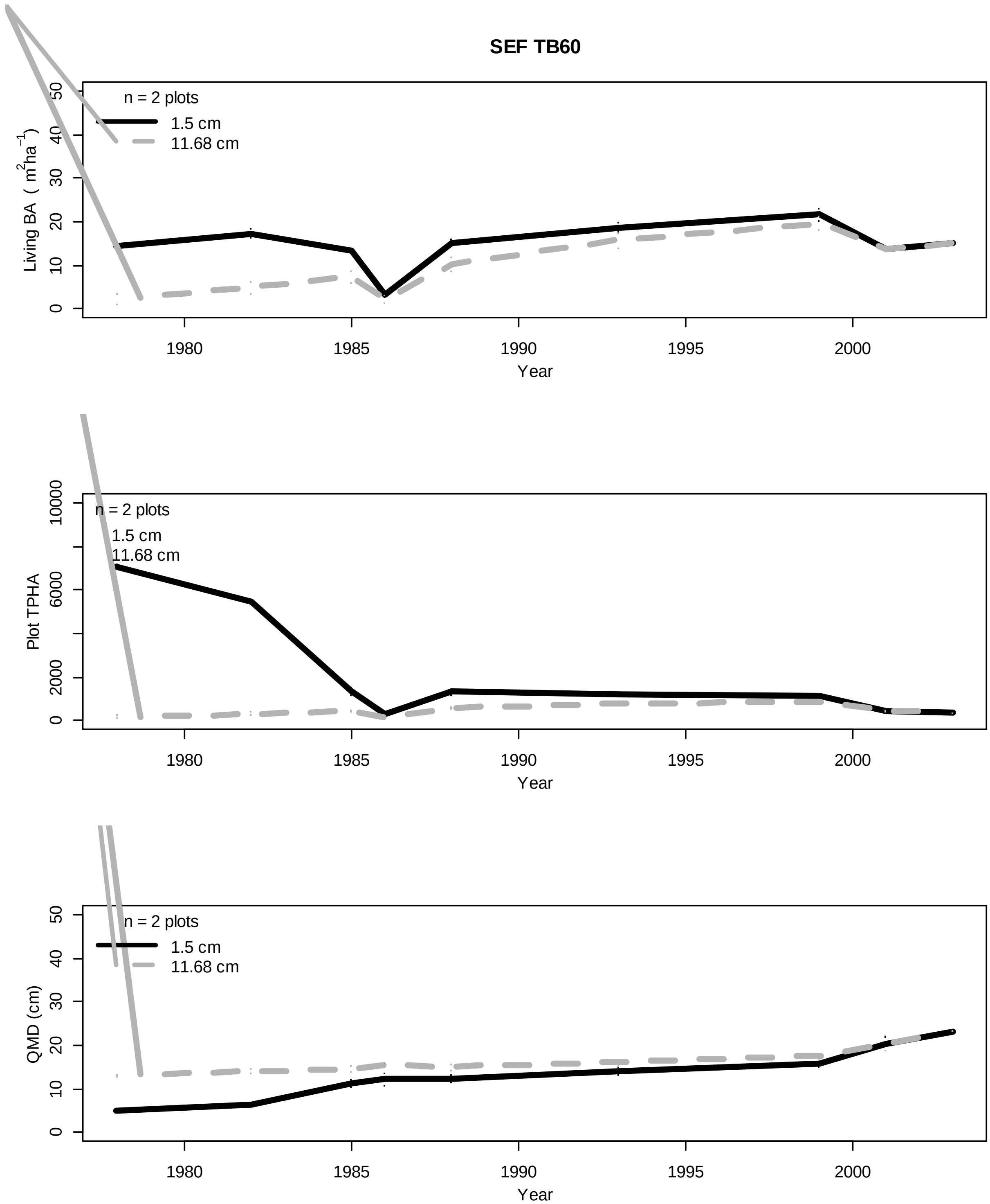


Figure B24. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Sinkin Experimental Forest (SEF) 60% thinned from below plots. Additional experiment level diameter re-measures may be available.

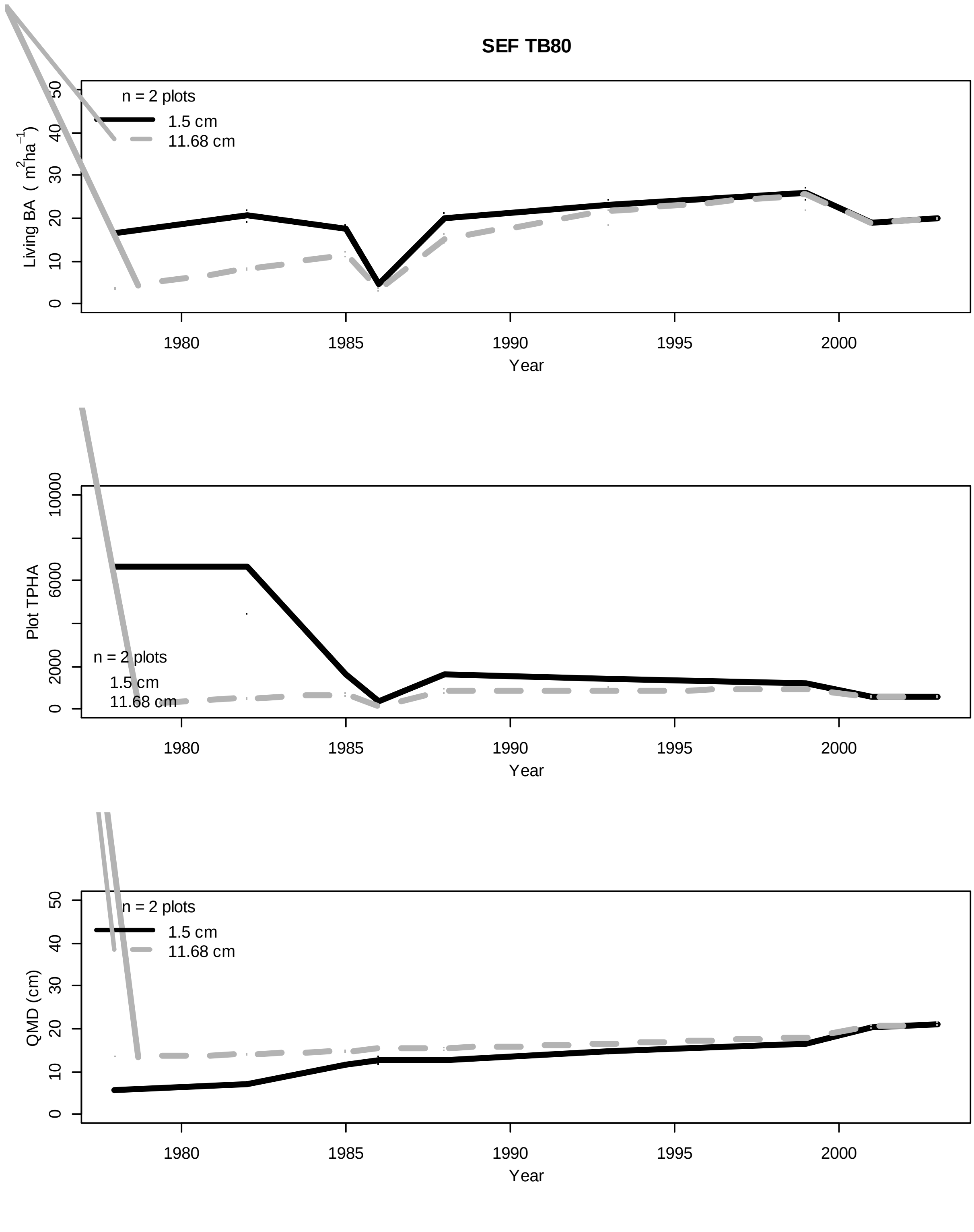


Figure B25. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Sinkin Experimental Forest (SEF) 80% thinned from below plots. Additional experiment level diameter re-measures may be available.

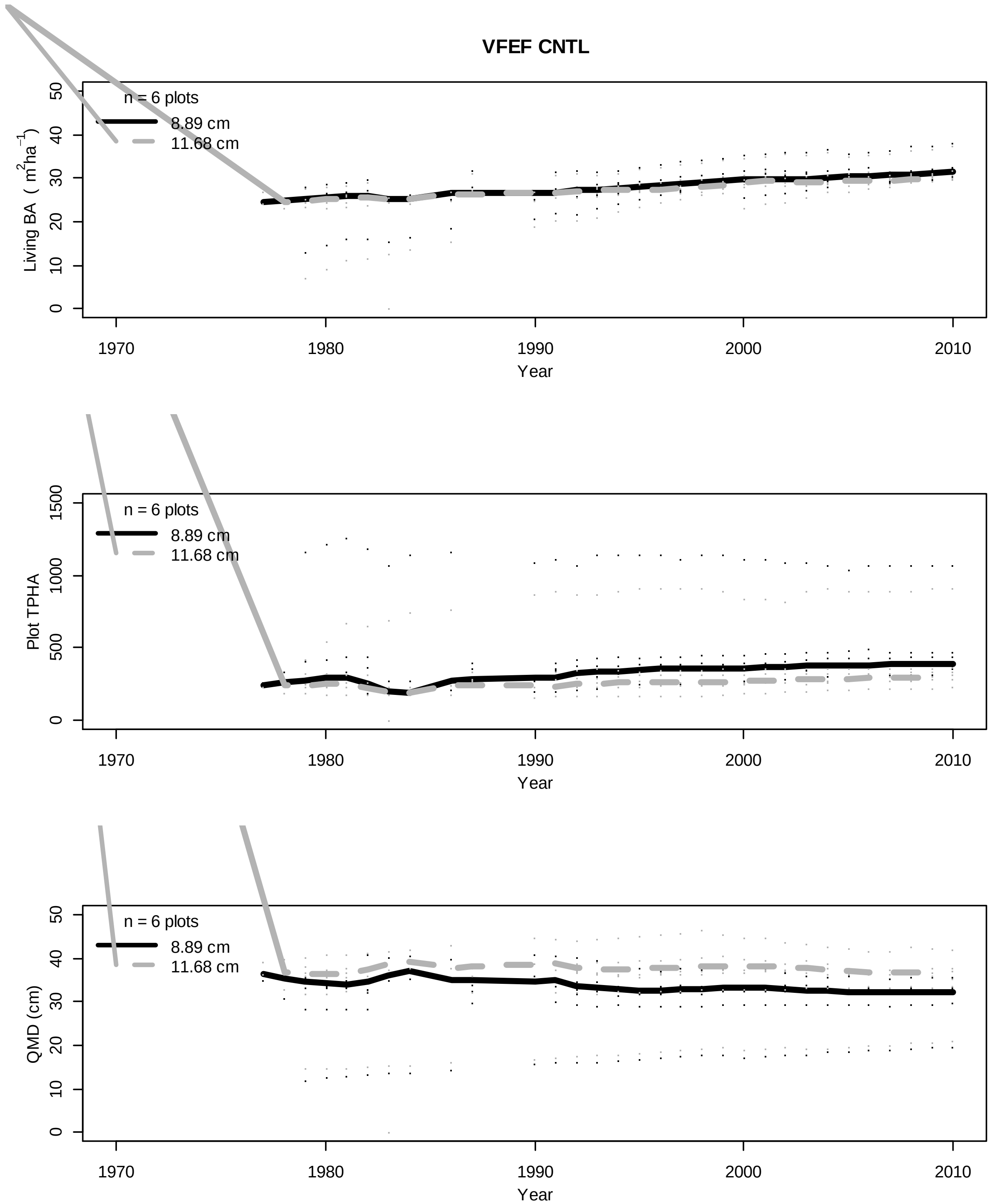


Figure B26. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Vinton-Furnace State Experimental Forest (VFSEF) control plots. Additional experiment level diameter re-measures may be available.

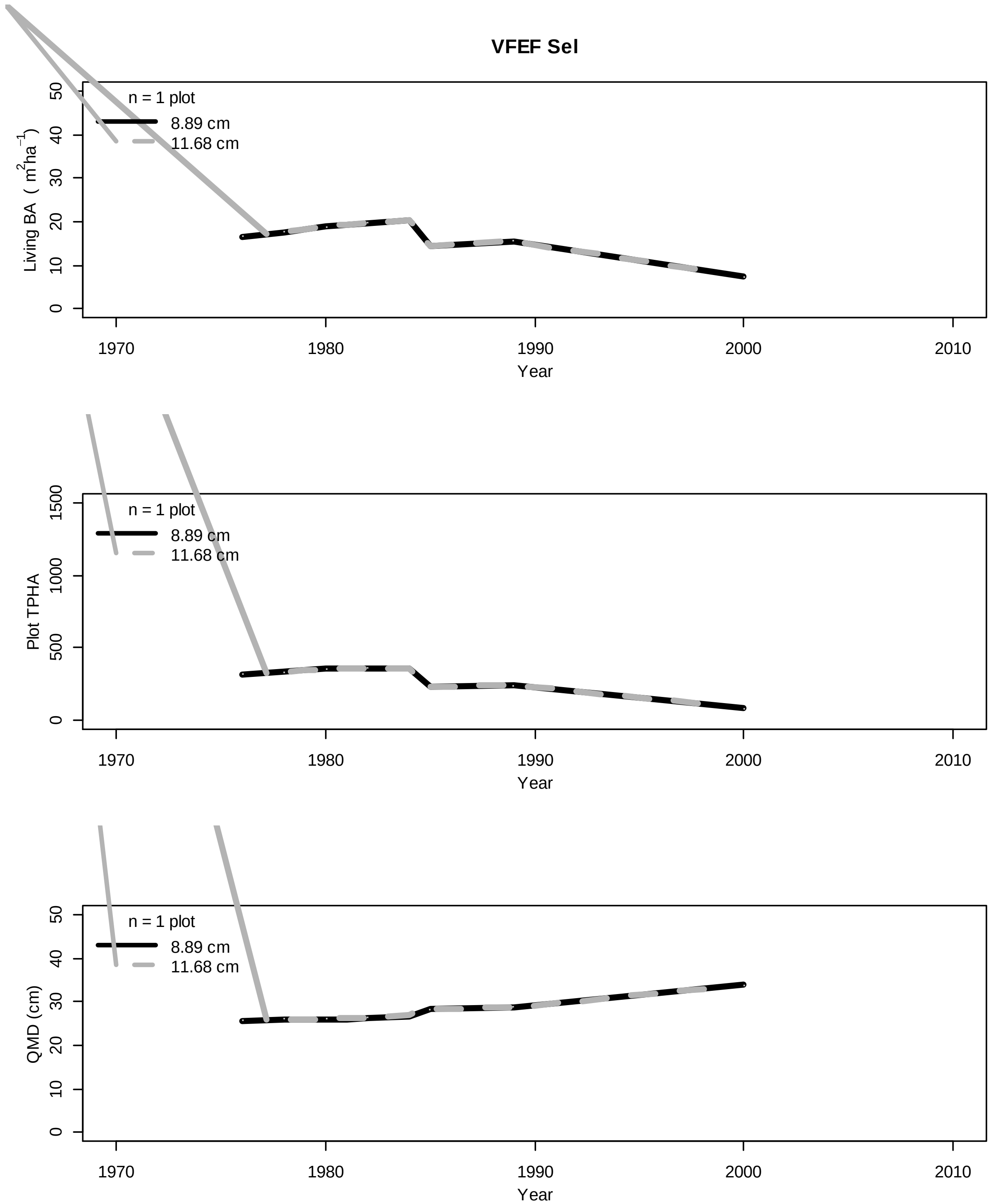


Figure B27. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection plots. Additional experiment level diameter re-measures may be available.

