Black Rock Forest and the Global Carbon Cycle: Rates of Carbon Sequestration from 1931-1994

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May 11, 1995

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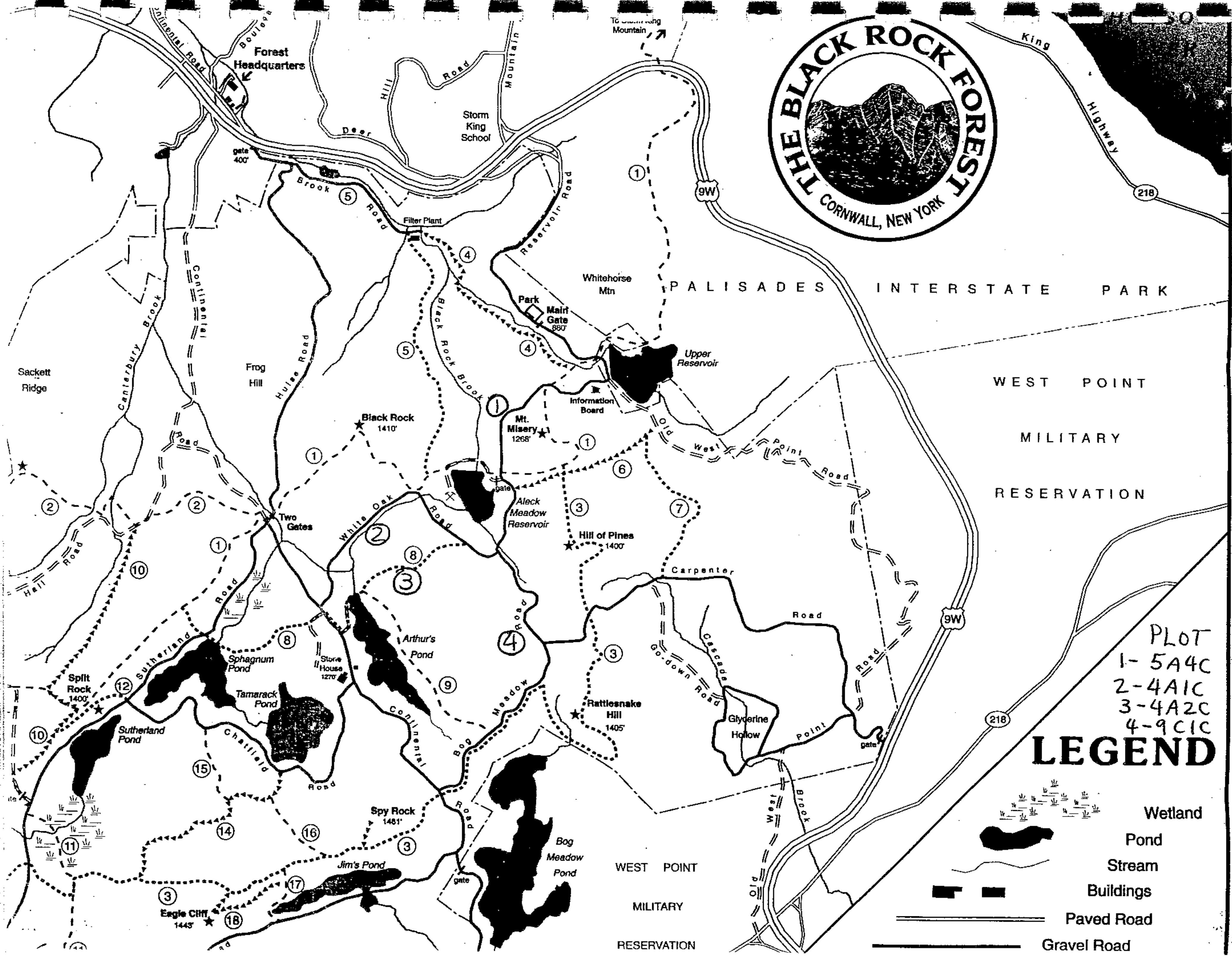


THE BLACK ROCK FOREST
CORNWALL, NEW YORK
PALISADES INTERSTATE PARK
WEST POINT MILITARY RESERVATION
King Highway
218
9W
To Storm King Mountain
Forest Headquarters
Continental Road
Boulevard
Storm King School
Deer Hill Road
Mountain
Reservoir Road
gate 400'
Brook Road
Filter Plant
Whitehorse Mtn
Park
Main Gate 860'
Upper Reservoir
Information Board
Mt. Misery 1268'
Black Rock 1410'
Black Rock Brook
Frog Hill
Hulse Road
Continental
Canterbury Brook
Sackett Ridge
Hall Road
Two Gates
White Oak Road
Aleck Meadow Reservoir
gate
Hill of Pines 1400'
Old West Point Road
Carpenter Road
Cascade
Go-down Road
Glycerine Hollow
Point
Arthur's Pond
Stone House 1270'
Sphagnum Pond
Tamarack Pond
Sutherland
Sutherland Pond
Split Rock 1400'
Chatfield Road
Continental Road
Bog Meadow Road
Rattlesnake Hill 1405'
Bog Meadow Pond
Spy Rock 1461'
Jim's Pond
Eagle Cliff 1443'
Old West Brook
LEGEND
Wetland
Pond
Stream
Buildings
Paved Road
Gravel Road
PLOT
1- 5A4C
2-4A1C
3-4A2C
4-9C1C

Abstract

In an attempt to better understand the role of forests in carbon storage, a study was undertaken at Black Rock Forest to quantify the above-ground carbon in this typical deciduous forest ecosystem. Regular measurements of tree biomass on four experimental plots over a 65-year period were updated, and these figures were converted into carbon figures, showing both present carbon stored and how the rates have changed over time. An average present carbon figure was computed, but there is considerable variation among plots, resulting most likely from land use history, age of tree stands, and variables such as available water and elevation. Overall the rates of carbon storage, as expressed by annual tree growth, have declined over the past 65 years, although among the different plots these rates vary considerably. Understanding the quantity and rates of carbon sequestration, and how they are expected to change over time and under other influences, such as climate change and other anthropogenic modifications of the environment, is critical to balancing the carbon budget.

Introduction

Quantification of the global carbon cycle is imperative not only for its inherent scientific worth, but also to show how human activity has impacted it and how these impacts may change natural cycles and potentially climate. Certain sources such emissions from fossil fuel combustion (Baes et al., 1977), and to a lesser extent, land use change and deforestation (Houghton et al., 1985; Houghton et al., 1987) can be quantified rather accurately, as can the atmospheric sink (Keeling et al., 1976). Determining the magnitude of the other sinks, the oceans, soils and sediments, and biospheric carbon, is more problematic. Atmospheric CO_2 levels do not match with the amounts expected from anthropogenic emissions, and thus there arises the phenomena of the "missing carbon sink" (Broecker et al., 1979; Woodwell et al., 1978; Houghton et al., 1986).

Table 1 - Global Carbon Budget, 1980, 10^{15} g C/yr

Release:	**Extreme**	**Median**	**Extreme**
Fossil Fuel Combustion, Cement Production	4.8	5.3	5.8
Tropical Forest Clearing	1.7	1.7	1.7
Accounted Sinks:			
Atmospheric Increase	-2.9	-2.9	-2.9
Ocean Uptake	-2.5	-2.2	-1.8
Nontropical Forest Clearing/Regrowth	-0.7	-0.7	-0.7
Carbon Exported by Rivers	-0.8	-0.8	-0.8
"Missing Carbon" Original*	(-0.3)	(1.2)	(2.8)
Revised Missing Sink	**-0.4**	**0.4**	**1.3**

*Sedjo (1992),with original missing sink adapted from Detwiler & Hall (1988). A minus indicates the need for a source; a plus the need for a sink. Parentheses indicate revised data on missing sink, coming from more accurate estimates of carbon release from soils due to deforestation, forest regrowth, and new information on carbon river content .

Studies quantifying the oceanic portion of the CO_2 sink, through measuring CO_2 partial pressures, eliminate the ocean as a substantial candidate for the missing sink (Tans et al., 1990). Complimenting this are updated data on forest stocks in both North America and Europe, which show forest regrowth during the 20th century, following periods of agricultural abandonment of land

(Kauppi et al., 1992; Birdsey et al., 1993; U.S. Environmental Protection Agency, 1993). Countering this are some models which take forest regrowth into account, and show the temperate and boreal systems in the Northern Hemisphere as a carbon source (Houghton et al.,1986). The above table summarizes recent attempts to quantify the global carbon budget, using older estimates from Detwiler and Hall (1988), and updating them using temperate forest regrowth as a substantial sink, based on data developed by the Economic Commission for Europe/Food and Agricultural Organization of the United Nations (ECE/FAO). More recent figures for tropical deforestation release are shown, with 1.7 Gt released annually, compared to the former 0.4-1.6 Gt range. Northern reforestation is included in the "nontropical forest clearing" category, because originally these forests were believed to be sources of carbon also (Houghton et al., 1986). The negative value of -0.7 Gt/yr release indicates that this is actually a sink. Overall the importance of these data show that contributing more accurate values to temperate reforestation could eliminate the need for a missing sink (Sedjo, 1993). Thus establishing improved carbon values for temperate forest ecosystems, which can then be extrapolated over larger land areas to give more exact figures, will help alleviate these discrepancies.

Present carbon values are primarily useful in the context of the past and future. There has been extensive regrowth in the Northern Hemisphere this century, allowing considerable carbon to be sequestered in young forests (Sedjo, 1992). The future of these forests as a carbon sink is unknown. Rates of above-ground carbon sequestration will decrease as forests reach a climax (EPA, 1993), although below-ground carbon in soils and organic matter could still accumulate. Influencing biosphere carbon sequestration are human induced changes in the environment, such as increased atmospheric CO_2 and pollution levels, and in variables such as precipitation, temperature, and soil moisture (Office of Technology Assessment, 1993). Forests may be affected on the physiological level, by increased respiration and growth, and on the ecological level, through changed detritus decomposition, soil respiration, and interspecific competition (Bazzaz, 1990; Luxmoore et al., 1993). Thus it is of upmost importance to quantify past and present carbon stocks, and correlate them with environmental variables, to predict future levels and how this will affect the forest carbon stocks and the global cycle.