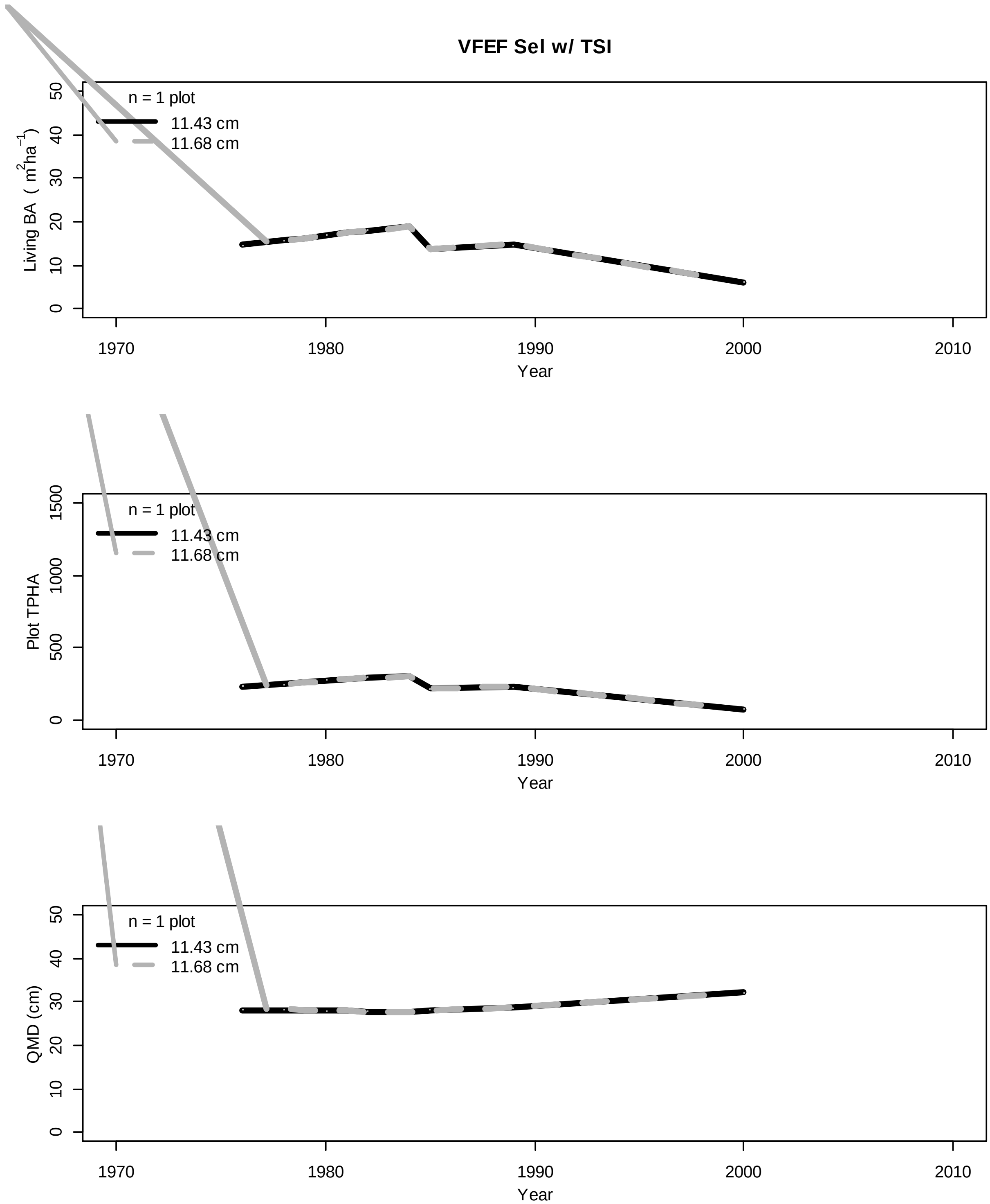


Figure B28. Effect of largest- minimum diameter truncation on stand attributes at the plot level with site specific and overall truncation summarizations through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection with timber stand improvement plots. Additional experiment level diameter re-measures may be available.

APPENDIX C. Plot level relative composition of dominant overstory type by unique treatment and site

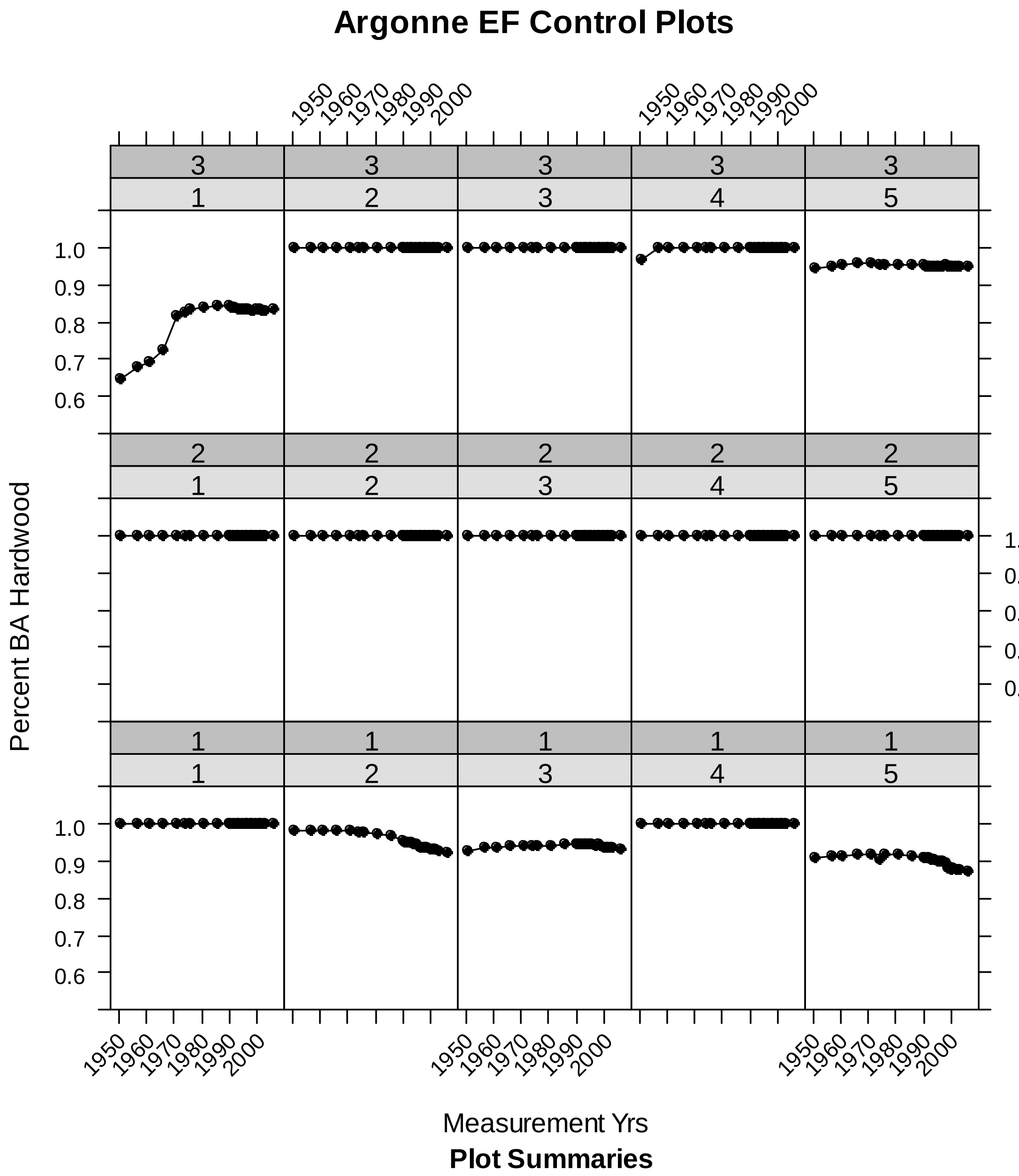


Figure C1. Relative composition as a percentage of living basal area through time on the Argonne Experimental Forest (AEF) control plots. The value in the darker grey section is standardized block or treatment replicate, while the value is in the lighter grey section is actual plot number.

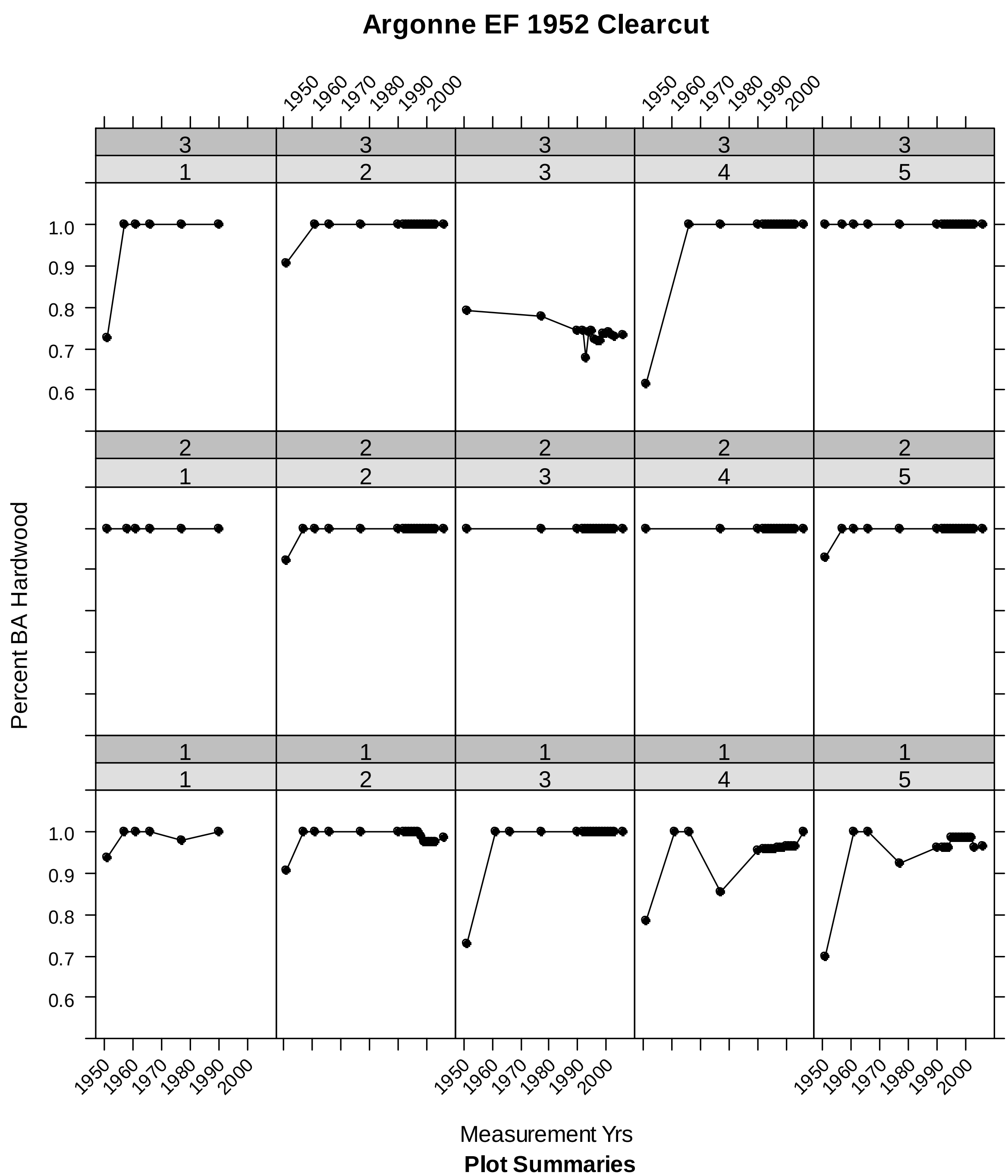


Figure C2. Relative composition as a percentage of living basal area through time on the Argonne Experimental Forest (AEF) clearcut (ca. 1951) plots. The value in the darker grey section is standardized block or treatment replicate, while the value is in the lighter grey section is actual plot number.

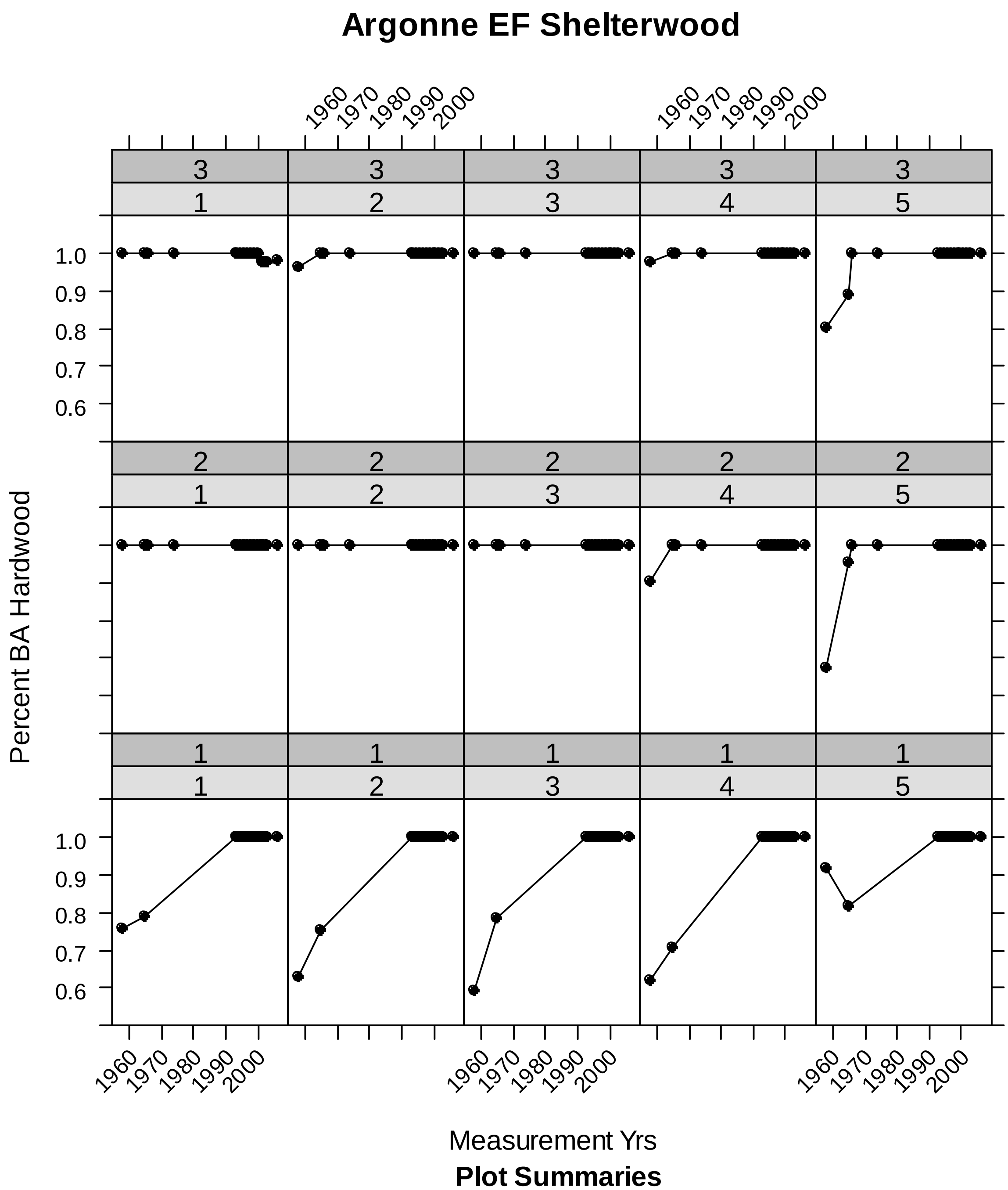


Figure C3. Relative composition as a percentage of living basal area through time on the Argonne Experimental Forest (AEF) two-stage shelterwood plots. The value in the darker grey section is standardized block or treatment replicate, while the value is in the lighter grey section is actual plot number.

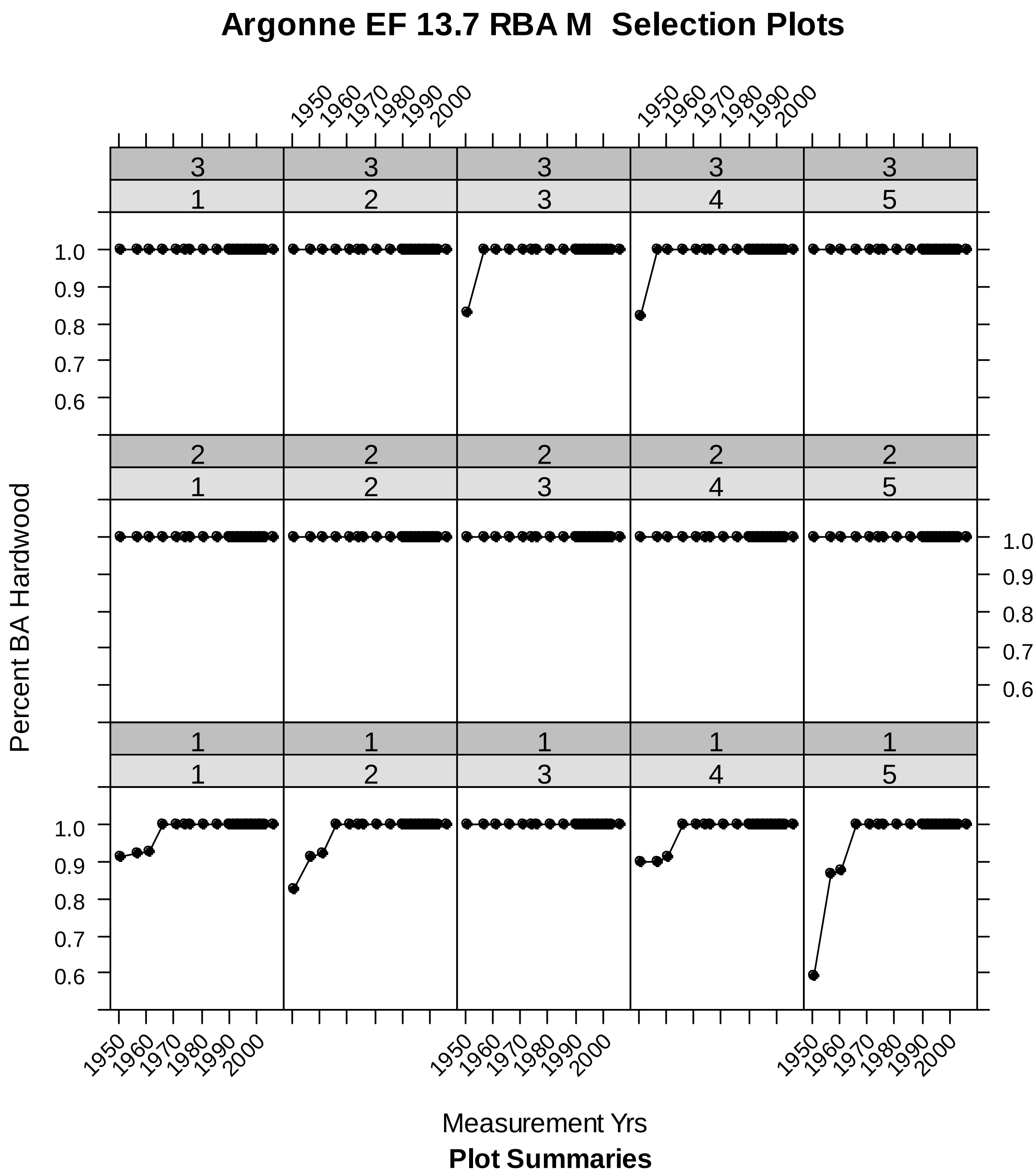


Figure C4. Relative composition as a percentage of living basal area through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in the darker grey section is actual treatment replicate, while the value is in the lighter grey section is actual plot number.

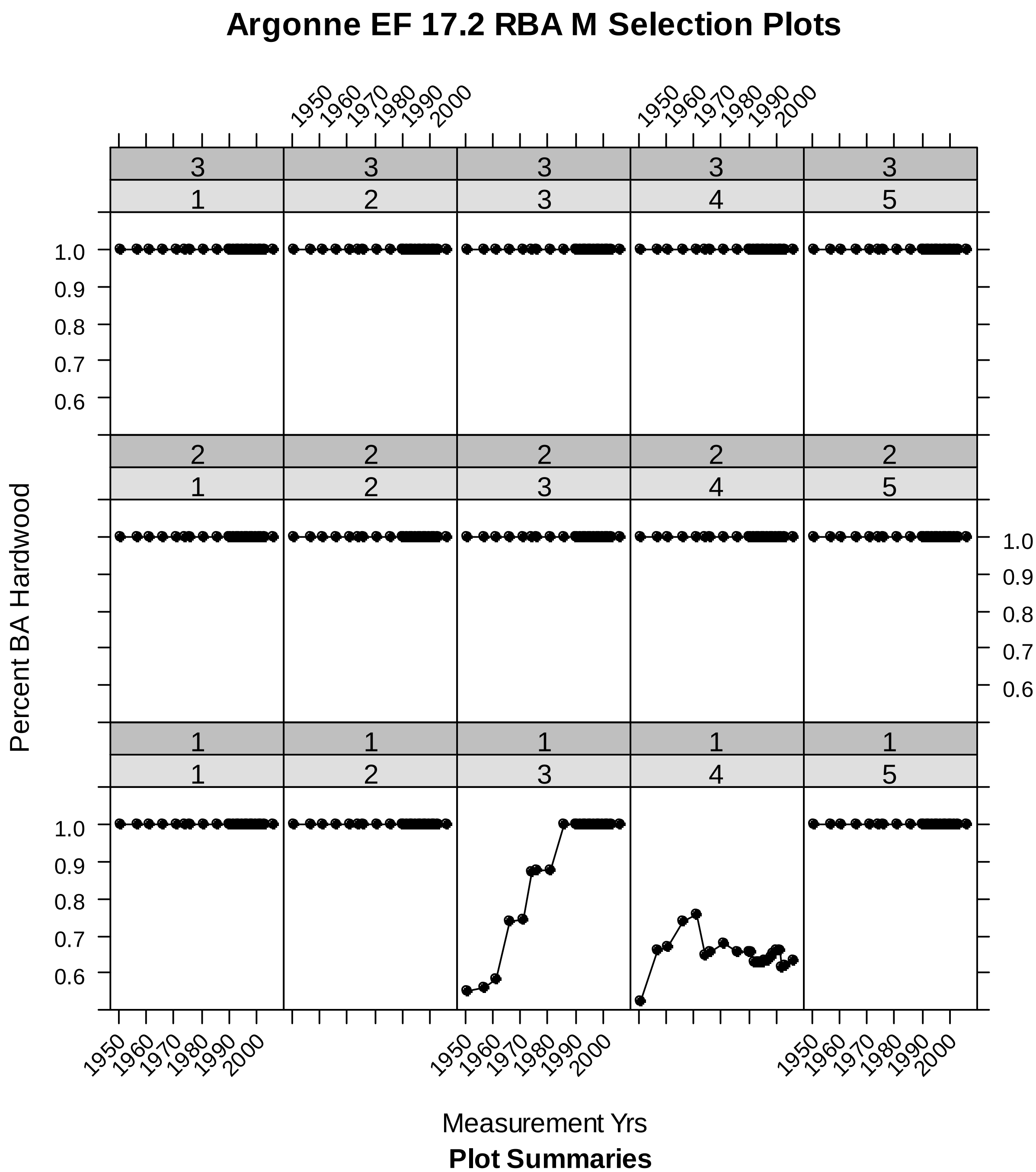


Figure C5. Relative composition as a percentage of living basal area through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in the darker grey section is actual treatment replicate, while the value is in the lighter grey section is actual plot number.

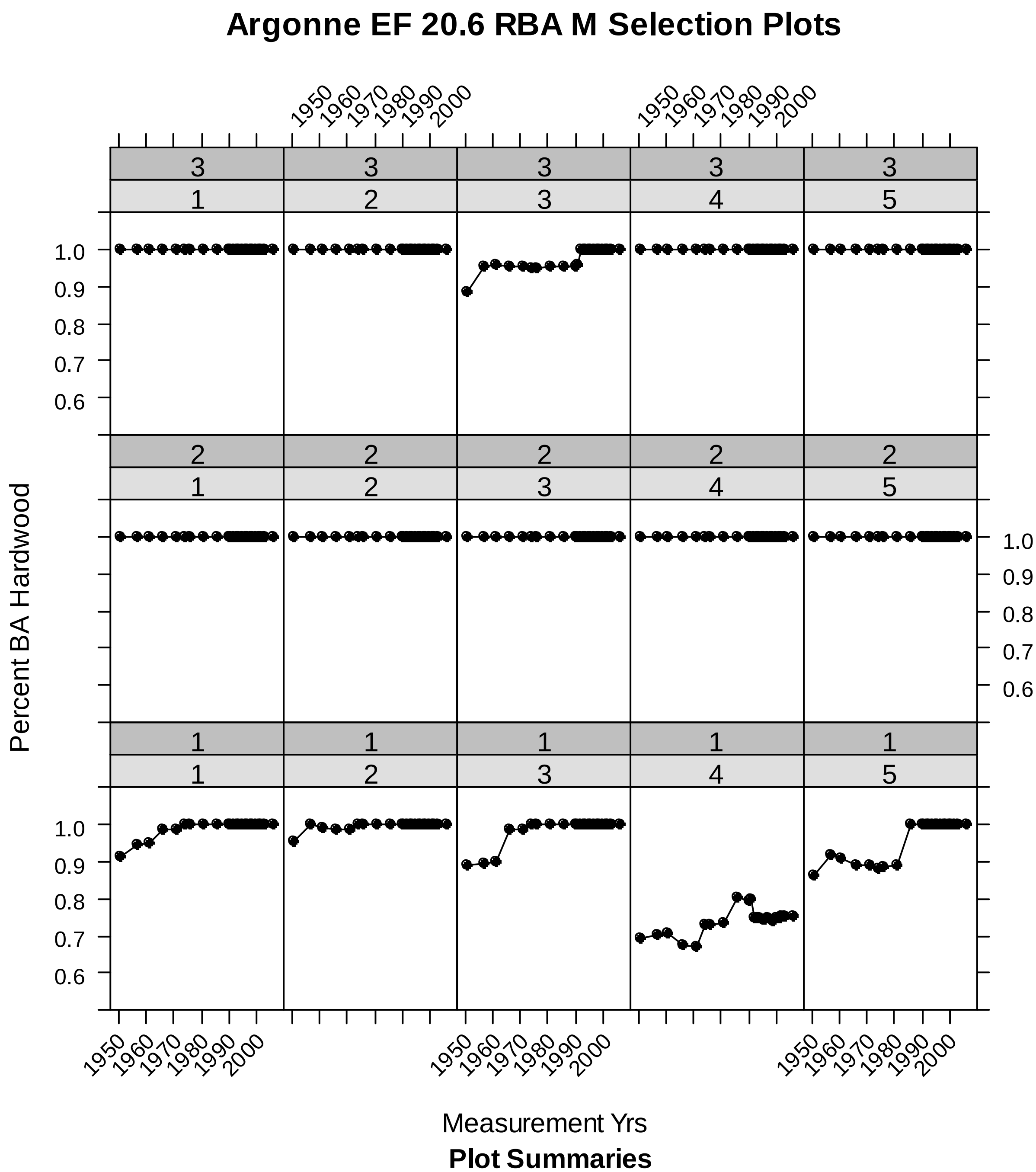


Figure C6. Relative composition as a percentage of living basal area through time on the Argonne Experimental Forest (AEF) residual basal area selection plots. The value in the darker grey section is actual treatment replicate, while the value is in the lighter grey section is actual plot number.

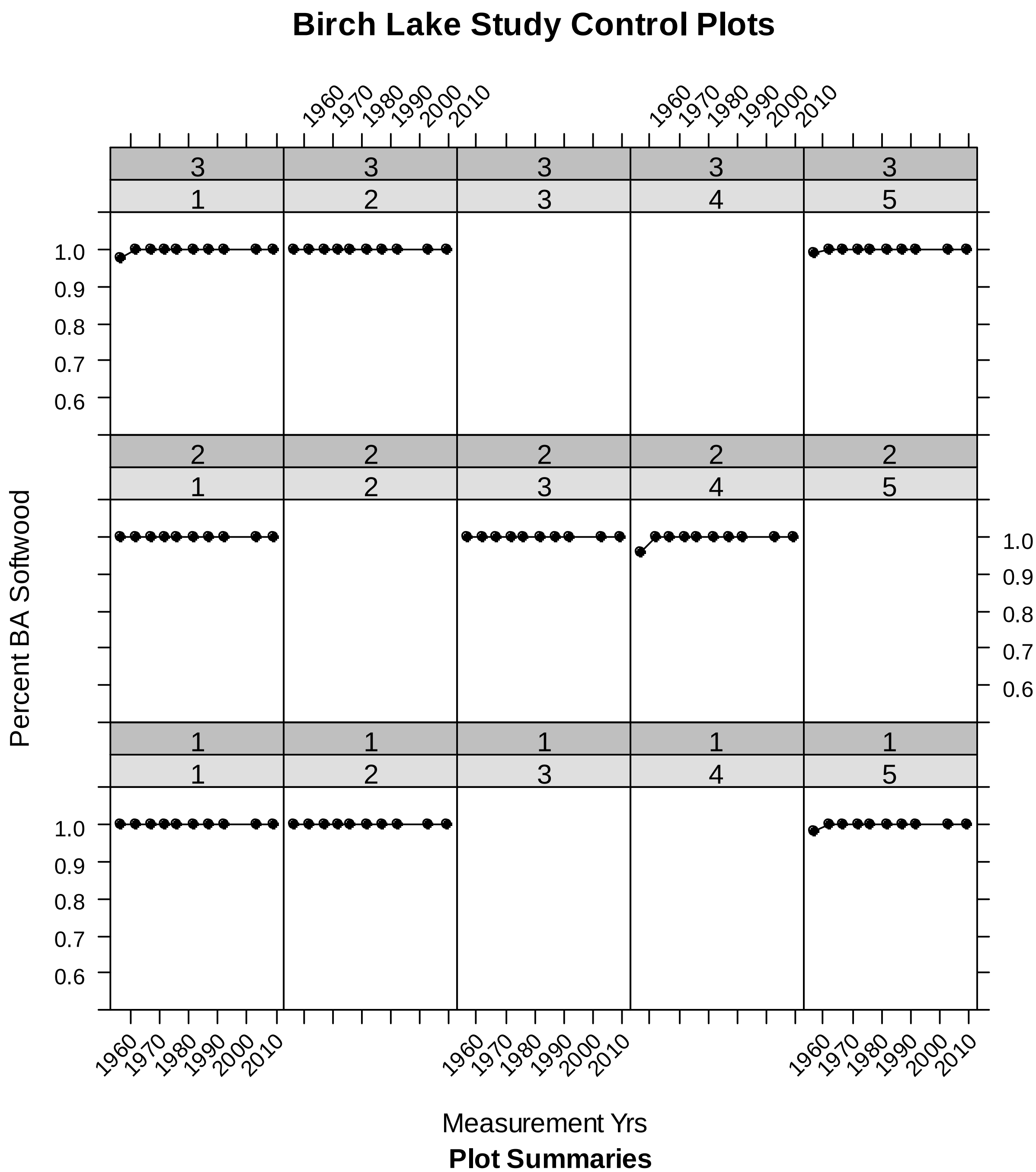


Figure C7. Relative composition as a percentage of living basal area through time on the Birch Lake Study (BLS) control plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is standardized plot number. Standardized replicates 1-3 are BLS blocks 5,9,16 respectively while standardized plots1-5 are Center, East, North East, Southwest, and West BLS plots respectively.

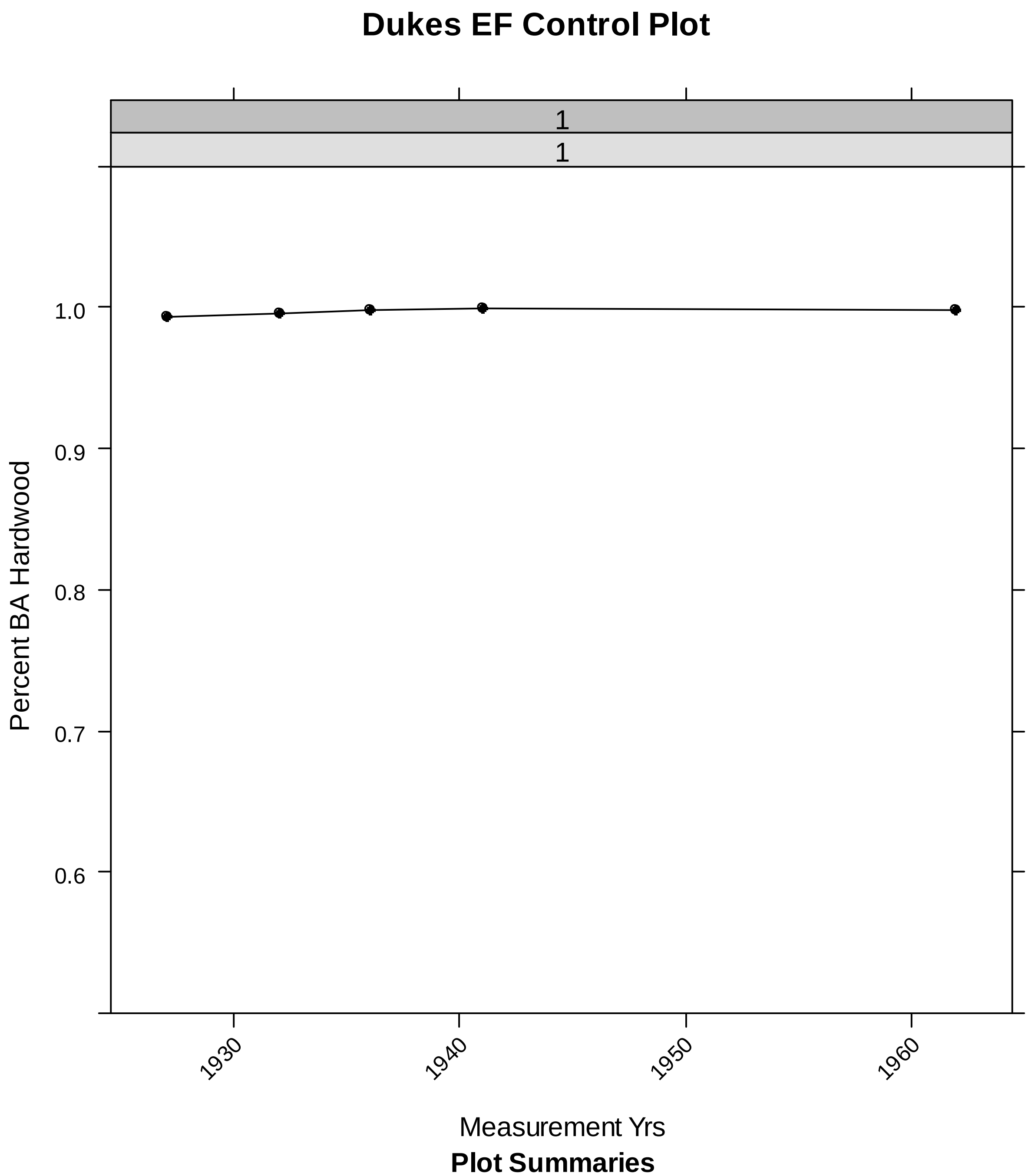


Figure C8. Relative composition as a percentage of living basal area through time on the Dukes Experimental Forest (DEF) control plot. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