In this study, I calculated the above-ground carbon component of Black Rock Forest, as found in four different sites in the area. Living trees (including roots) in New York comprise 29% of the total ecosystem carbon. Other components include the soils, which hold 61% of the ecosystem carbon, the forest floor (9%), and the understory plants (1%) (Department of Agriculture, 1992). Forests located in the northern states, including the deciduous forests of New York, tend to sequester proportionally more carbon in the soils and detritus than those of more southern latitudes. This is a function of the decreased temperatures, which retards oxidation of carbon, and increased precipitation, which increases vegetation and fine root production. Within the living trees, the above ground parts, such as stem, branches, and foliage, store 83% of the carbon, whereas the remaining 17% is found in the roots (DOA, 1992). Thus the above ground tree segments contain 24% of the total ecosystem carbon (83% of 29%).

Basal area measurements, done at approximately five-year intervals dating back to 1931, were converted to metric tons carbon per hectare, which by comparison showed substantial differences among the sites. Variables among these sites are analyzed, in an attempt to explain this differentiation. An average carbon figure for BRF as a whole was computed, to compare it with other well studied NE forests (Hubbard Brook, VT & Brookhaven, NY), and also generalized figures for New York forests, which were derived by the Department of Agriculture. The average BRF carbon value is also useful in showing how carbon storage rates have changed over the past 65 years, and how the biomass growth has been affected by variables such as temperature and precipitation. General consequences of increased anthropogenic influxes will be discussed in their effects on tree growth and forest health.

Rough predictions on how temperate forests and their ability to sequester carbon will be affected in the future in response to changing climate will be made. Temperature and atmospheric levels of CO_2 are expected to rise, as will the input of anthropogenic nitrogen, while precipitation and soil moisture are expected to decrease for the Northeastern U.S. (OTA, 1993). Therefore responses will be on both the physiological and ecological levels of the ecosystems. Different scenarios based on these variable parameters of precipitation changes and increasing CO_2 will be discussed.

Methods

Field data methods are very straightforward. Stem wood carbon content is based on basal area measurements. Four paired plots with areas 0.1-0.25 ha were laid out in 1931. All trees on the plots with diameters greater than 2.5 cm were marked at diameter breast height (dbh, approximately 1.35 meters from ground), measured with a tape (calibrated to give the diameter from the circumference), given a permanent number, and these data along with species were recorded. Diameter measurements, which had been taken in five-year intervals, were updated for the summer of 1994, and then converted to basal area (m^2/ha) by using diameter to area (square meters), and individual hectare conversions based on plot size.

$$(((dhb/2)^2)* 3.14)/100,000) * \text{ha conversion factor}$$

Hectare conversion factors were developed by measuring the lengths and diagonals of the plot to calculate area, and dividing into the area of a hectare. Having all values on a per hectare basis assures ease of comparison between plots.

Table 2 - Conversion Factors

Plot	Area (sq.m)	C.F. (sq.m/ha)
4A1C	889.1	11.25
4A2C	375.3	26.64
5A4C	410.6	24.36
9C1C	983.3	10.17

The above conversion factors represent each plot's respective land area and the conversion factor that is used to normalize this area (ranging from 3.8% to 9.8% of a hectare) to the area of one whole hectare.

Trees were divided into categories on the basis of species, and using their dbh cm, previously established (Pastor et al., 1984; Whittaker & Woodwell, 1968) regression equations were applied to determine biomass (see Table 3). These regression equations were established initially by measuring the trees' dbh, and then individual components of the tree (branches, main stem, etc.) were measured and oven-dried to determine above-ground biomass. This process was done repeatedly for each species to ensure accurate averages. These biomass values were multiplied by 50%, using the most common conversion figure used by biologists and the USFS. Hardwood species (such as those found in BRF) biomass contains 50% carbon by weight (Koch, 1989). Thus the carbon content of the above ground components (stem wood, branches, and foliage) was determined for each tree, which can not be done using other methods such as standing stock estimates used by the U.S. Forest Service (USFS).

Table 3 - Regressions: Total above ground weight in g

$\ln y = a + b \ln(\text{dbh cm})$

	a	b	r^2
Red maple	4.5893	2.4300	0.997
Sugar maple	5.0249	2.4285	0.998
Yellow birch	5.1428	2.3729	0.998
Red oak	4.9967	2.3944	0.994

(Pastor et al, 1984)

other 4.938 2.406

Table 4 - Regressions:
Total above ground weight in g
$\log_{10} y = a + b \log_{10}$ (dbh cm)

	a	b	r^2
Chestnut oak	2.3948	2.1900	0.994 (r)
White oak	2.3058	2.1666	0.993
Am. Beech	2.2916	2.3916	0.997
Other	2.2968	2.1357	0.991

(Whittaker & Woodwell, 1968)

All conversions and data analysis were done on an Excel v.4 spreadsheet. As can be shown in comparing trees with the same diameter but different species, there is considerable variation in the amount of carbon stored. Some species, such as sugar maple, are "denser" than others, such as red maple, and sequester more carbon than other species with the same trunk diameter. These data show the effect of species type on biomass, comparing 10 cm, 20 cm, 30 cm, and 40 cm dbh respectively. This will play an important role in the comparison of carbon storage among plots, as species composition differs among sites.

Table 5 - Effects of Species on Biomass using Regressions
Kilograms Carbon/Tree

SPECIES	10 CM	20 CM	30 CM	40 CM
CO	19.2	87.7	213.1	400.2
RO/SO/BO	18.3	96.4	254.6	507
WO	14.8	66.6	160.4	299.1
RM	13.3	71.4	191.2	384.7
SM	20.4	109.9	294.1	591.4
YB/BB	20.2	104.6	273.9	542
BE	18.7	103.1	279.8	568.1
OTHER	17.8	94.1	249.7	499

Key: CO-chestnut oak; RO, SO, BO - red, scarlet, black oak; WO - white oak; RM - red maple; SM sugar maple; YB, BB - yellow & black birch; BE - American beech. All figures represent kilograms carbon.

Results

The results are grouped together as follows. The primary data and topic of this paper are the above ground carbon figures (in metric tons per hectare) from the four plots: 4a1c (Arthur's Brook), 4a2c (White Oak Trail), 5a4c (Mt. Misery), and 9c1c (Bog Meadow). The data include initial biomass and carbon when the plots were first established in 1931-36, and all figures from subsequent measurements of the trees. Here, "establishing" the plot is meant as the first episode where the trees were measured and record was made of their species, and the boundaries of the plots were delineated. Some plots were already well established at the time of the initial study, with trees up to 50 years in age. There are also data relating to the rates of carbon sequestration over time, and how these rates differ among plots and over the decades.

Secondary results include those data of more forestry-related nature, which nonetheless are valuable in explaining differences in carbon sequestration rates among plots. They include tables and graphs showing species composition in each plot, overall density changes (density being the number of trees/stems per hectare) over time, and size distribution over time.

Other results include the West Point, NY meteorological data, which have been measured since 1821. The station has taken measurements on temperature, precipitation, and atmospheric influxes of important cations and anions during the past 15 years. The temperature and precipitation are of greater relevance in their correlation to forest growth. Temperature data include yearly and decade averages, while precipitation data include total yearly, total summer, decade average yearly and summer, and deviation from mean for year and summer.