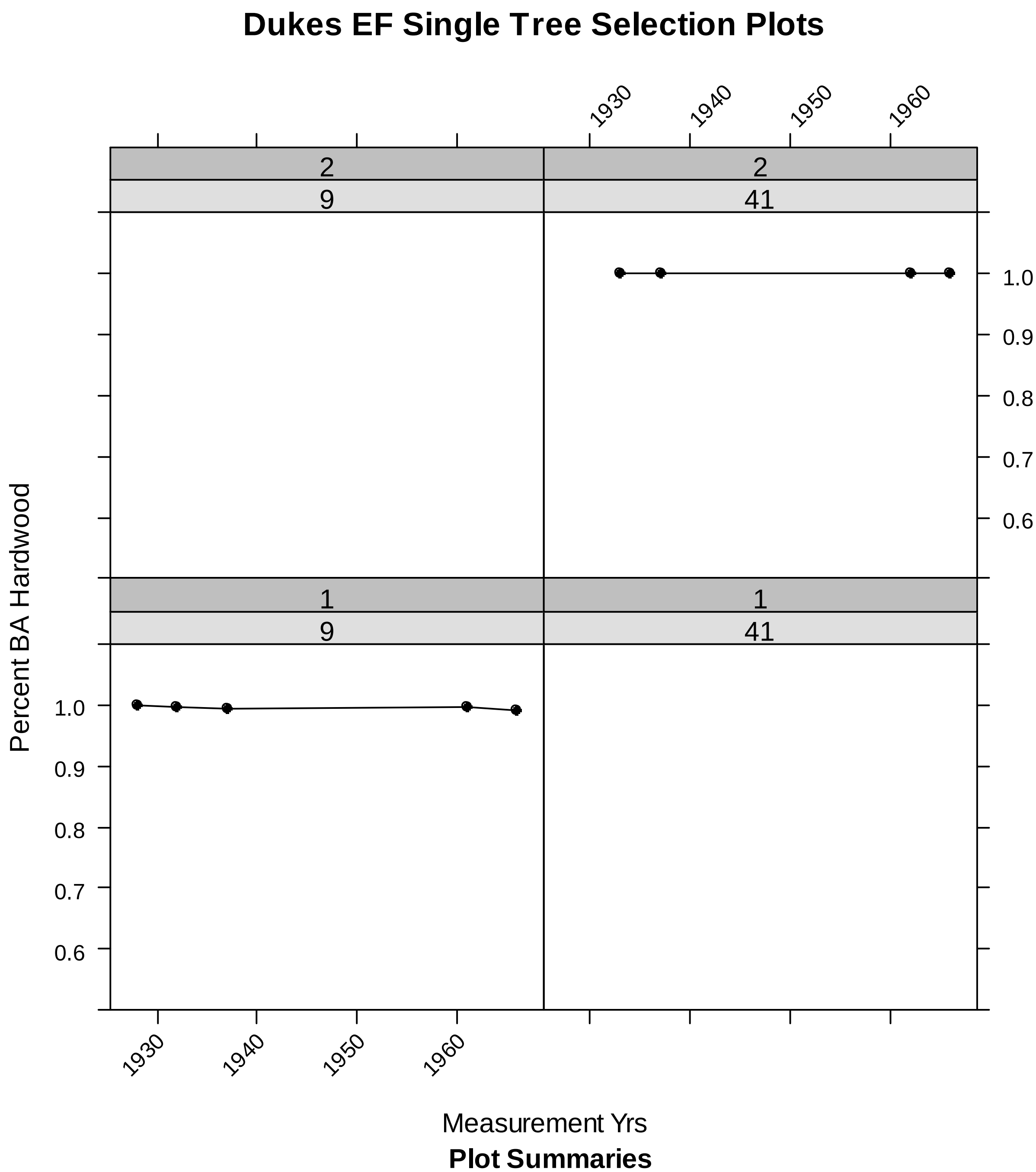


Figure C9. Relative composition as a percentage of living basal area through time on the Dukes Experimental Forest (DEF) single tree selection plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual (PSP) plot number. Subset of measurements (ca. 1942- 1960) was excluded based on site-level changing minimum diameter limits.

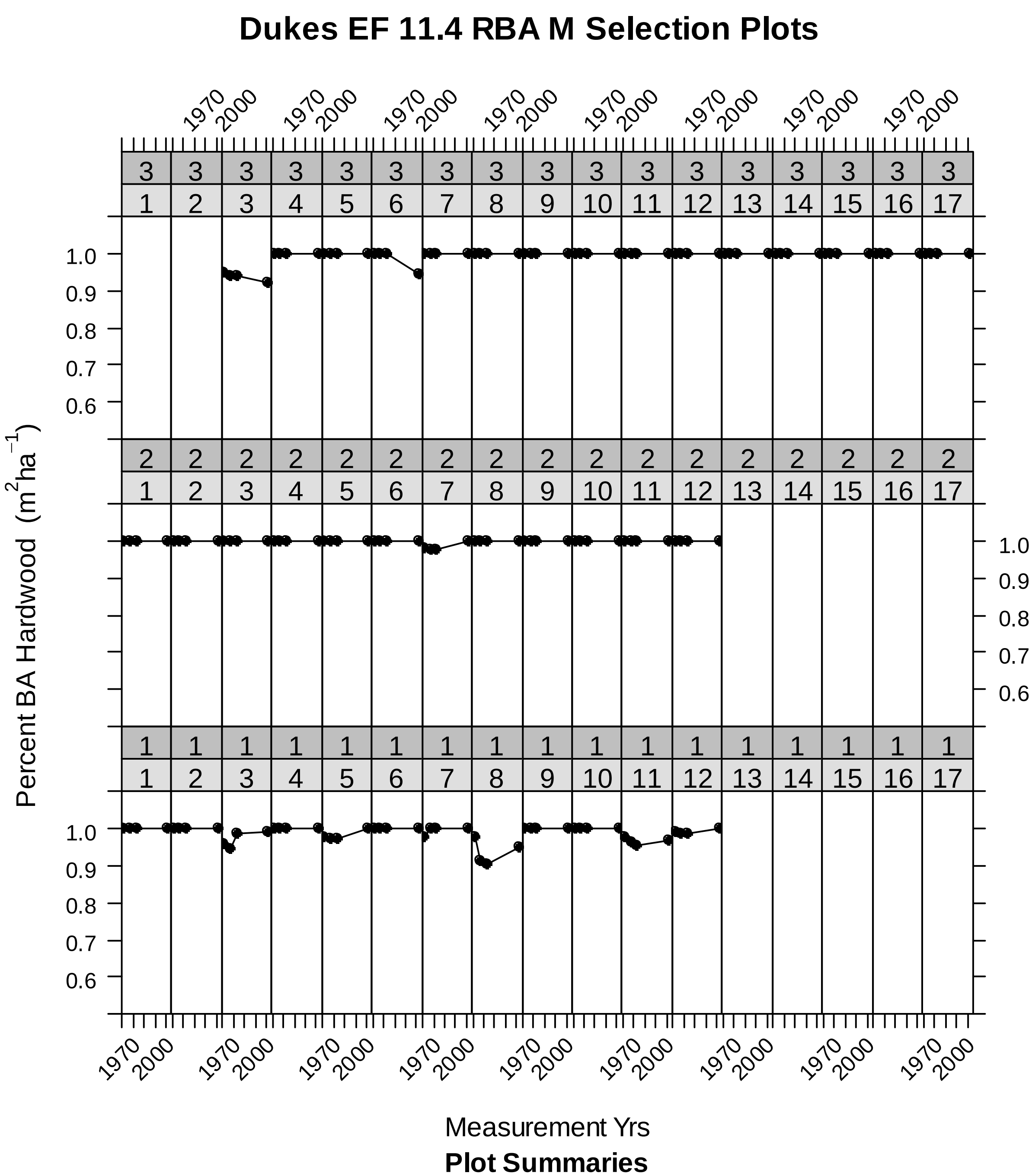


Figure C10. Relative composition as a percentage of living basal area through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in the darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in the lighter grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

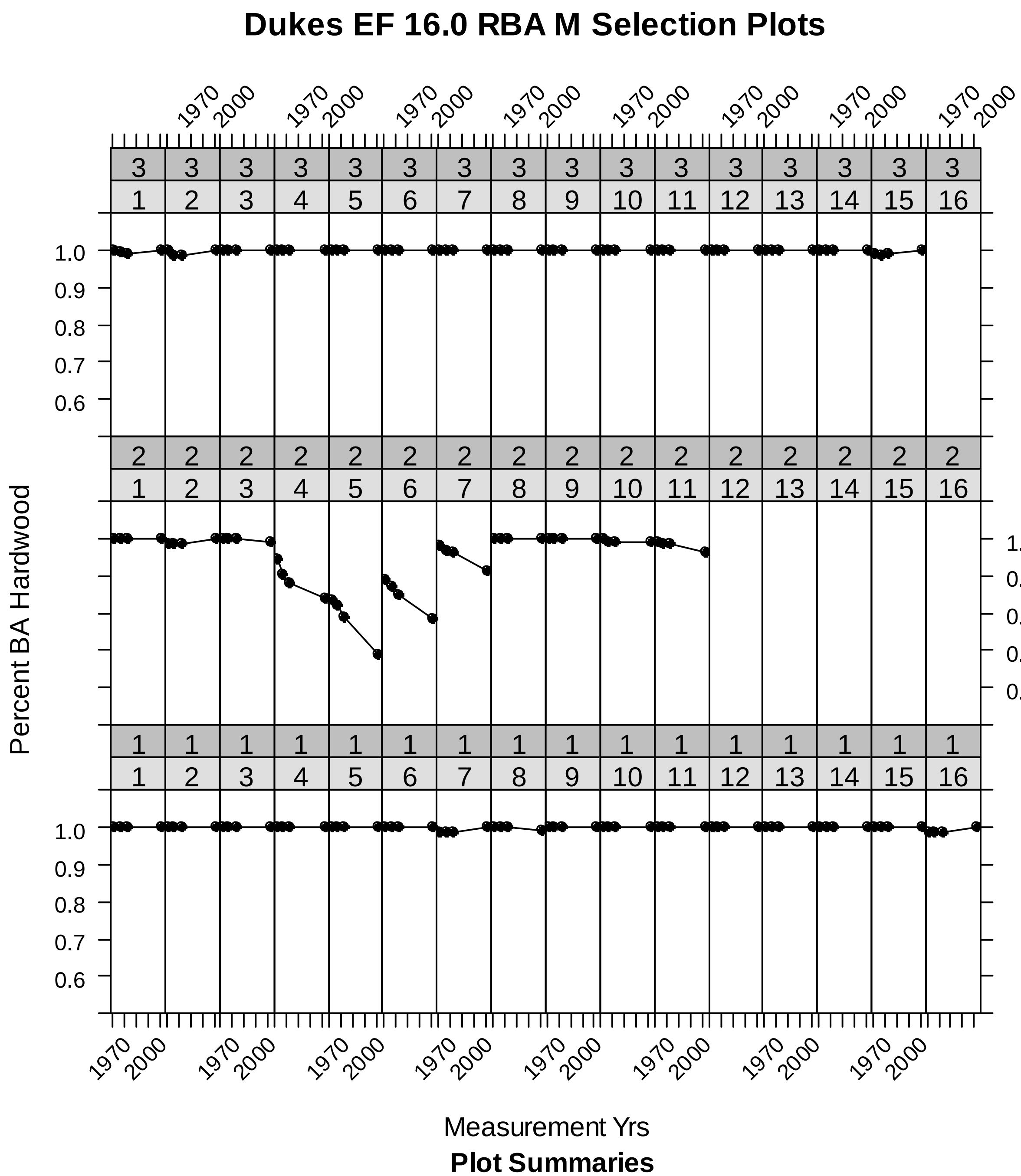


Figure C11. Relative composition as a percentage of living basal area through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in the darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in the lighter grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

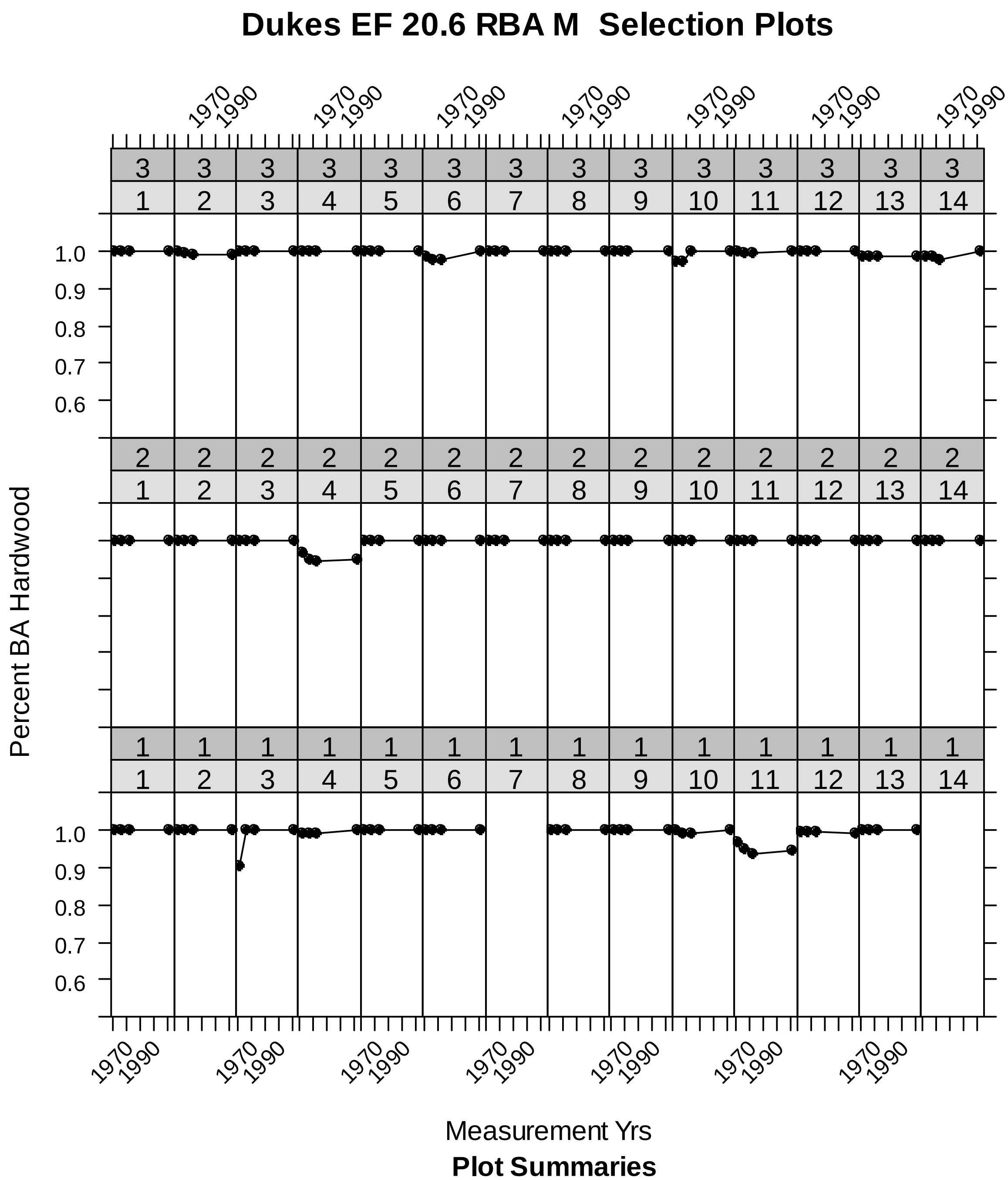


Figure C12. Relative composition as a percentage of living basal area through time on the Dukes Experimental Forest (DEF) 10-year selection plots. The value in the darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in the lighter grey section is actual plot number. Subset of measurements (pre-1960) was excluded based on site-level changing minimum diameter limits.

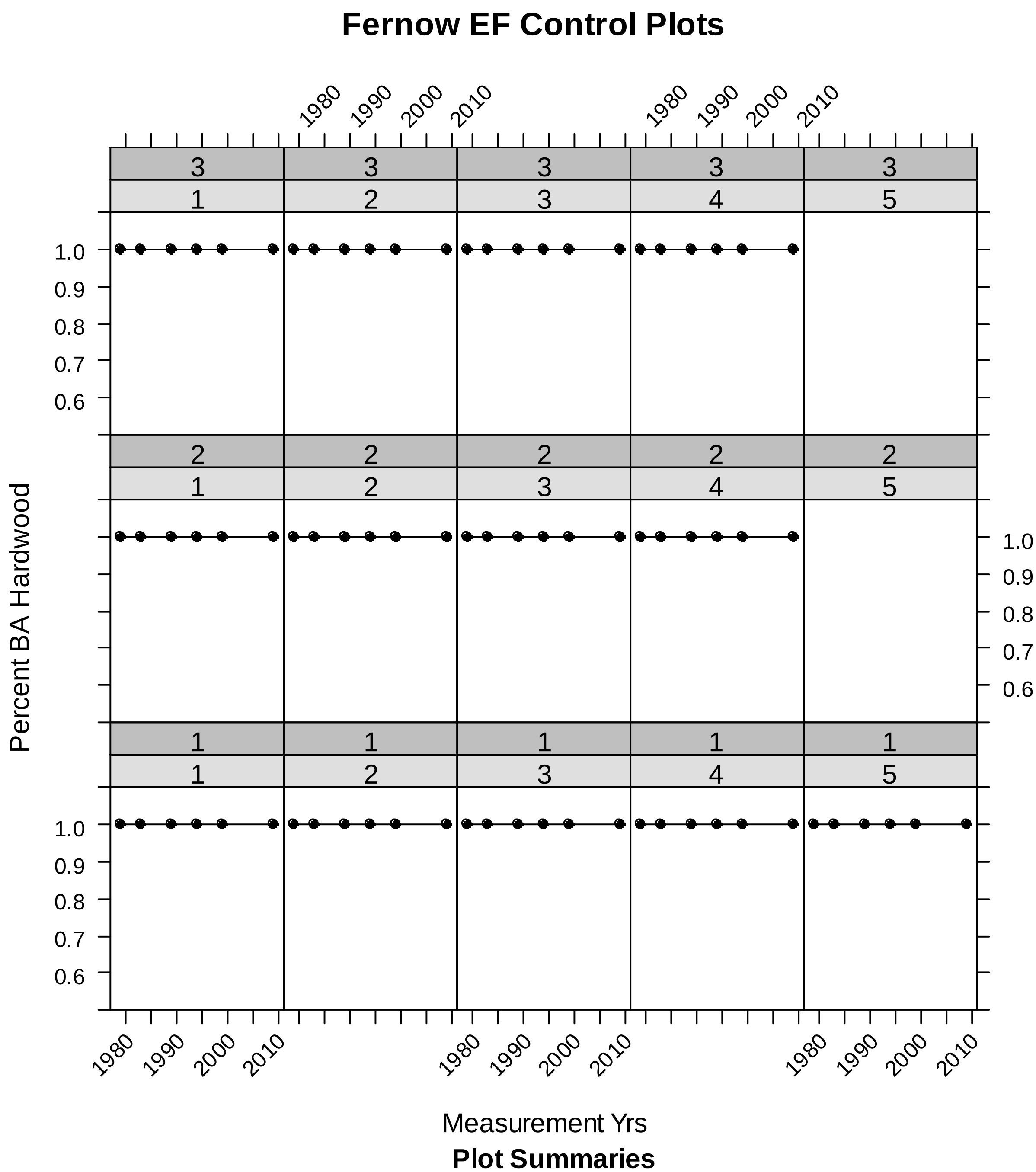


Figure C13. Relative composition as a percentage of living basal area through time on the Fernow Experimental Forest (FEF) control plots. The value in the darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in the lighter grey section is actual plot number.

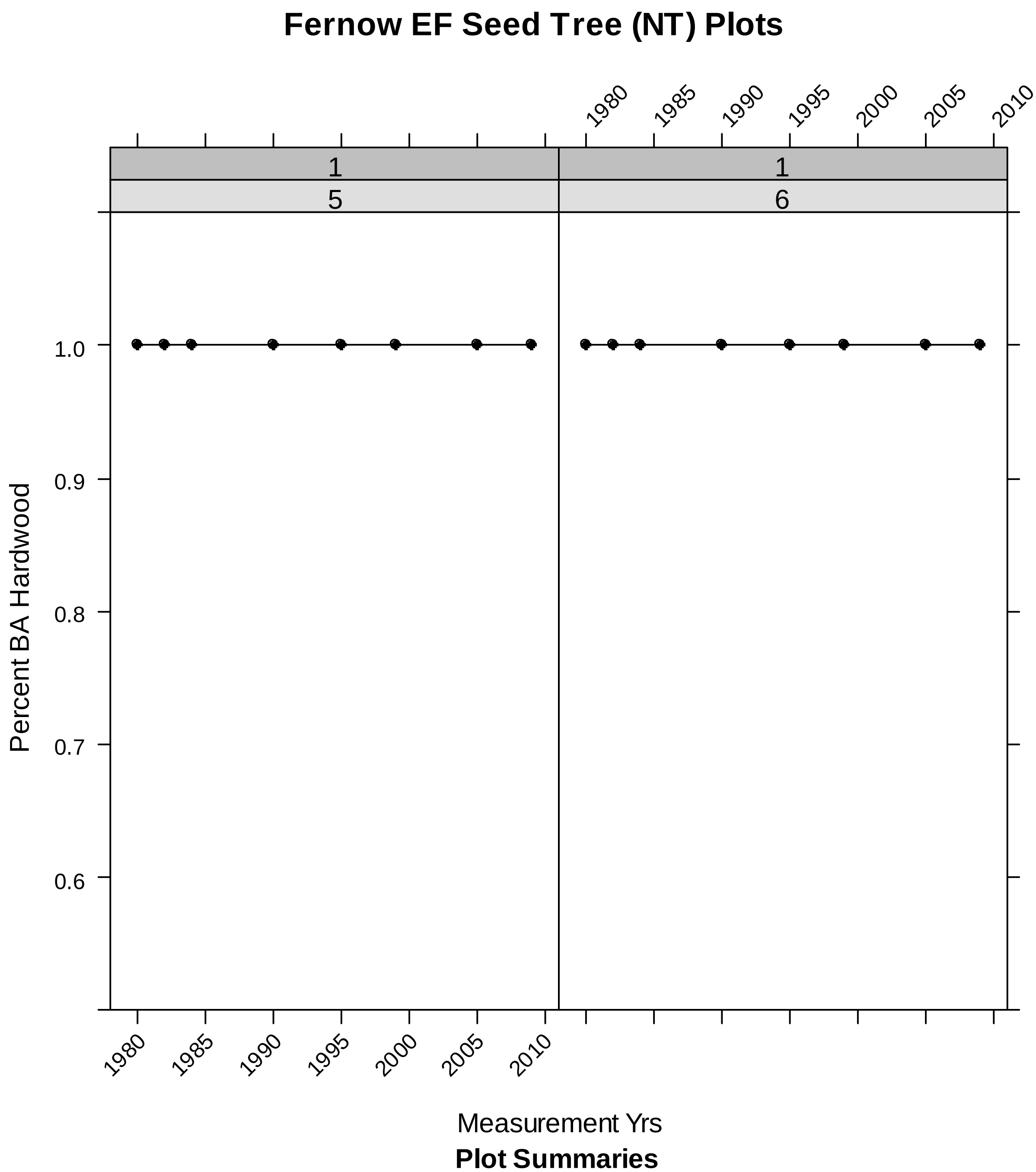


Figure C14. Relative composition as a percentage of living basal area through time on the Fernow Experimental Forest (FEF) non-thinned seed tree plots. The value in the darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in the lighter grey section is actual plot number.

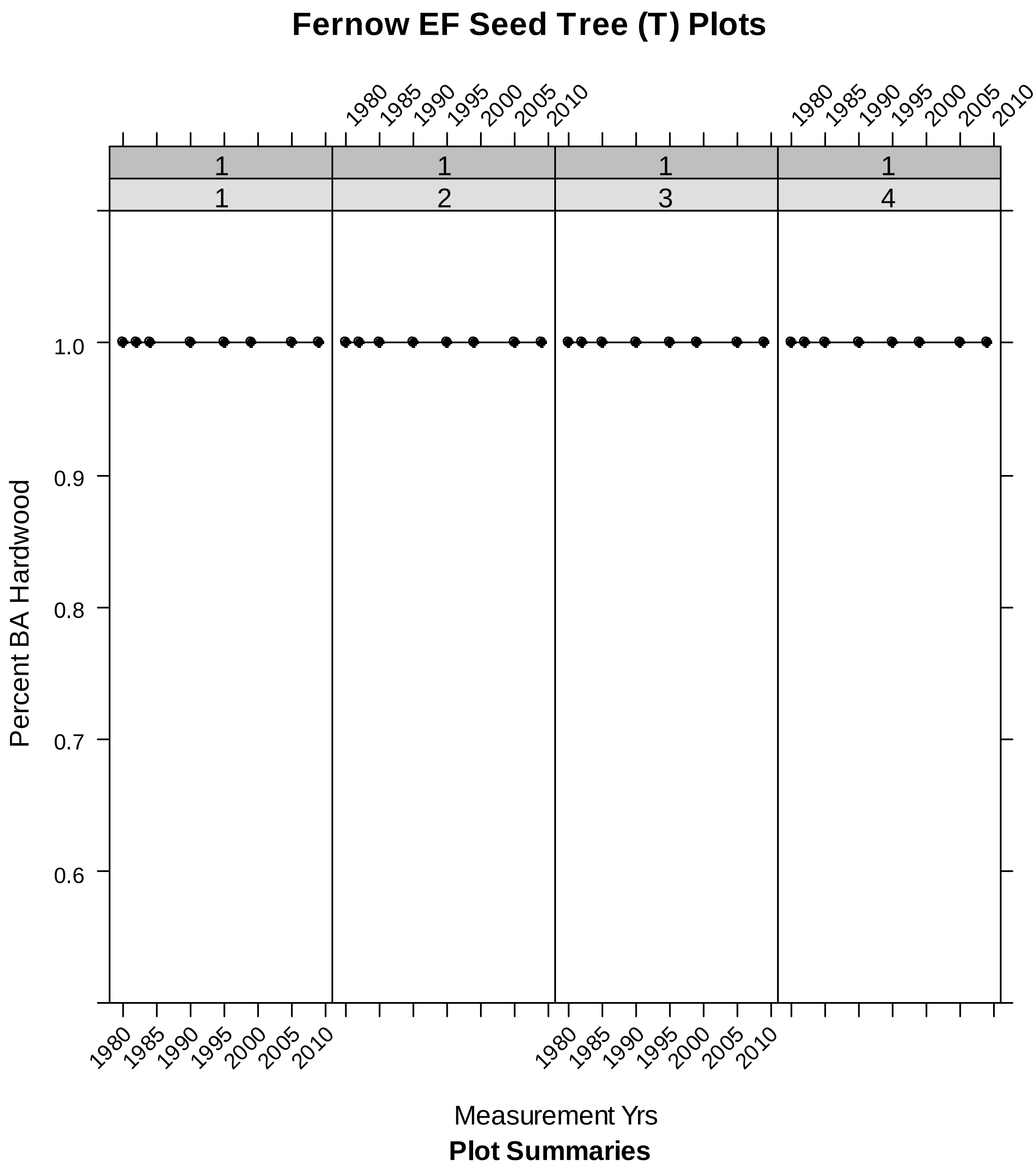


Figure C15. Relative composition as a percentage of living basal area through time on the Fernow Experimental Forest (FEF) thinned seed tree plots. The value in the darker grey section is standardized treatment replicate (A:1, 2:B), while the value is in the lighter grey section is actual plot number.

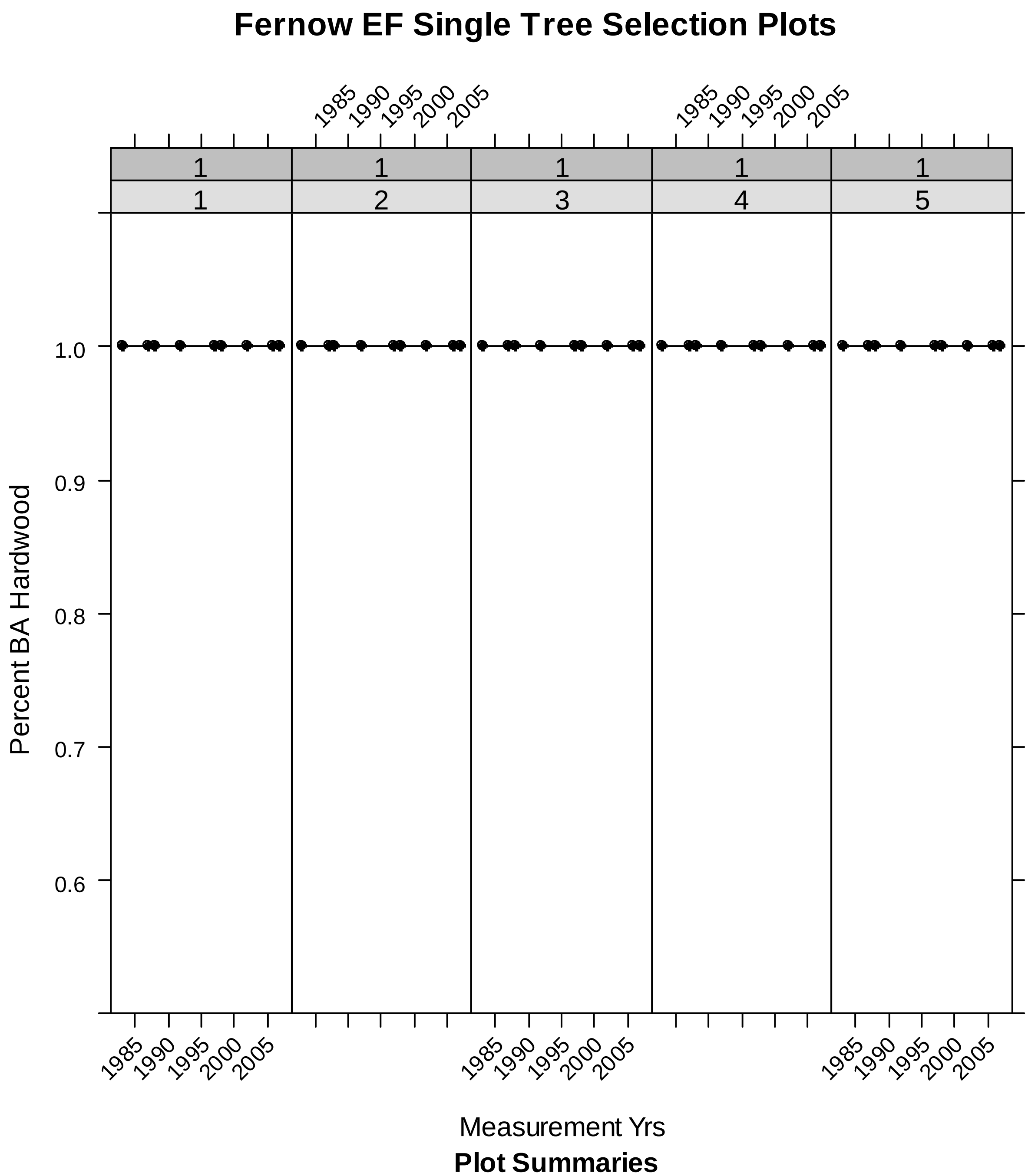


Figure C16. Relative composition as a percentage of living basal area through time on the Fernow Experimental Forest (FEF) single-tree selection plots. The value in the darker gray section is standardized treatment replicate (A:1), while the value is in the lighter grey section is actual plot number.

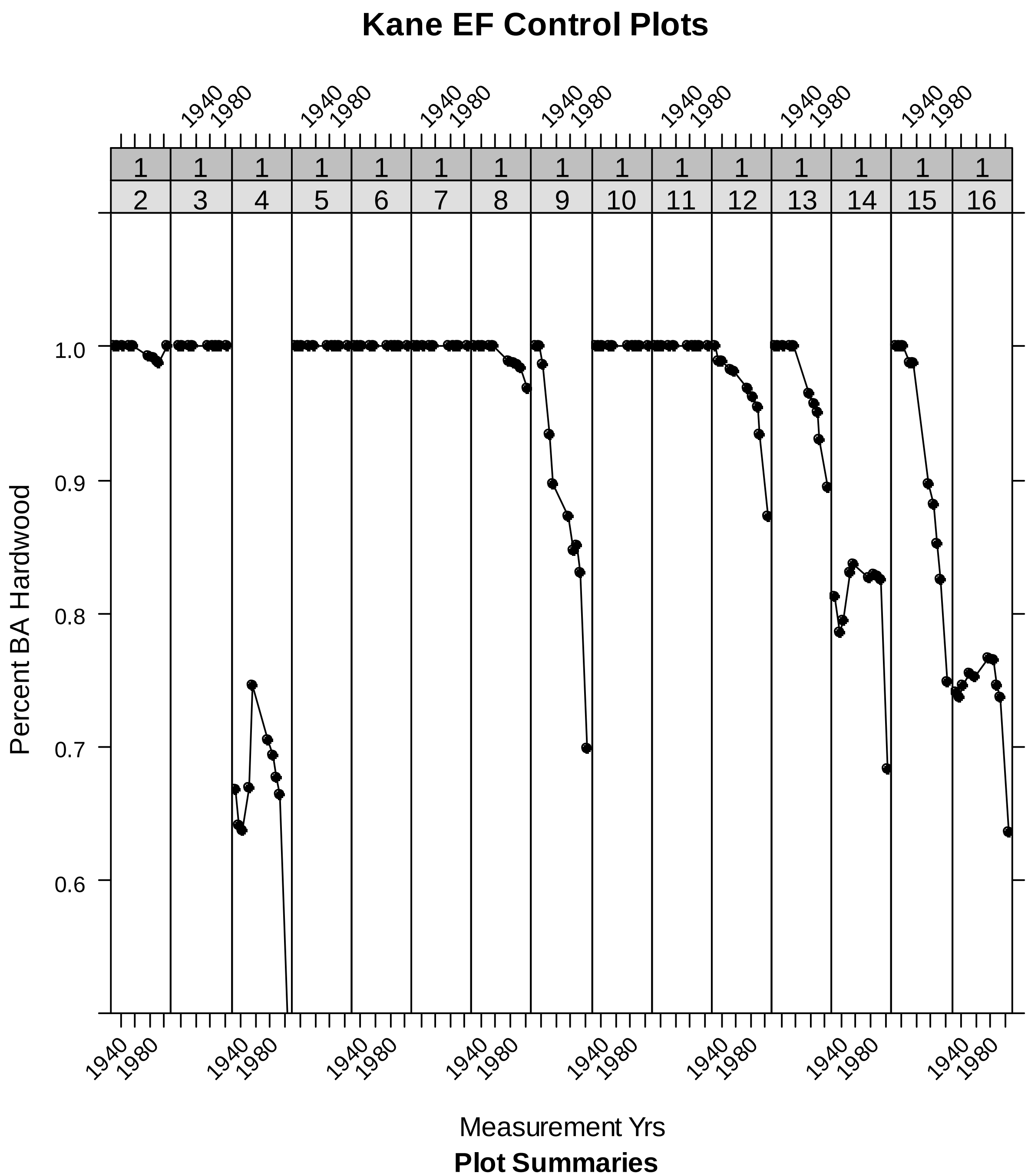


Figure C17. Relative composition as a percentage of living basal area through time on the Kane Experimental Forest (KEF) control plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number.