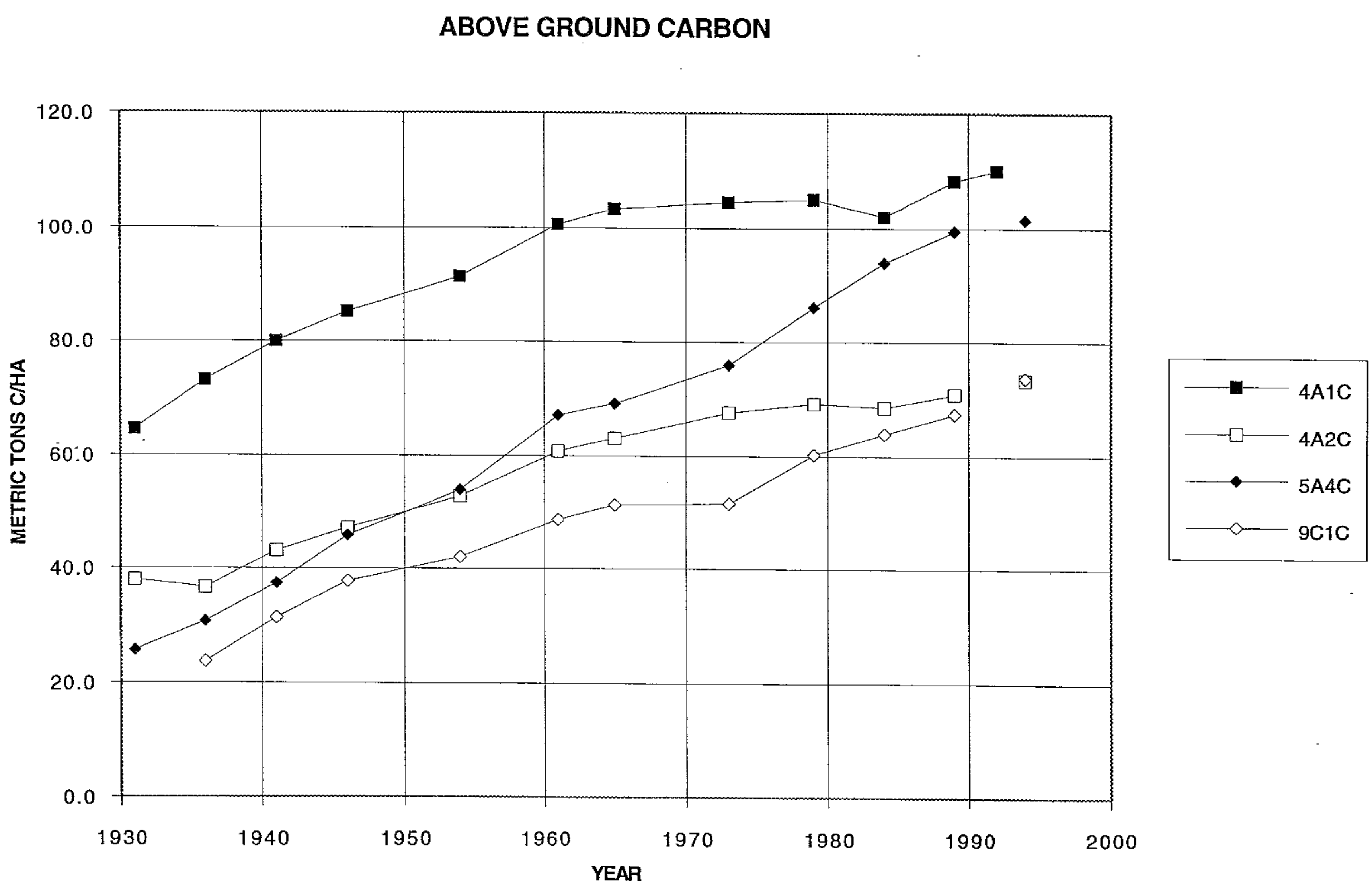
I. Carbon figures

Table 6 documents the total above ground carbon stored in all trees having diameters greater than 2.5 cm. These figures do not include shrubs and grasses, as these ecosystems components contain minimal carbon compared to the trees. The above ground sections of trees contain 24% of the total ecosystem carbon (the whole tree contains 29%), whereas the understory vegetation contain only 1%. Although the plots were not measured in the same years, original figures (at different dates) were multiplied by growth rates between the measurements, so resulting in "standard" dates, to allow more ease of comparison. Both the original dates and standardized dates are given below in tables 6 and 7. Since plot 9c1c had no measurement before 1936, and one can not back extrapolate, it is blank for 1931. Plot 4a1c was last measured in 1993, and thus is blank for 1994.

Table 6 - Unstandardized Carbon Figures (Metric tons C/ha)

YEAR	4a1c	4a2c	5a4c	9c1c
1931	64.6	38.0	-	-
1932	-	-	25.7	-
1936	73.1	36.6	-	23.7

Figure 2


ABOVE GROUND CARBON
120.0
100.0
80.0
60.0
40.0
20.0
0.0
METRIC TONS C/HA
1930
1940
1950
1960
1970
1980
1990
2000
YEAR
4A1C
4A2C
5A4C
9C1C

1937	-	-	32.0	-
1941	79.9	43.1	-	31.4
1942	-	-	38.7	-
1946	85.2	47.2	-	37.8
1947	-	-	47.6	-
1954	91.3	52.8	53.9	42.1
1961	100.6	60.8	67.1	-
1964	-	-	-	51.5
1965	103.3	63.1	69.1	-
1972	-	-	-	49.9
1973	104.5	67.6	75.9	-
1976	-	-	-	56.4
1978	-	69.5	-	-
1979	105.0	-	86.1	-
1981	-	-	-	62.8
1983	-	68.1	-	-
1984	102.0	-	93.9	-
1986	-	-	-	64.7
1988	-	70.4	-	-
1989	108.3	-	99.5	-
1992	110.0	-	-	70.2
1994	-	73.3	101.5	73.7

Table 7 - Standardized Dates (Metric tons carbon/ha)

YEAR	4a1c	4a2c	5a4c	9c1c
1931	64.6	38	25.5	-
1936	73.1	36.6	30.7	23.7
1941	79.9	43.1	37.4	31.4
1946	85.1	47.2	45.9	37.8
1954	91.3	52.8	53.9	42.1
1961	100.6	60.8	67.1	48.7
1965	103.3	63.1	69.1	51.3
1973	104.5	67.6	75.9	51.6
1979	105	69.2	86.1	60.3
1984	102	68.5	93.9	63.9
1989	108.2	70.9	99.5	67.4
1993	110	-	-	-
1994	-	73.3	101.5	73.7

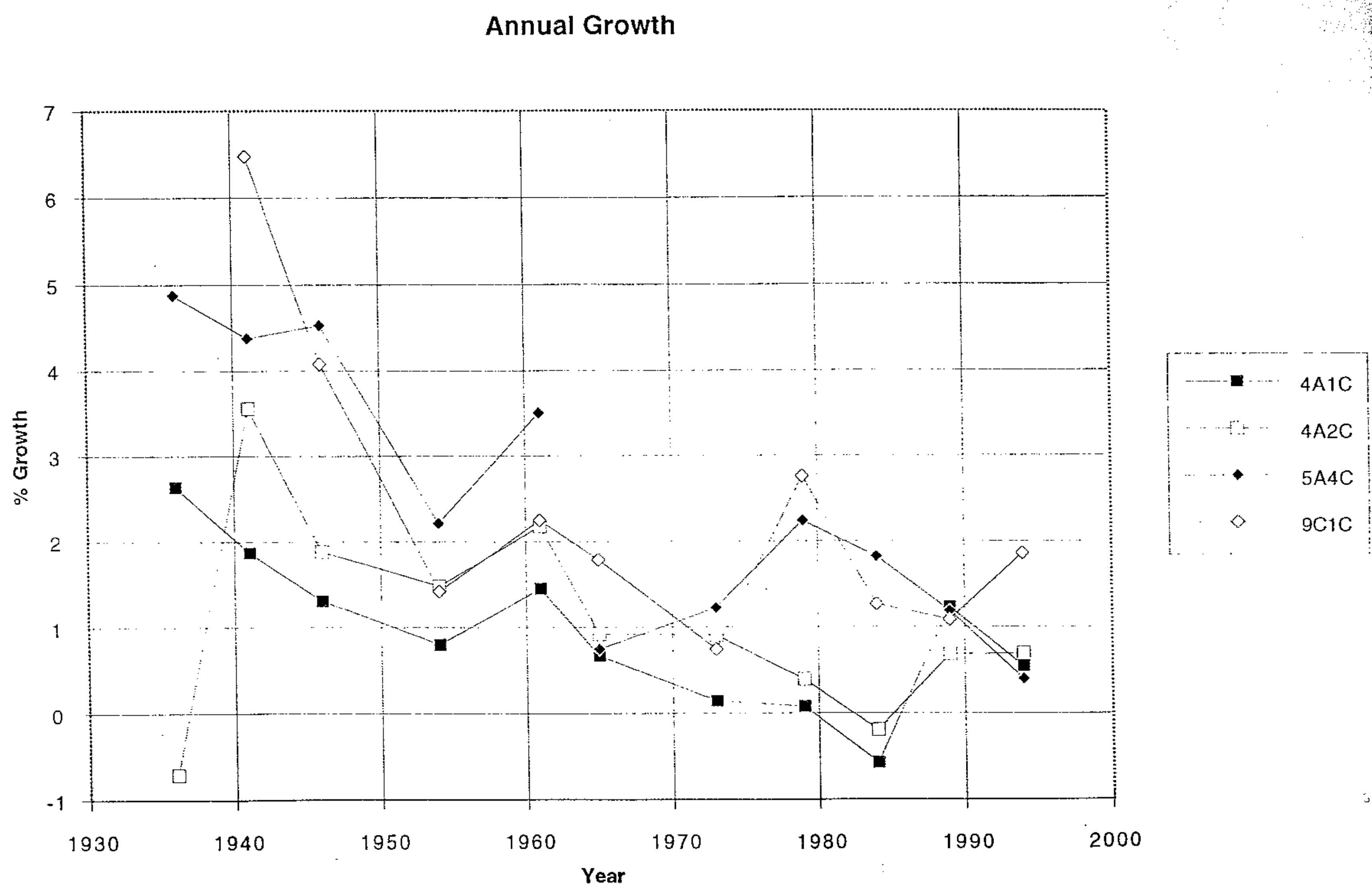
As can be seen above, there is considerable variation among plots. Plot 4a1c started with the greatest amount of carbon (approx. 65 metric tons/ha), which was 170% more than the lowest, 9c1c, and 150% and 70% more than 5a4c and 4a2c respectively. Presently (1993-94) plot 4a1c also contains the most carbon, over 110 metric tons per hectare. However, it has lost its much of its considerable lead over the other plots. Plot 5a4c has roughly 101 metric tons, or 91% of the amount found in 4a1c. Plots 4a2c and 9c1c each contain roughly 73 metric tons, or 66% of 4a1c's carbon content. Overall, from 1931 (or 1936 in the case of 9c1c) to 1993-94, plots 4a1c and 4a2c showed 70% and 93% increase in carbon respectively, whereas 5a4c and 9c1c each more than doubled, with 295% and 211% increases.

Examining the growth rates on a yearly basis is also of interest, to demonstrate different growth patterns early in the plots' history compared to later years. One can also more easily document simultaneous trends in growth, i.e. if there is a climate disturbance such as drought which would affect the plots equally, causing a decline in growth. Table 8 documents the annual percentage growth, showing the change in growth during the different (approximate) 5-year increments.

Table 8 - Annual percentage growth (% carbon increase)

	4a1c	4a2c	5a4c	9c1c
1931-36	2.64	-0.71	4.88	
1936-41	1.87	3.56	4.38	6.48
1941-46	1.31	1.88	4.52	4.08
1946-54	0.81	1.48	2.21	1.42
1954-61	1.45	2.18	3.50	2.25
1961-65	0.68	0.92	0.75	1.79
1965-73	0.14	0.91	1.22	0.75
1973-79	0.08	0.39	2.24	2.76
1979-84	-0.57	-0.2	1.82	1.26
1984-89	1.23	0.69	1.19	1.09
1989-94	0.55*	0.7	0.4	1.86

Figure 3


Annual Growth
7
6
5
4
3
2
1
0
-1
% Growth
1930
1940
1950
1960
1970
1980
1990
2000
Year
4A1C
4A2C
5A4C
9C1C

*Plot 4a1c last measurement in 1993.

The overall trend among all four plots showed a decline in the growth rates, that carbon sequestration rates decrease with time. Figure 3 represents the data from table 8 over time. Plot 4a1c demonstrated the most gradual, steady rate of declining growth, going from 2.64% in the first decade of measurements to 0.55% over the past four years (1989-93), with a small increase in the period 1984-89. Plot 4a2c, after an initial loss in carbon, showed a gradual decline in growth. The two greatest peaks in growth occurred in 1936-41, with 3.56% annual growth, and 1954-61, with 2.18% growth.

Plots' 5a4c and 9c1c growth patterns were somewhat more sporadic. Both showed the strongest growth up to 1946. Plot 5a4c had a peak in growth during 1931-46 (4.59%) and a smaller peak in the 1954-61 period (3.5%). The periods with lowest growth were 1961-65 and 1989-94, each with 0.75% and 0.4%. Plot 9c1c also demonstrated the greatest growth in its early years, with the 1936-41 period having 6.48% growth. As with plot 5a4c, there were peaks in 1954-61 (2.25%) and 1973-79 (2.76%). Plot 9c1c experienced its slowest growth in the interval 1965-73, with 0.75%.

Table 9 - Annual Increases (Metric Tons C/ha/yr)

YEAR	4A1C mT/yr	4A2C mT/yr	5A4C mT/yr	9C1C mT/yr
1931-36	1.70	-0.27	1.00	-
1936-41	1.37	1.30	1.34	1.54
1941-46	1.05	0.81	1.69	1.28
1946-54	0.77	0.70	1.01	0.54
1954-61	1.33	1.15	1.89	0.95
1961-65	0.68	0.56	0.51	0.66