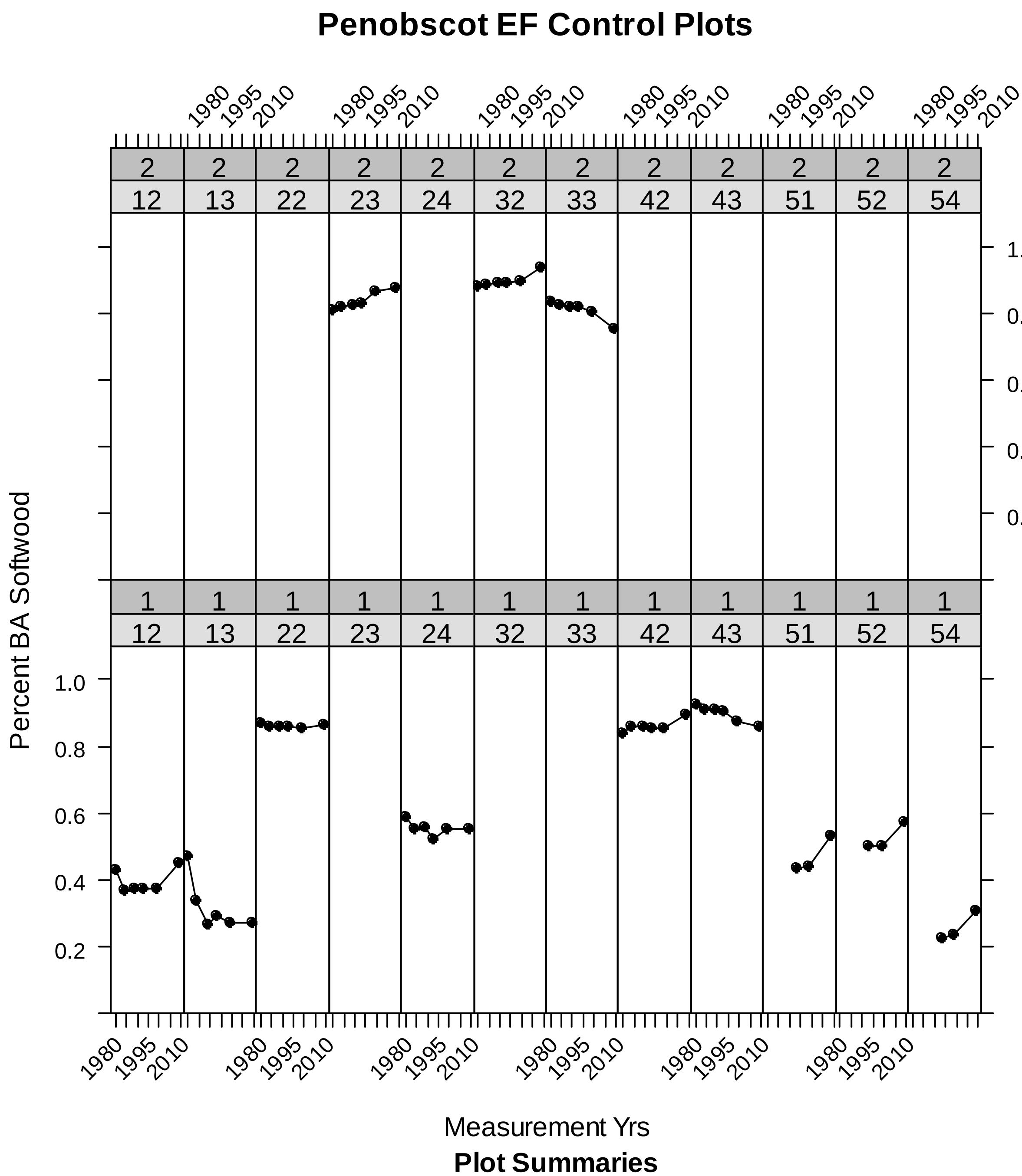


Figure C18. Relative composition as a percentage of living basal area through time on the Penobscot Experimental Forest (PEF) control plots. The value in the darker grey section is standardized treatment replicate (1: MU 32A, 2: MU 32B), while the value is in the lighter grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

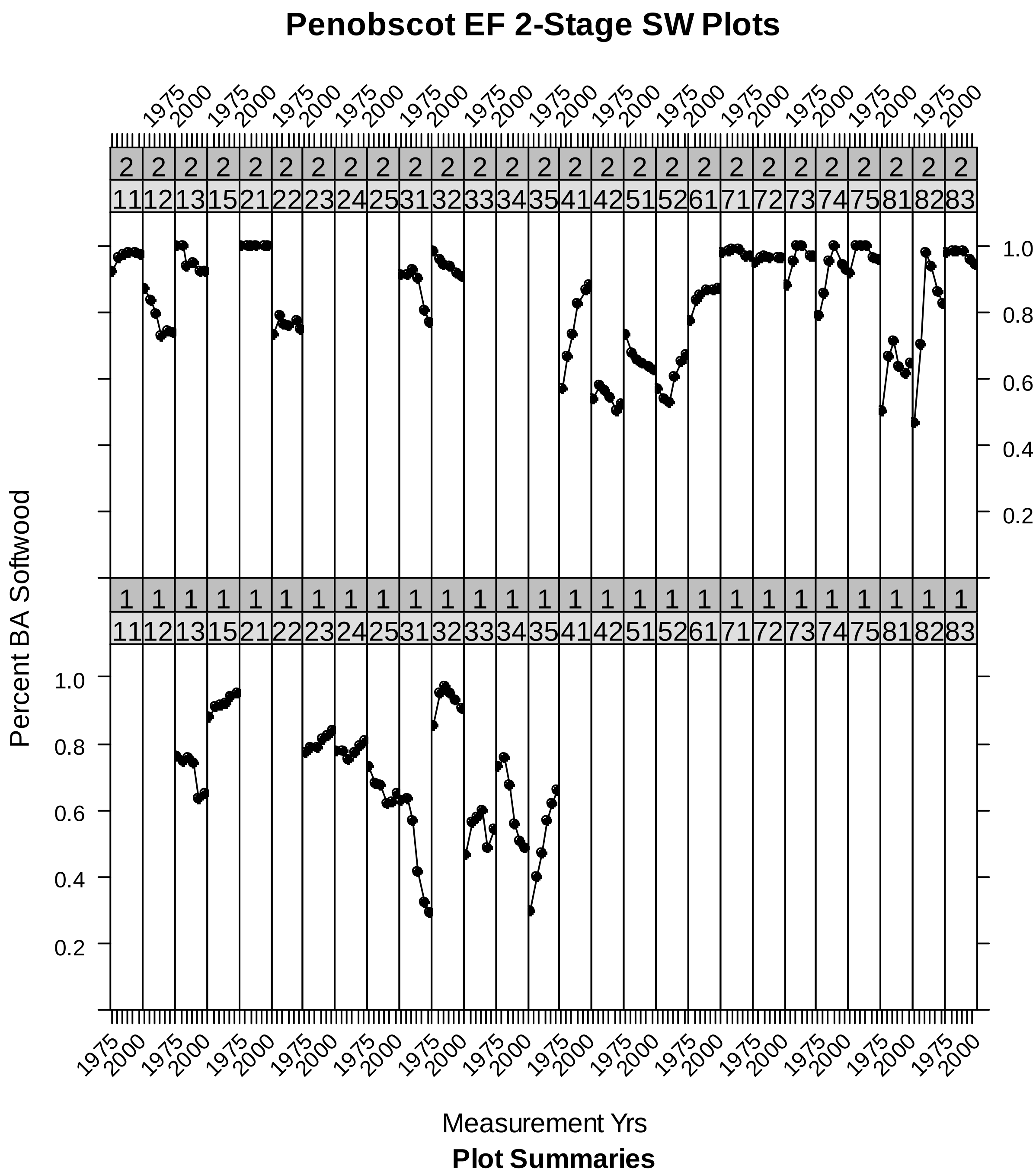


Figure C19. Relative composition as a percentage of living basal area through time on the Penobscot Experimental Forest (PEF) two-stage shelterwood plots. The value in the darker grey section is standardized treatment replicate (1: MU 21, 2: MU 30), while the value is in the lighter grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

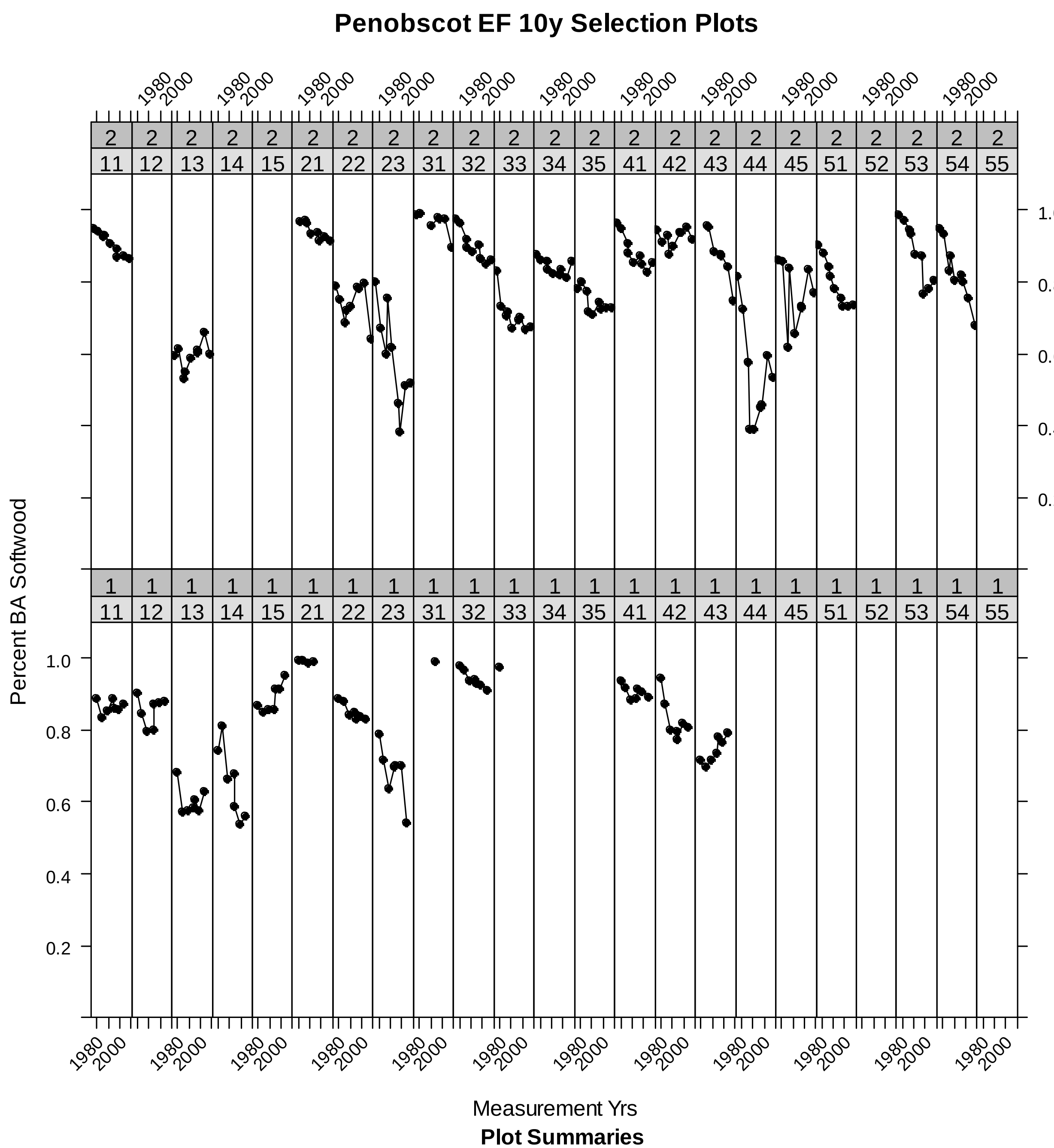


Figure C20. Relative composition as a percentage of living basal area through time on the Penobscot Experimental Forest (PEF) ten-year selection plots. The value in the darker grey section is standardized treatment replicate (1: MU 12, 2: MU 20), while the value is in the lighter grey section is actual plot number. Subsets of measurements (pre-1977) were excluded based on unavailable tree-list data.

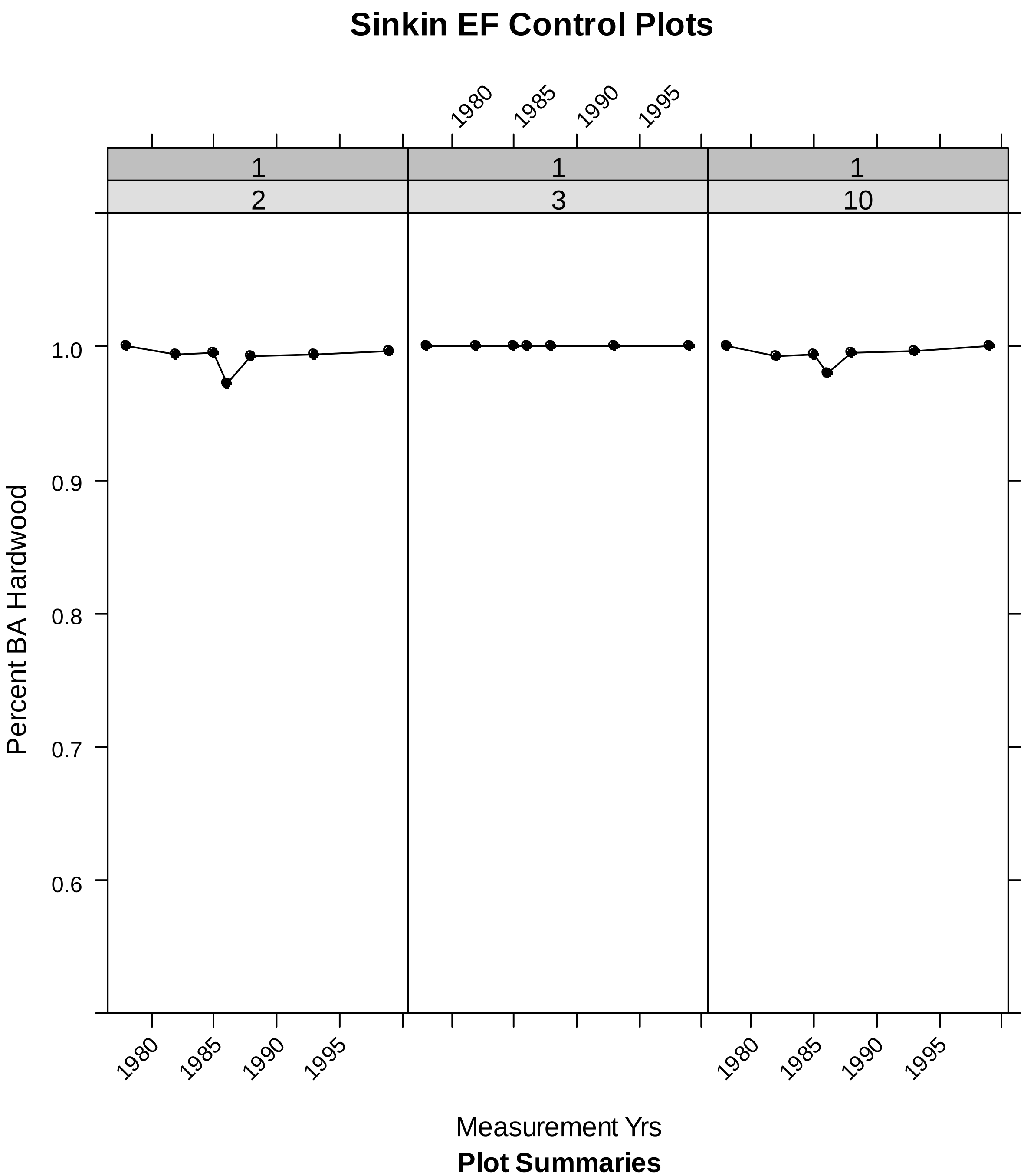


Figure C21. Relative composition as a percentage of living basal area through time on the Sinkin Experimental Forest (SEF) spatial distribution control plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number. Noncommercial tree species compose the “non-hardwood” composition on the SEF.