Figure 4a

4a1c Growth in Carbon

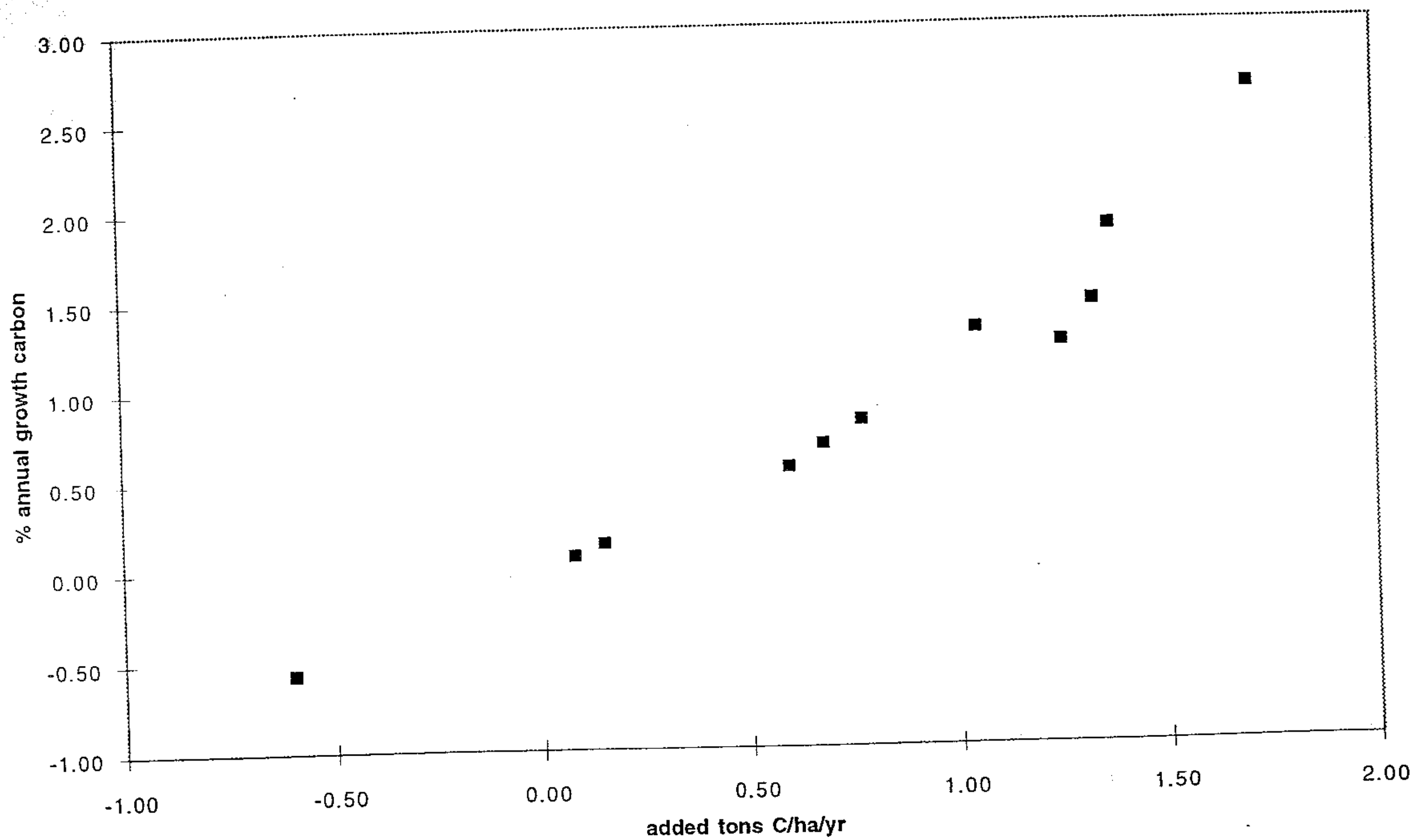


Figure 4b

4a2c Growth in Carbon

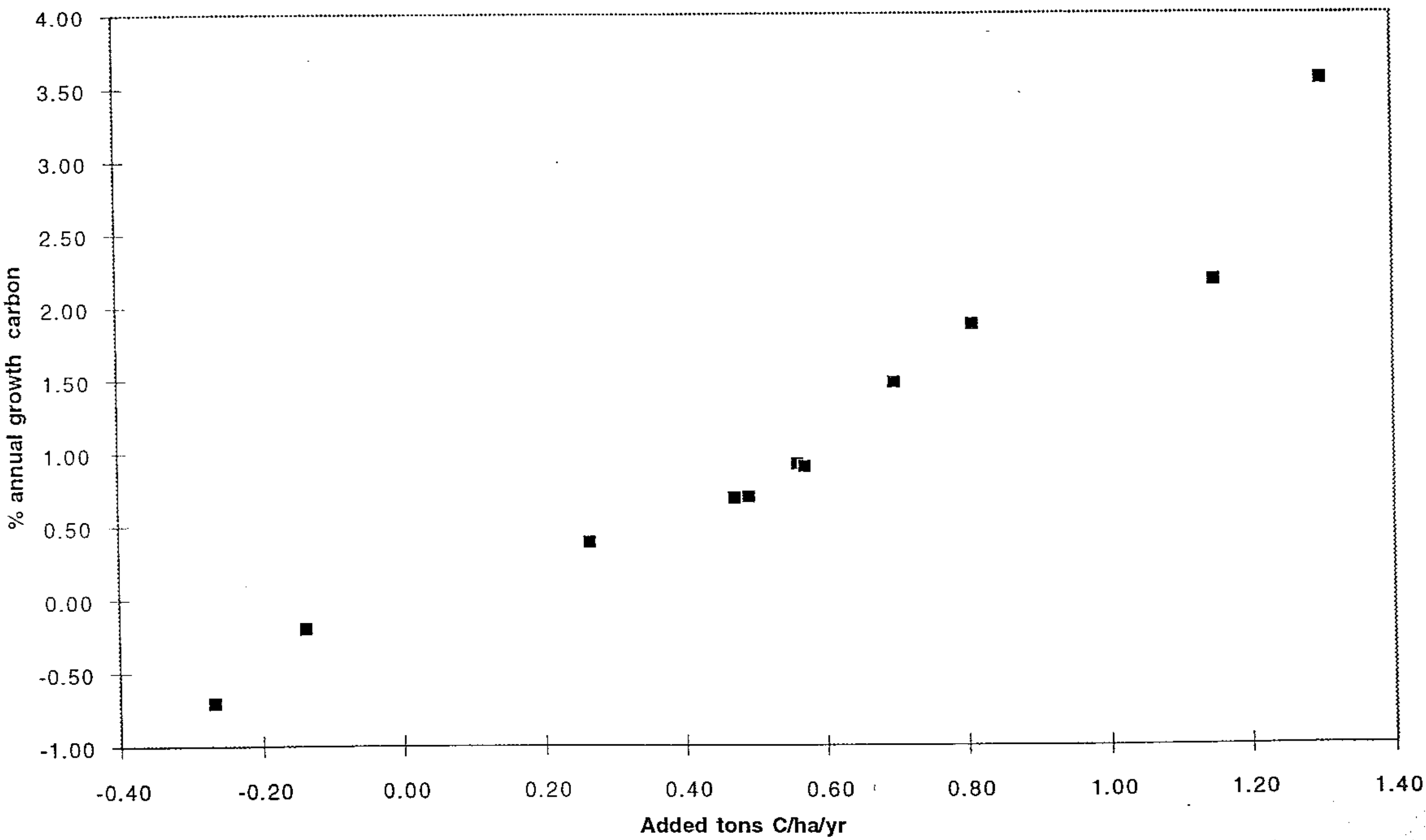


Figure 4c

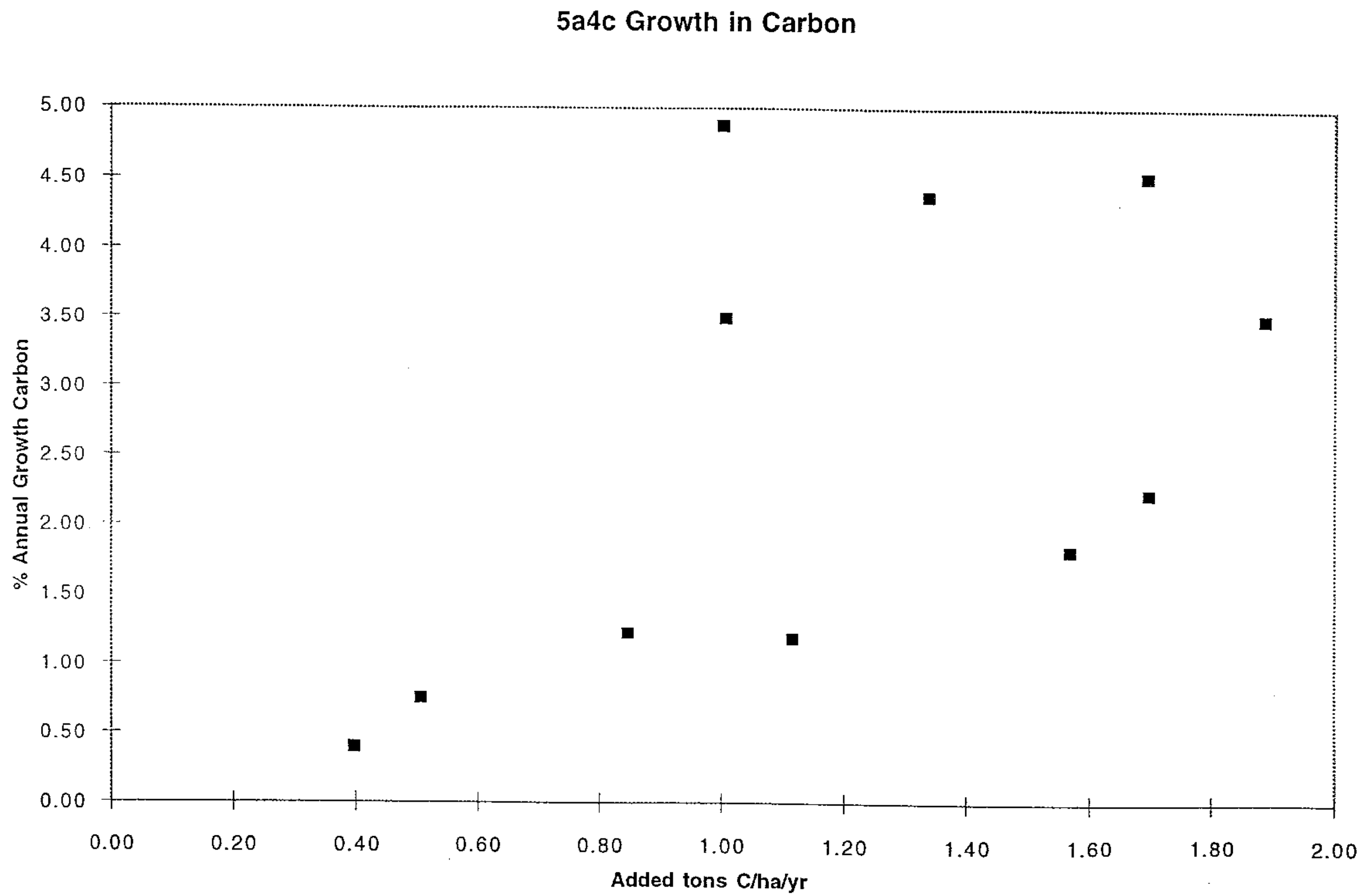
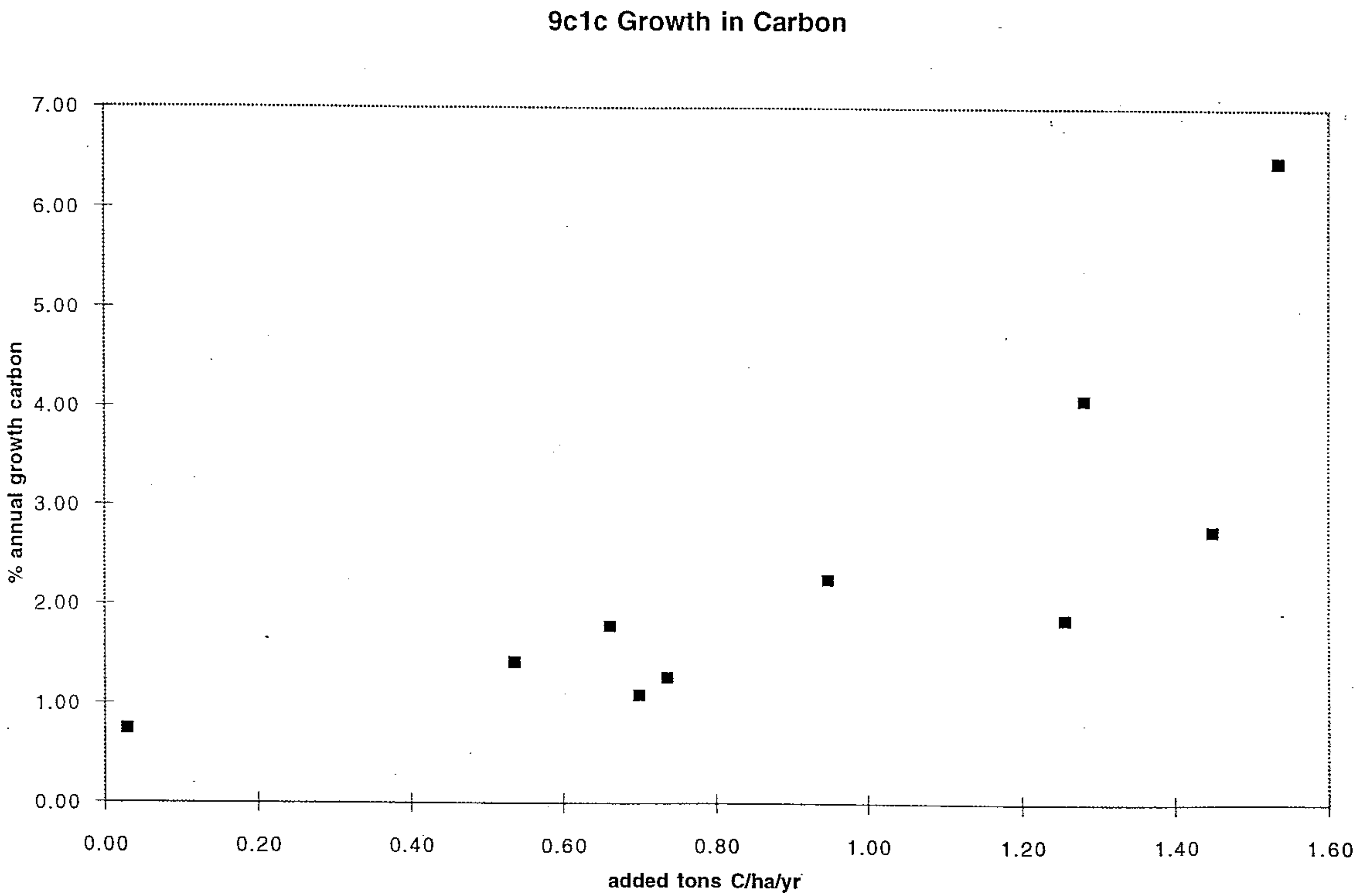

5a4c Growth in Carbon
% Annual Growth Carbon
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
Added tons C/ha/yr

Figure 4d


9c1c Growth in Carbon
% annual growth carbon
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
added tons C/ha/yr

1965-73	0.15	0.57	0.85	0.03
1973-79	0.08	0.27	1.70	1.45
1979-84	-0.60	-0.14	1.57	0.74
1984-89	1.25	0.47	1.12	0.70
1989-94	0.60*	0.49	0.40	1.25
Average	0.76	0.54	1.19	0.91
Average % Growth**	1.18%	1.42%	4.63%	3.84%

*Plot 4a1c last measurement in 1993.
**Average % growth was calculated by dividing original carbon values (for 1931/36) by average increase in tons/ha/yr.

Correlated with the annual growth rates are the increases in carbon in terms of added metric tons per year. These absolute values are more indicative of carbon sequestration, although they mirror the changes in percentage growth in table 8. There is a range from 1.89 tons/ha/yr for plot 5a4c in the years 1954-61, to intervals of lost biomass for plots 4a1c and 4a2c in the years of 1931-36 and 1979-84. Comparisons of average annual additions show plot 5a4c having added the most carbon on an annual basis (1.19 tons/ha/yr), whereas 4a2c increased by less than half of this rate: 0.54 tons/ha/yr. In the past five years (1989-94), the plots 4a1c, 4a2c, and 5a4c have all shown decreases in growth, adding merely 0.4 - 0.6 tons/ha/yr. Only 9c1c grew exceptionally well, expanding by 1.25 tons/ha/yr in 1989-94, considerably above its average of 0.91 tons.

The average annual increases in tons/ha/yr are used to compute average increases in percent of starting biomass. 5a4c, consistent with its high annual increases in absolute values, also had the highest annual percent growth, at 4.63%. 4a1c, although it sequestered more than 4a2c on an annual basis (0.76 tons compared to 0.54 tons/ha/yr), had a lower growth rate: 1.18% to 4a2c's 1.42%, because it started with a higher base biomass. When comparing annual percentage growth and absolute additions in biomass (metric tons/ha/year) over time, the strongest correlation is shown by plots 4a1c and 4a2c. Figures 4a-4d demonstrates that increases in rates of carbon storage in terms of metric tons very clearly translated into increased growth rates. With plots 5a4c and 9c1c the correlation is somewhat less evident, in that higher growth rates would not necessarily indicate more biomass stored in that time increment. However, in general, even with the greater amount of "scatter", percentage growth and absolute growth are related.

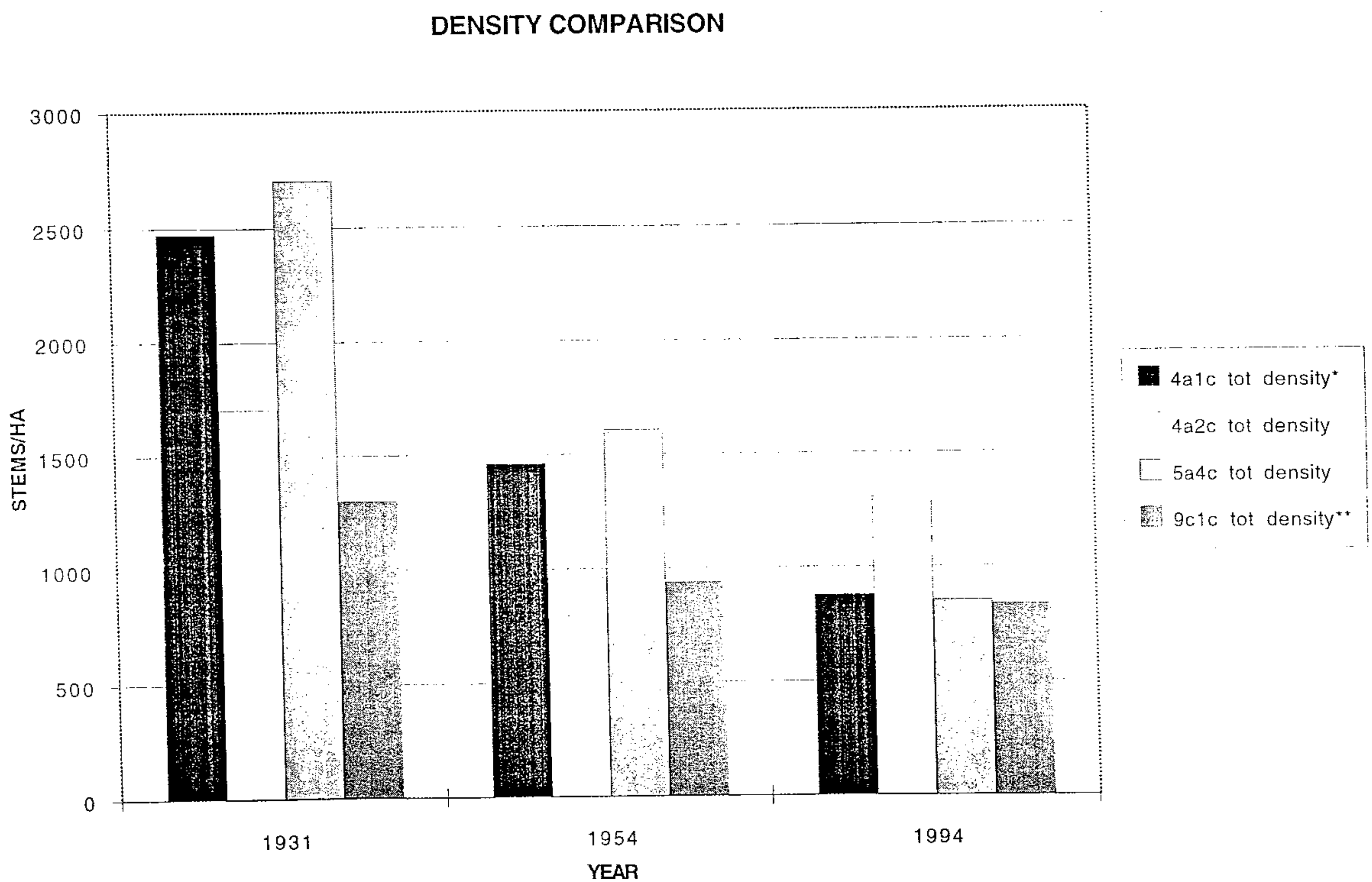
II. Secondary Data

The differences in growth and carbon rates can be partially explained in terms of plot characteristics, namely age and density of trees, total basal area, and species composition. Density represents the numbers of tree stems greater than 2.5 cm on a given area of land, and basal area is the amount of land area covered by stem wood. As can be seen in tables 10 and 11, the plots show considerable variation in their density and basal area measurements. All plots showed decreases in density over time, except 4a2c, which is explained that as a forest ages smaller trees are weeded out due to fewer resources. Plot 4a2c experienced considerable ingrowth of young red oak and red maple, which increased its density. Plots 4a1c and 5a4c both started out with nearly twice as many trees per hectare as plot 9c1c, with 4a2c falling roughly in the middle. By 1994, plots 4a1c, 5a4c, and 9c1c had roughly the same densities, and 4a2c had considerably more trees per hectare. In comparing basal area (see table 11), although plots 4a1c and 5a4c had similar densities initially, 4a1c had twice the basal area, indicating that its trees are of much greater size. Plots 5a4c and 9c1c have more than doubled their basal area over the past 65 years, whereas 4a2c has added percentage wise considerably less. 4a2c's high density to basal area values indicate that many smaller trees grow more densely together here, as this plot has experienced high ingrowth of young red maple and red oak. In comparison of the basal areas, 4a1c and 5a4c had similar figures (30.6 m^2/ha and 30.8 m^2/ha respectively), whereas 4a2c, with far greater density than either of these two plots, had far less basal area (24.8 m^2/ha), more comparable to the basal area of 9c1c (23.4 m^2/ha).

Table 10 - Density and Species Composition (stems/ha)

	1931	**1954**	**1994**
4a1c tot density	2475	1463	878*
4a1c % bb	10%	6%	10%
4a1c % co	11%	12%	9%
4a1c % rm	16%	14%	8%
4a1c % ro	7%	8%	9%
4a1c % yb	12%	14%	22%
4a1c % sm	30%	34%	35%
4a1c % other	13%	12%	8%
4a2c tot density	1705	959	1305
4a2c % bb	3%	3%	4%
4a2c % co	64%	67%	29%
4a2c % rm	20%	19%	35%
4a2c % ro	11%	8%	24%
4a2c % other	2%	3%	8%
5a4c tot density	2704	1608	853
5a4c % bb	12%	17%	17%
5a4c % co	13%	8%	6%
5a4c % rm	36%	45%	34%

Figure 5


DENSITY COMPARISON
STEMS/HA
3000
2500
2000
1500
1000
500
0
1931
1954
1994
YEAR
4a1c tot density*
4a2c tot density
5a4c tot density
9c1c tot density**

5a4c % ro	16%	18%	14%
5a4c % other	23%	12%	29%
9c1c tot density	1302**	936	834
9c1c % bb	0%	0%	13%
9c1c % co	29%	32%	20%
9c1c % rm	15%	21%	43%
9c1c % ro	46%	39%	18%
9c1c % other	10%	9%	6%

*4a1 density for 1993; ** 9c1c density for 1936
Key: bb - black birch; co - chestnut oak; rm - red maple; ro - red oak; yb - yellow birch; sm - sugar maple; other include black, scarlet, & white oaks, pignut hickory, American beech, gray birch, hemlock, blackgum, striped maple, & shadbush.

Table 10 also shows the differences in species composition among plots. Plots 4a1c and 5a4c are the most diverse in terms of species variety. Plot 4a1c has the greatest representation of sugar maple, followed by yellow birch and black birch. Over time the composition of sugar maple and black birch has remained consistent, whereas yellow birch has doubled. Plot 5a4c consists primarily of red maple and the other classification, which in this case is black gum, hemlock, and chestnut. There are also considerable black birch. The relative numbers have remained fairly constant throughout the 63 years. Both plots 4a2c and 9c1c are far more representative of the typical deciduous forest in the lower Hudson Valley. There are fairly equal representations of the red and chestnut oaks, and red maples. From 1931 to 1994, plot 4a2c has lost half its chestnut oaks (in general there is a decline at BRF), while roughly doubling the numbers of red oak and red maple. Conversely, plot 9c1c shows a tremendous decline in red oaks while keeping the chestnut oaks stable, but like 4a2c, red maple have more than doubled. The general increase in red maple is due to its nature as a later successional species, usually following the red oaks and birches in these ecosystems.

As stated earlier (see table 5), certain species tend to sequester more carbon relative to their size. Both yellow and black birches, and sugar maples, are "denser" trees, whereas white oaks and red maples have the lowest biomass values. Red and chestnut oaks, and the "other" category, have intermediate masses.

Table 11 - Basal Area

	1931	1954	1994
4a1c tot ba	23.52	29.77	30.57*
4a2c tot ba	14.68	18.78	24.84
5a4c tot ba	12.2	20.86	30.78
9c1c tot ba	10.03**	15.56	23.37

* 4a1c basal area for 1993; ** 9c1c basal area for 1936

The final valuable data in helping to interpret the carbon figures are the size class distribution. Due to the nature of the regression equations used in determining biomass from the diameter, large trees store disproportionally more carbon than smaller trees, even if their respective basal areas (comparing one large tree and two smaller ones) were to be equal. Thus knowing the proportion of different size classes will help explain why two plots with similar basal areas might have different carbon contents.