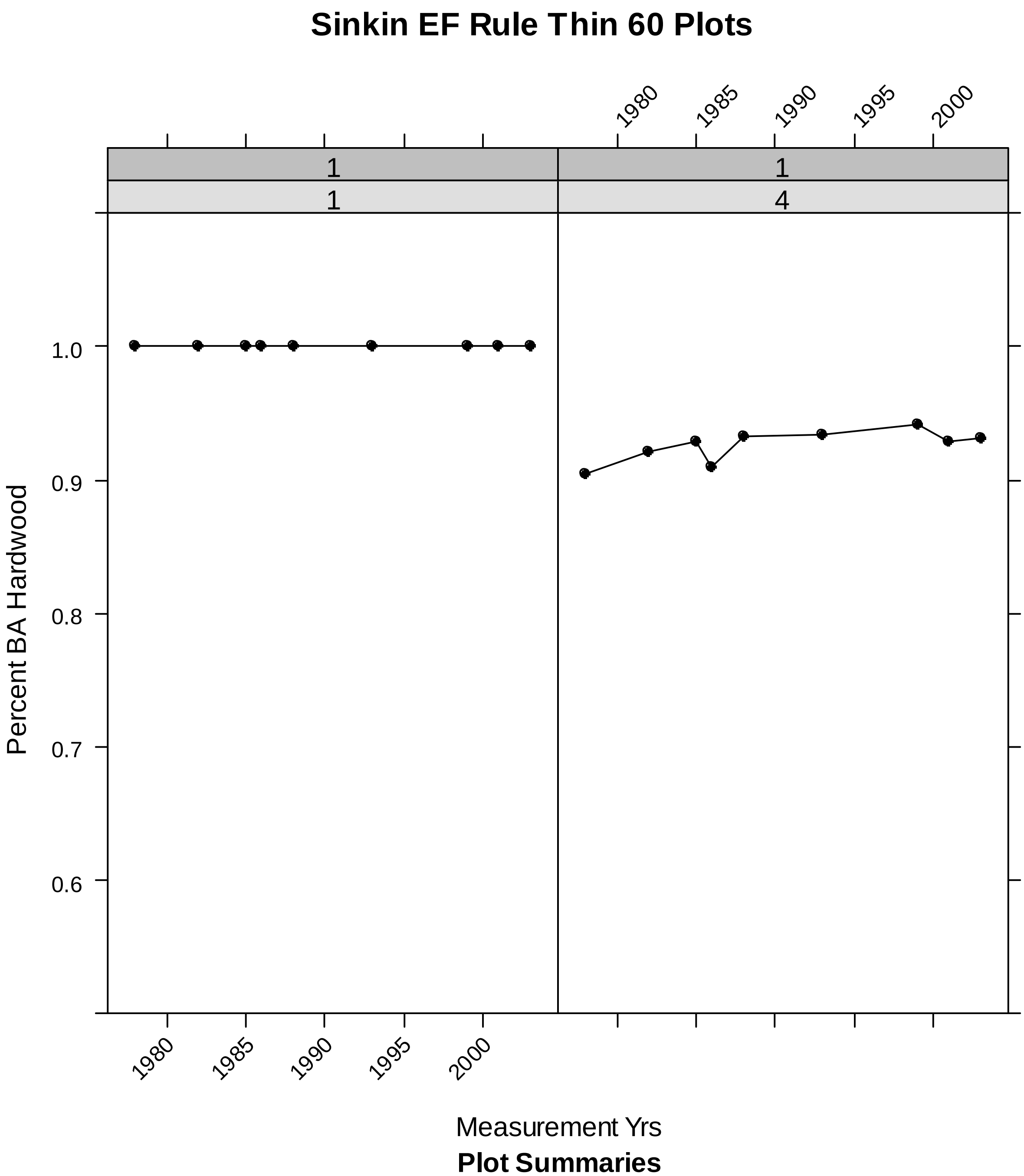


Figure C22. Relative composition as a percentage of living basal area through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (60%) plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number. Noncommercial tree species compose the "non-hardwood" composition on the SEF.

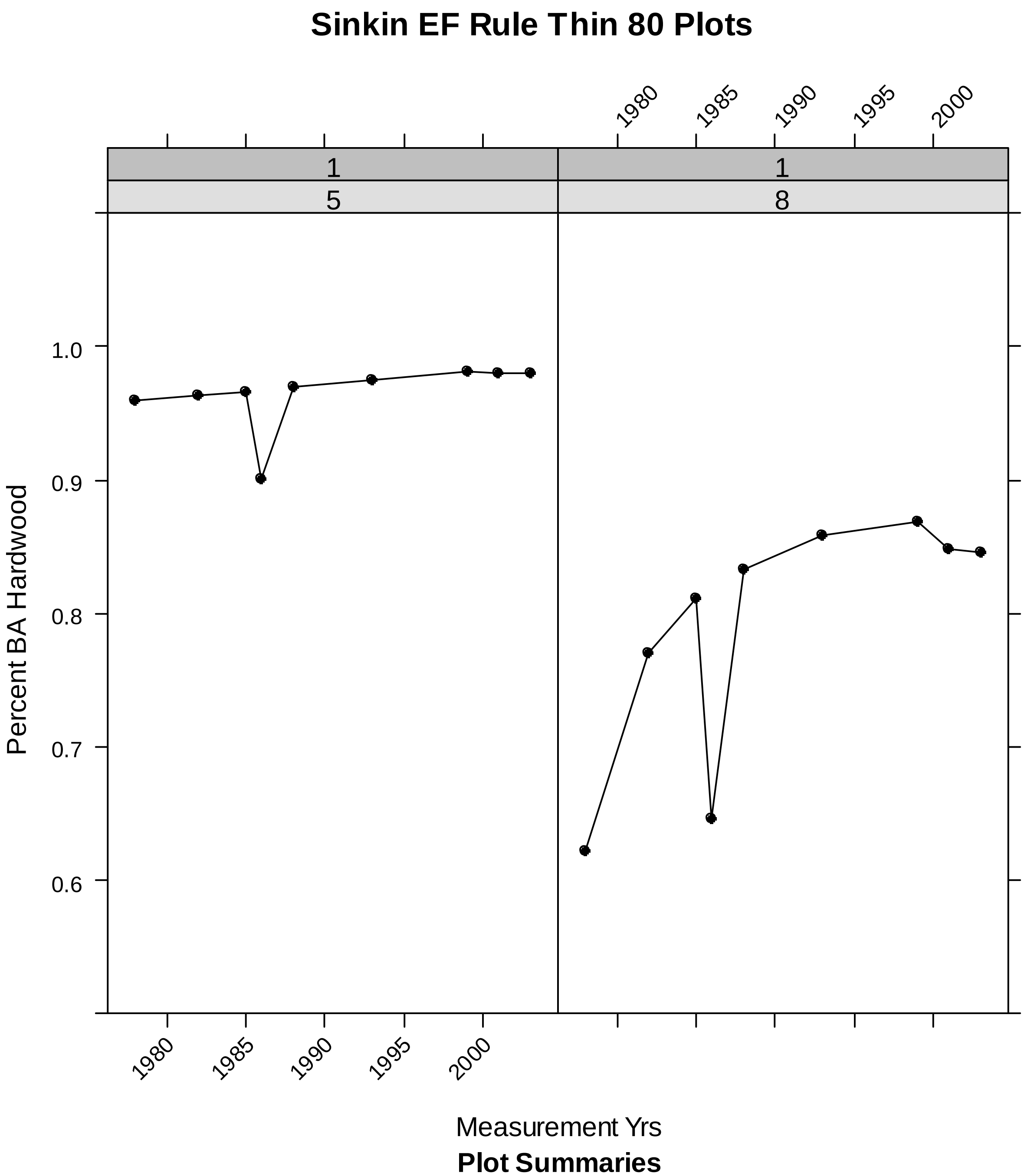


Figure C23. Relative composition as a percentage of living basal area through time on the Sinkin Experimental Forest (SEF) spatial distribution rule thin (80%) plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number. Noncommercial tree species compose the “non-hardwood” composition on the SEF.

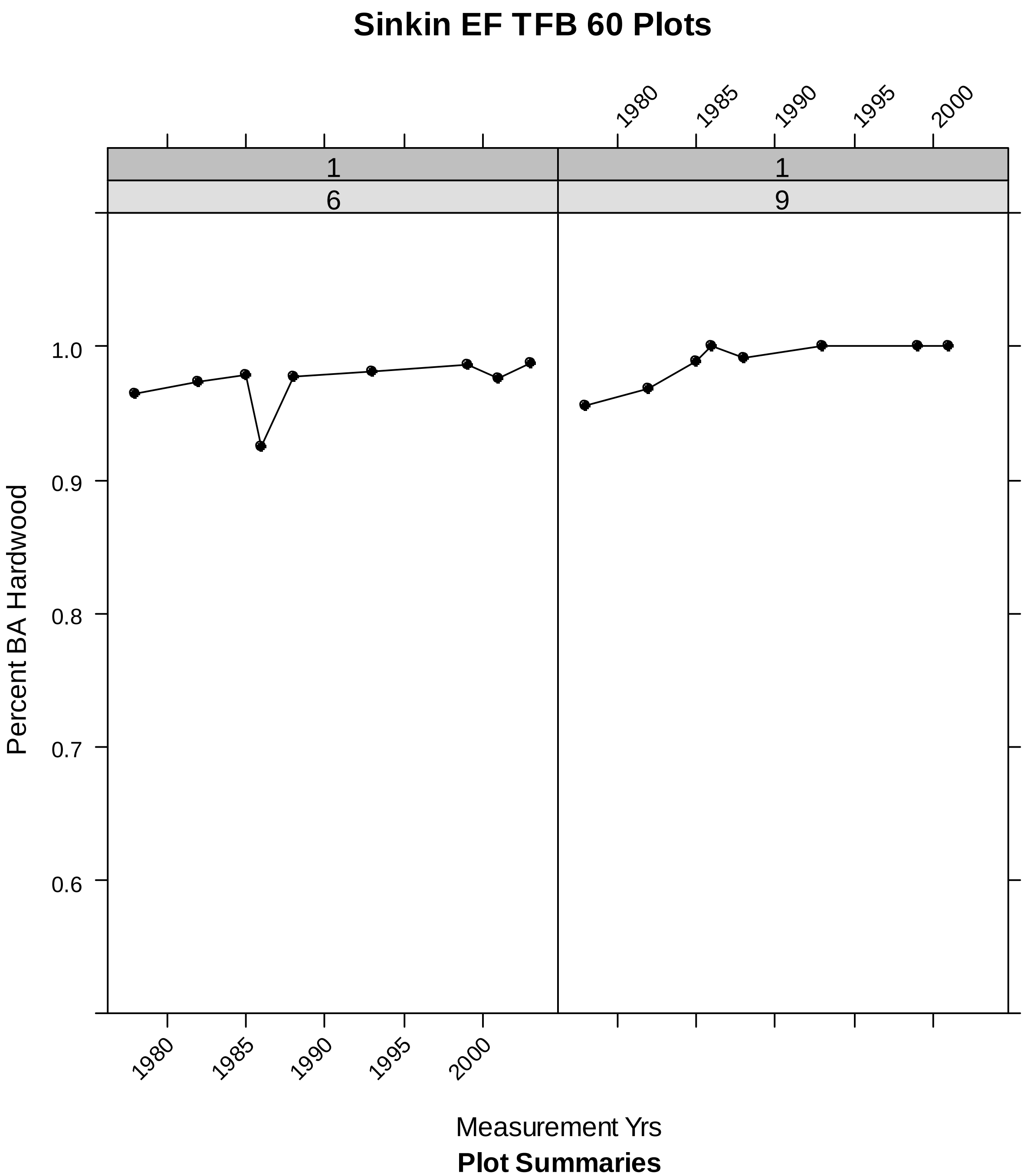


Figure C24. Relative composition as a percentage of living basal area through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (60%) plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number. Noncommercial tree species compose the “non-hardwood” composition on the SEF.

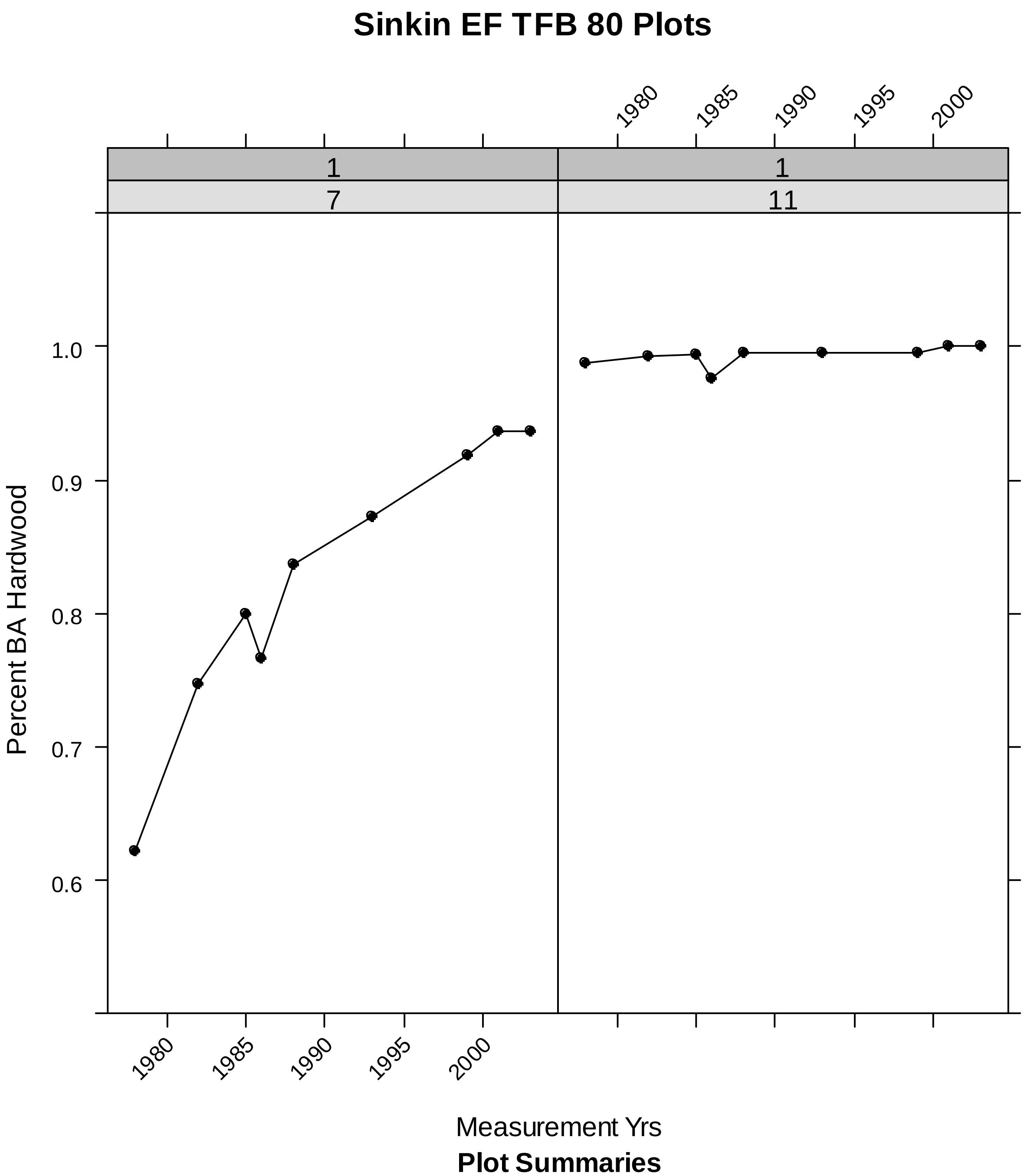


Figure C25. Relative composition as a percentage of living basal area through time on the Sinkin Experimental Forest (SEF) spatial distribution thinned from below (80%) plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number. Noncommercial tree species compose the “non-hardwood” composition on the SEF.