Table 12 - Size Class Distribution (Stems/ha)

PLOT	TREE DBH	1931	1954	1994
4A1C	0-10 CM	1406	495	293
	10-20 CM	990	574	248
	20-30 CM	79	360	158

Figure 6a

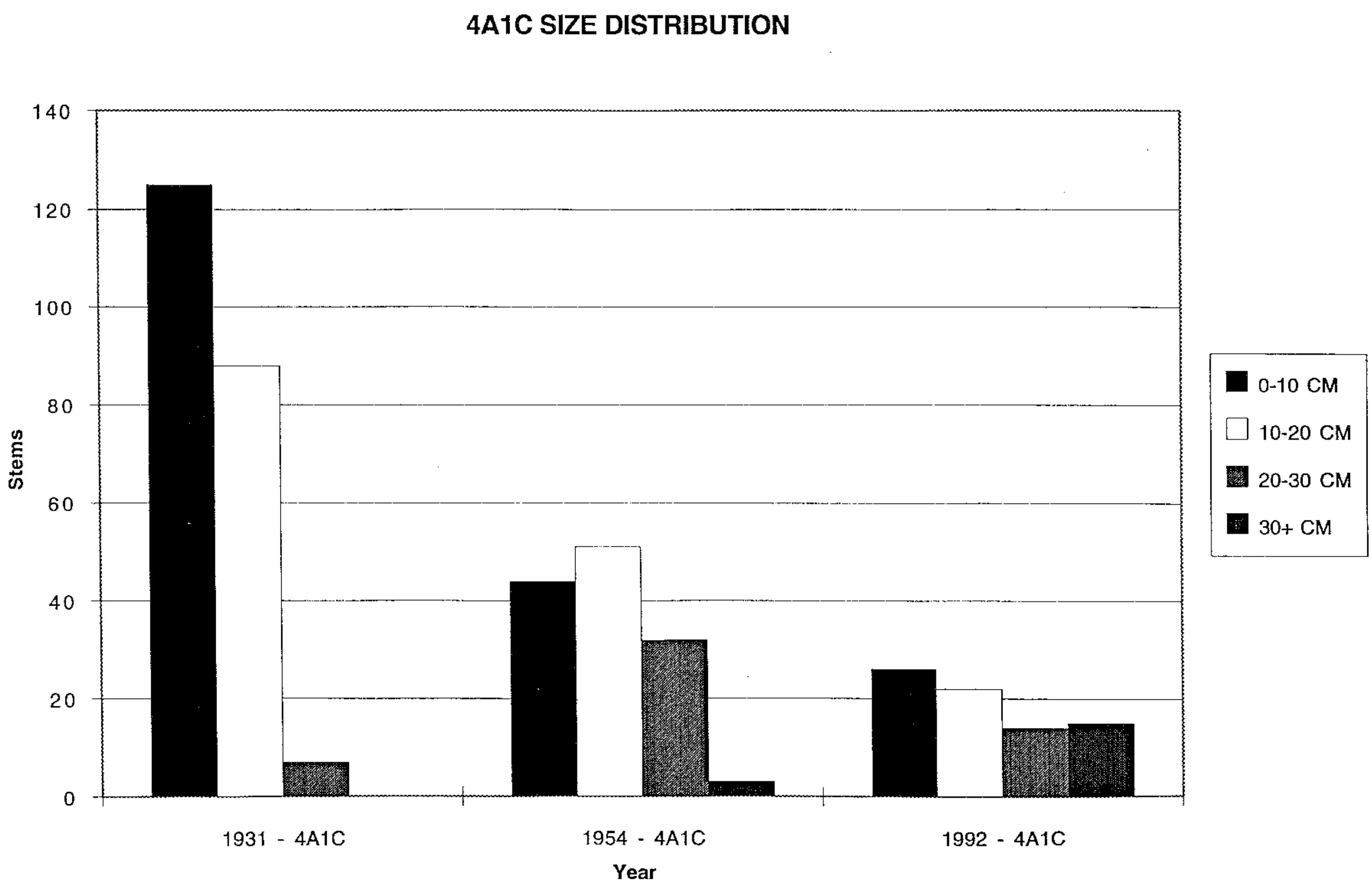

4A1C SIZE DISTRIBUTION
140
120
100
80
60
40
20
0
Stems
0-10 CM
10-20 CM
20-30 CM
30+ CM
1931 - 4A1C
1954 - 4A1C
1992 - 4A1C
Year

Figure 6b

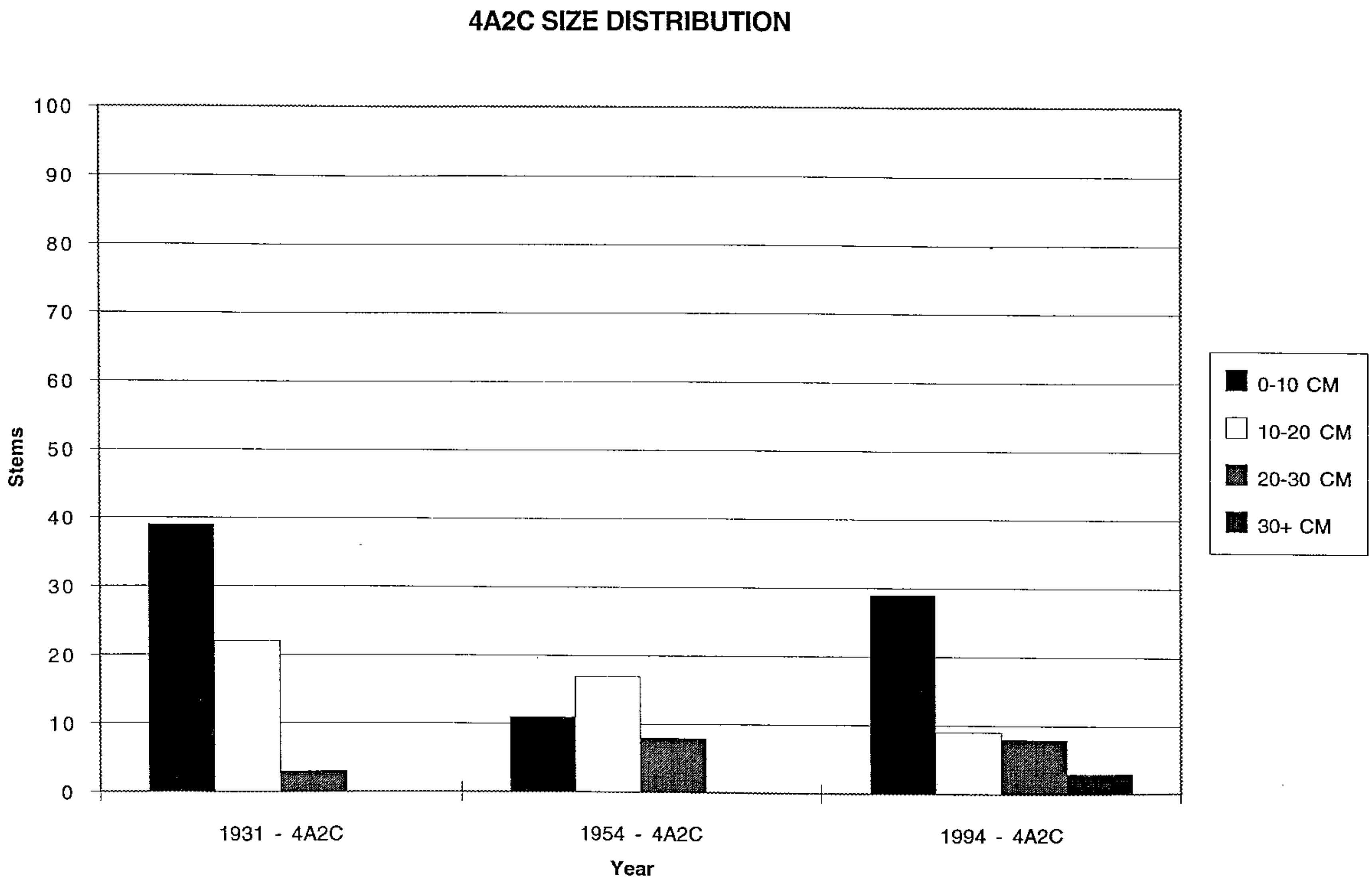

4A2C SIZE DISTRIBUTION
Stems
100
90
80
70
60
50
40
30
20
10
0
1931 - 4A2C
1954 - 4A2C
1994 - 4A2C
Year
0-10 CM
10-20 CM
20-30 CM
30+ CM