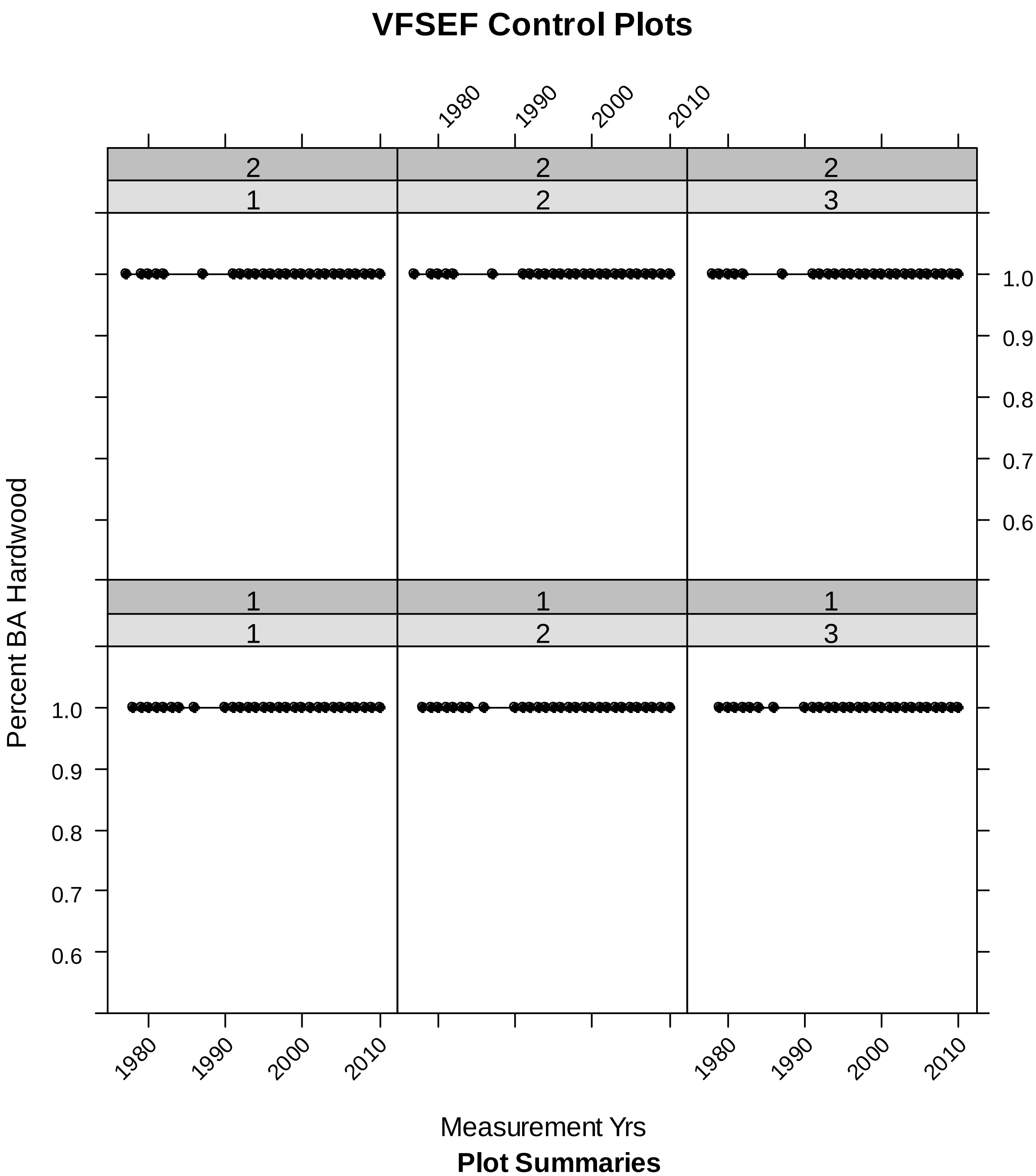


Figure C26. Relative composition as a percentage of living basal area through time on the Vinton-Furnace State Experimental Forest (VFSEF) control plots. The value in the darker grey section is standardized treatment replicate (1-2, Study 25, 27 respectively), while the value is in the lighter grey section is actual plot number.

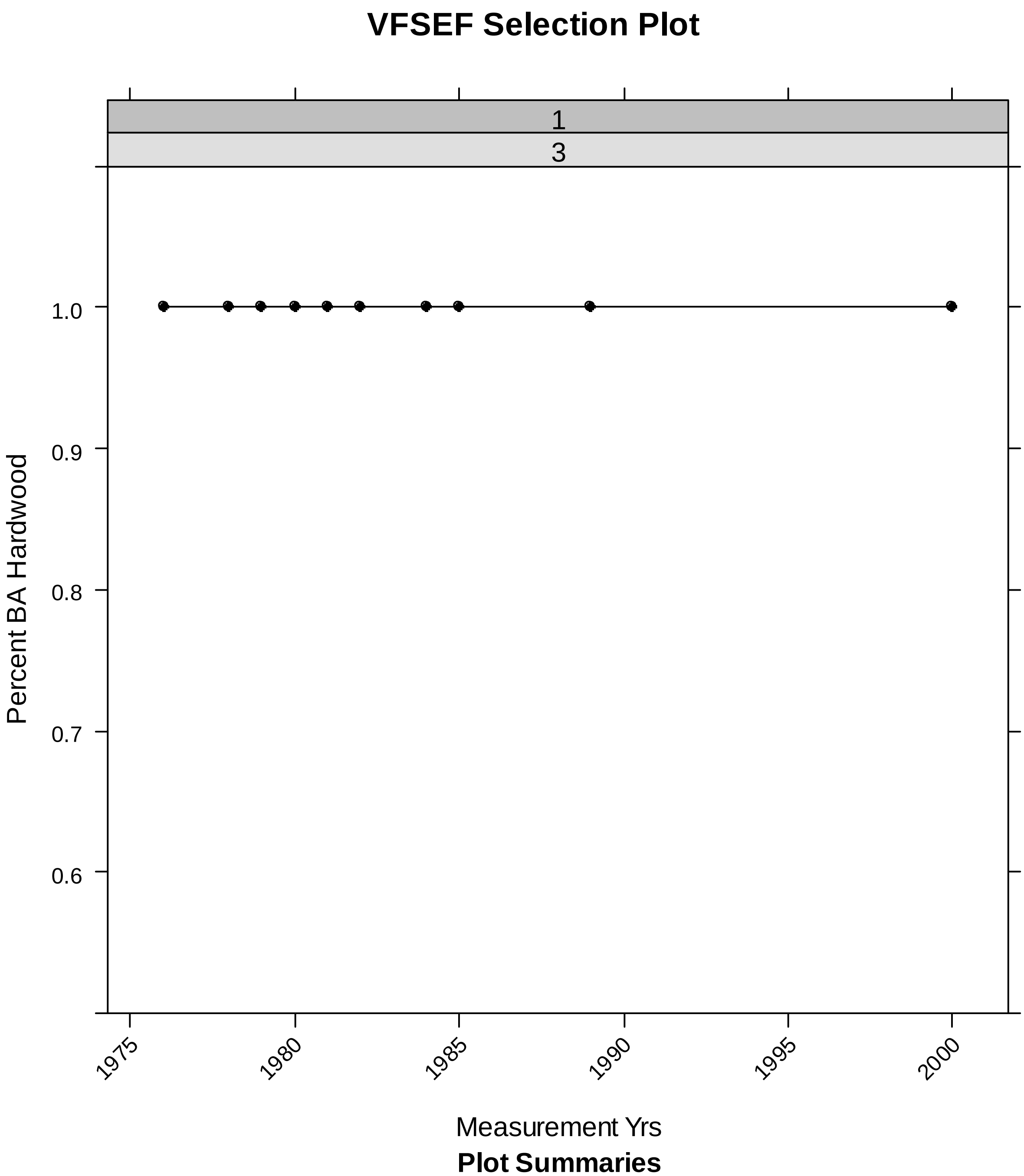


Figure C27. Relative composition as a percentage of living basal area through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number.

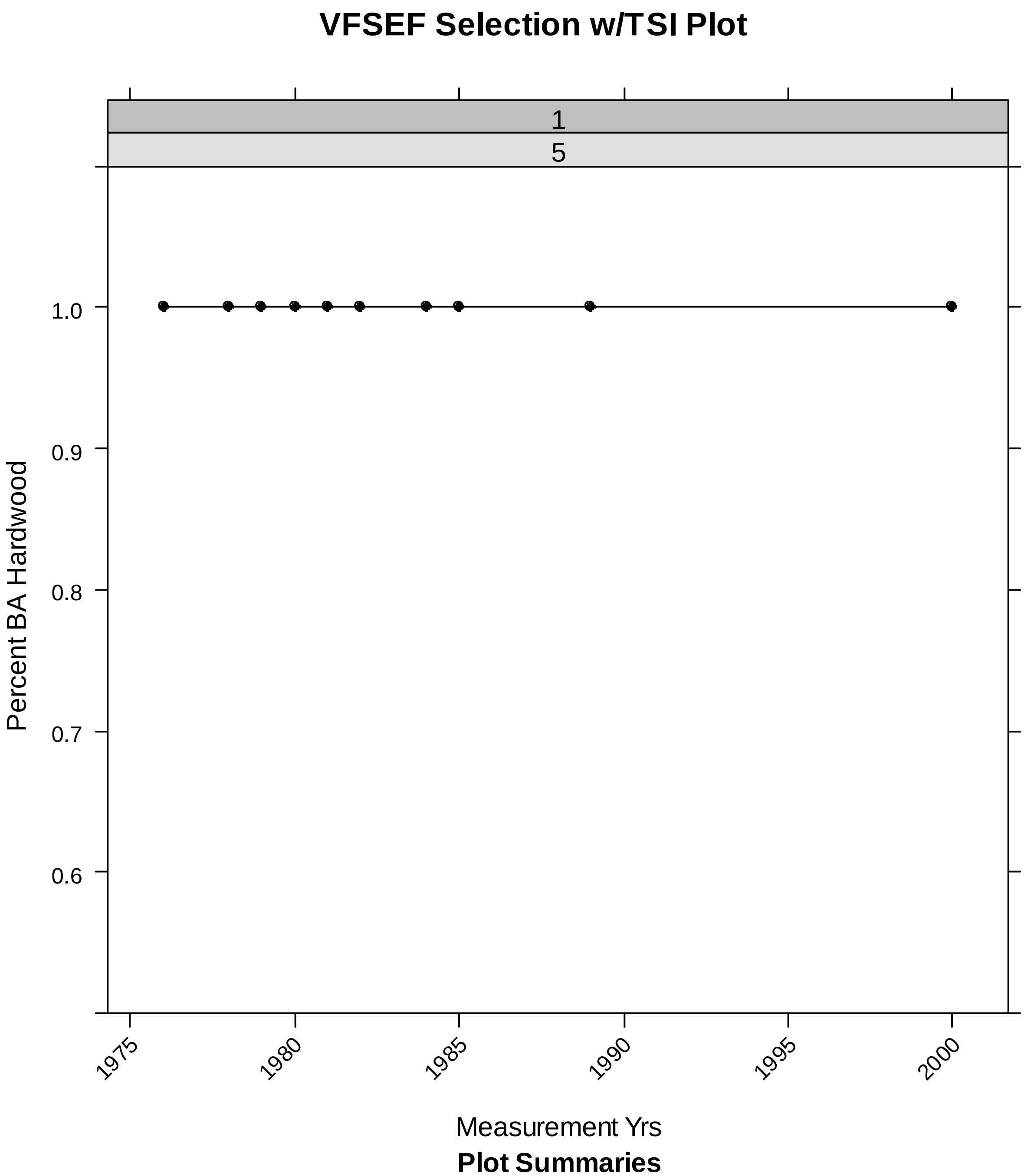


Figure C28. Relative composition as a percentage of living basal area through time on the Vinton-Furnace State Experimental Forest (VFSEF) selection with timber stand improvement plots. The value in the darker grey section is standardized treatment replicate, while the value is in the lighter grey section is actual plot number.

APPENDIX D. Additional study information

TABLE D1. Selected annual operating costs (FT 2008) from Experimental Forests of the US Forest Service Northern Research Station

USFS Site	Annual Operating Cost (USD)		Notes
	Data Management	*Total*	
AEF	$8,552	$39,379	
BLS*	-	-	Not USFS EFR
DEF	$8,552	$38,979	
FEF	$80,916	$438,416	
FEF	$24,699	$344,464	
PEF	*$62,400*	$162,000	
SEF	-	$142,000	Shared costs with Kaskaskia & Paoli EF
VFSEF	$80,000	$281,000	
Total NRS**	**$572,191**	**$3,824,503**	

Source: NRD-INF-07-09
*Within Superior National Forest, MN
** Not including Big Falls, Coulee, and Udell Experimental Forests

TABLE D2. Number of individual tree measurements by site, level of truncation, and tree status.

Site	Plot		Non-Truncated Standardized Data*		Site Level Truncation (1.27-11.684 cm)		Standardized Truncation (11.684 cm)	
	n	*Size (Ha)*	*Live*	*Total*	*Live*	*Total*	*Live*	*Total*
AEF	75	0.04	31149	36674	30109	35634	30054	30054
BLS	9	0.08	8067	8298	7857	8088	7769	7769
DEF **	124	0.08-0.81	17124	18151	14225	15252	14225	18442
FEF	24	0.08-0.20	37288	41454	37288	41454	12800	12800
KEF	17	0.04	12412	14893	11206	13687	3201	3202
PEF***	74	0.01-0.08	23341	25845	23341	25845	20879	19368
SEF	11	0.25	55738	70532	55721	70515	11935	40410
VFEF	8	0.04-0.81	28385	29510	27762	28887	23944	23944
Total	**342**	**-**	**213504**	**245357**	**207509**	**239362**	**124807**	**184144**

*Following removal of DEF (yrs: 1942-1960, 2007), PEF (yrs:1954-1977, plots less than 0.08HA)
**Excluding 2 plots from 1927 clearcut, raw data available in database
***Excluding all plots smaller than 0.08 Ha

TABLE D3. FIA species included in database.

Original FIA code	FIA Common Name	FIA Scientific Name
12	Balsam fir	Abies balsamea
68	eastern redcedar	Juniperus virginiana
71	tamarack (native)	Larix laricina
90	spruce spp.	Picea
94	white spruce	Picea glauca
105	jack pine	Pinus banksiana
110	shortleaf pine	Pinus echinata
125	red pine	Pinus resinosa
129	eastern white pine	Pinus strobus
241	northern white-cedar	Thuja occidentalis
261	eastern hemlock	Tsuga canadensis
315	striped maple	Acer pensylvanicum
316	red maple	Acer rubrum
318	sugar maple	Acer saccharum
319	mountain maple	Acer spicatum
322	bigtooth maple	Acer grandidentatum
351	red alder	Alnus rubra
355	European alder	Alnus glutinosa
356	serviceberry	Amelanchier
357	common serviceberry	Amelanchier arborea
370	birch spp.	Betula
371	yellow birch	Betula alleghaniensis
372	sweet birch	Betula lenta
375	paper birch	Betula papyrifera
379	gray birch	Betula populifolia
400	hickory spp.	Carya
402	bitternut hickory	Carya cordiformis
407	shagbark hickory	Carya ovata
421	American chestnut	Castanea dentata
471	eastern redbud	Ceriss canadensis
490	dogwood spp.	Cornus spp.
491	flowering dogwood	Cornus florida
500	hawthorn	Crataegus
520	persimmon spp.	Diospyros spp.
531	American beech	Fagus grandifolia
540	ash spp.	Fraxinus
541	white ash	Fraxinus americana
543	black ash	Fraxinus nigra
544	green ash	Fraxinus pennsylvanica
601	butternut	Juglans cinerea
621	yellow-poplar	Liriodendron tulipifera
651	cucumbertree	Magnolia acuminata
655	mountain magnolia	Magnolia fraseri

682	Red Mulberry	Morus Rubra
693	blackgum	Nyssa sylvatica
701	eastern hophornbeam	Ostrya virginiana
711	sourwood	Oxydendrum arboreum
729	Sycamore spp.	Platanus spp.
740	cottonwood and poplar spp.	Populus
741	balsam poplar	Populus balsamifera
743	bigtooth aspen	Populus grandidentata
746	quaking aspen	Populus tremuloides
760	cherry and plum spp.	Prunus
761	pin cherry	Prunus pensylvanica
762	black cherry	Prunus serotina
800	oak, deciduous	Quercus
802	white oak	Quercus alba
806	scarlet oak	Quercus coccinea
823	bur oak	Quercus macrocarpa
824	blackjack oak	Quercus marilandica
832	chestnut oak	Quercus prinus
833	northern red oak	Quercus rubra
835	post oak	Quercus stellata
837	black oak	Quercus velutina
901	black locust	Robinia pseudoacacia
931	sassafras	Sassafras albidum
951	American basswood	Tilia americana
972	American elm	Ulmus americana
975	slippery elm	Ulmus rubra
998	unknown hardwood	Tree broadleaf
999	Unknown dead hardwood	Unknown
9898	Non-commercial Species	----

AUTHOR BIOGRAPHY

Sarah was born on July 2, 1988 and raised in the coulee region of Minnesota, on the banks of the mighty Mississippi River. One day, the existence of an intriguing and exciting career in forestry dawned on her and she promptly made plans to attend the University of Wisconsin-Stevens Point.

While a student at the University of Wisconsin- Stevens Point, Sarah became involved in a variety of natural resource and forestry organizations including Society of American Foresters, Timbersports Team, UWSP Fire Crew, Women in Natural Resources, and the College of Natural Resources Undergraduate Research Symposium. Sarah also worked as a peer advisor in the College of Natural Resources Student Success Center. While she enjoyed chopping wood, running portable sawmills, and marking trees; her fascination with the quantitative aspects of forestry pushed Sarah to consider a path into research. Sarah graduated cum laude in 2010 with a BS in Forest Administration and Utilization and a minor in Business Administration.

Wanting to meld her interests in biometrics, forestry, business, research, and travel she sought out a position in quantitative graduate studies at the University of Maine in Orono, Maine. Sarah currently lives in Bangor, Maine and is a candidate for the Master of Science degree in Forest Resources at the University of Maine in August 2012.