Figure 6c

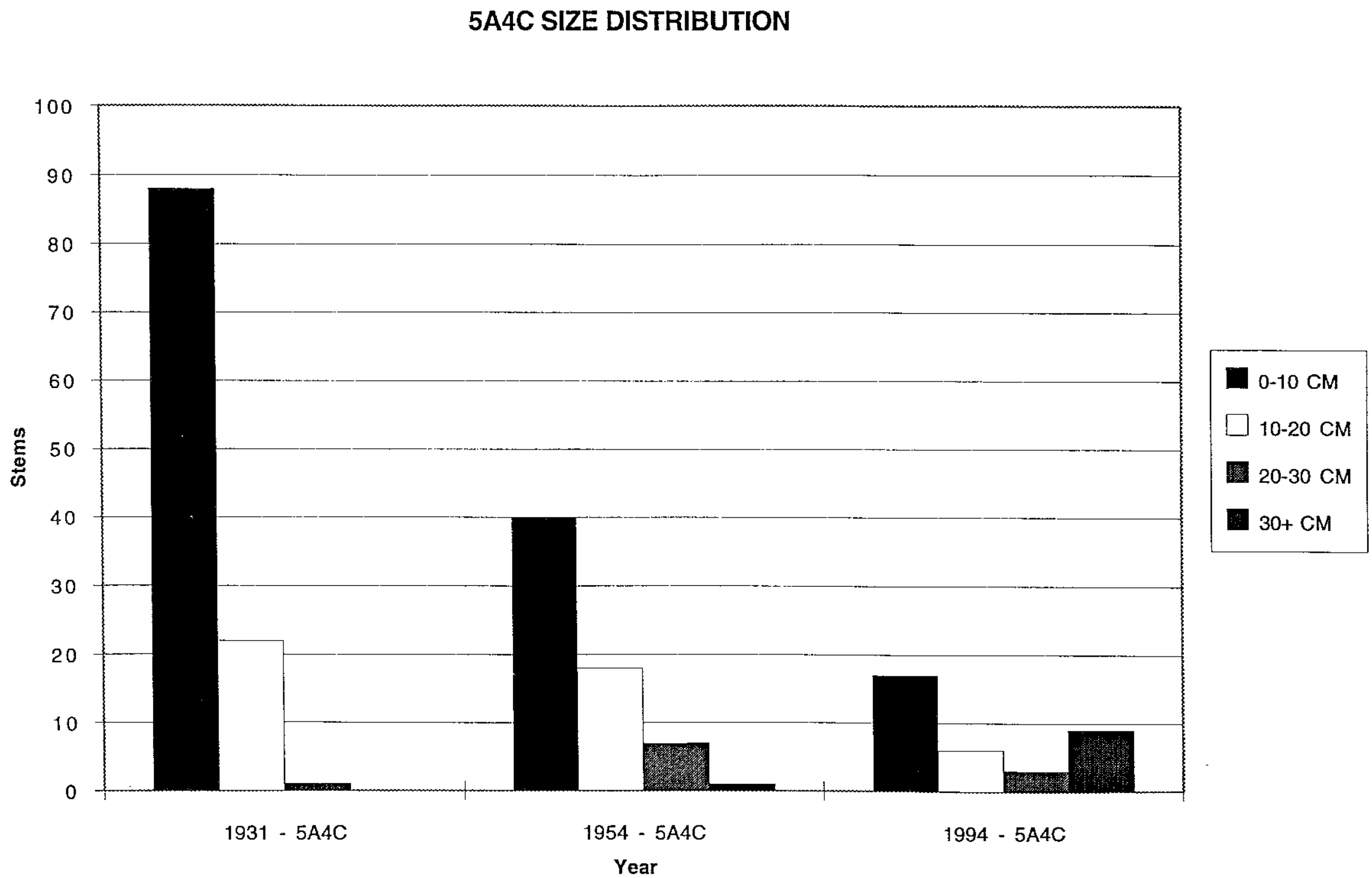
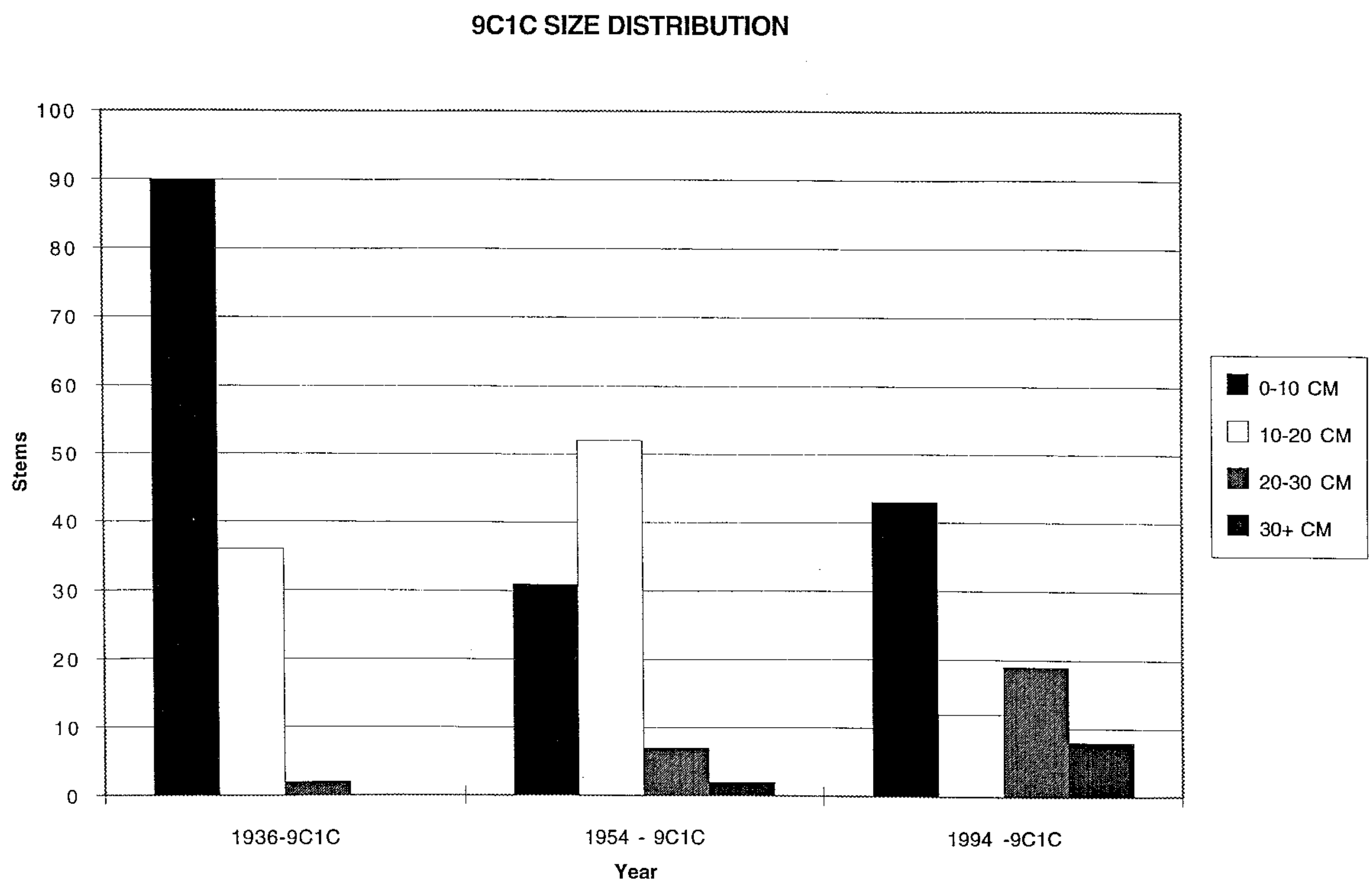

5A4C SIZE DISTRIBUTION
100
90
80
70
60
50
40
30
20
10
0
Stems
1931 - 5A4C
1954 - 5A4C
1994 - 5A4C
Year
0-10 CM
10-20 CM
20-30 CM
30+ CM

Figure 6d


9C1C SIZE DISTRIBUTION
Stems
100
90
80
70
60
50
40
30
20
10
0
1936-9C1C
1954 - 9C1C
1994 -9C1C
Year
0-10 CM
10-20 CM
20-30 CM
30+ CM

	30+ CM	0	34	169
	TOTAL	2475	1463	866
4A2C	0-10 CM	1039	293	773
	10-20 CM	586	453	240
	20-30 CM	80	213	213
	30+ CM	0	0	80
	TOTAL	1705	959	1305
5A4C	0-10 CM	2144	974	414
	10-20 CM	536	438	146
	20-30 CM	24	171	73
	30+ CM	0	24	219
	TOTAL	2704	1608	853
9C1C	0-10 CM	915	315	437
	10-20 CM	366	529	122
	20-30 CM	20	71	193
	30+ CM	0	20	81
	TOTAL	1302	936	834

All plots obviously started with smaller diameter trees in 1931 than later in their histories. All plots had over 56-80% of trees in the first size class (0-10 cm), although the second size class is well represented on plot 4a1c (40%). In absolute number of stems, 4a1c and 5a4c had considerably higher densities than plots 4a2c and 9c1c. Plots 4a1c (2475 stems/ha) and 5a4c (2703 stems/ha) had much more growth than plots 4a2c (1704 stems/ha) and 9c1c (1302 stems/ha). In 1954, one sees that larger size classes were better represented on all plots. The size class 10-20 cm now dominated the plots 4a1c (39%), 4a2c (47%), and 9c1c (57%), with plots 4a1c and 4a2c also having a considerable proportion in the third size class. On plot 5a4c the smallest size class still had the greatest number of trees (61%). In 1994, there was substantial representation of the largest size class (30+ cm) on plots 4a1c (20%), 5a4c (25%), and 9c1c (10%). Plot 4a2c showed the poorest growth, with 60% of the trees in the first size class. However, 4a2c had the highest density (1305), whereas the other plots all had lower density ranges (834-878), so thus the small size in trees was partially compensated for by greater number of stems. In general, among all the plots the smaller trees decreased as they either died due to competition or grew into larger size classes. Only on plots 4a2c and 9c1c were there more trees in the smallest size class in 1994 than 1954. This can partially be explained by natural forest succession dynamics, as there are always periods of growth were many young trees take root, only to eventually succumb to the larger trees' success and their monopoly on resources and light.

III. West Point Meteorological Data

The two key variables gathered by the West Point Meteorological Station (WPMS) having the greatest relevance to forest growth are temperature and precipitation. Data is presented graphically, showing average temperature from 1821-1992 and average precipitation from 1850-1992. The average temperatures include annual averages and decade averages. The overall annual average is 49.56 degrees Fahrenheit; as can be seen from graph 6 the range is from 46.2 to 52.4 approximately. The decade average graph 7 shows temperature trends over longer periods of time. The decades spanning 1930-1959 were warmer than average, after which there followed a three decade interval of slightly below average temperatures. The years 1990-92 have once again been considerably warmer than average.

Table 13 - Decade Average Temperature

Figure 7

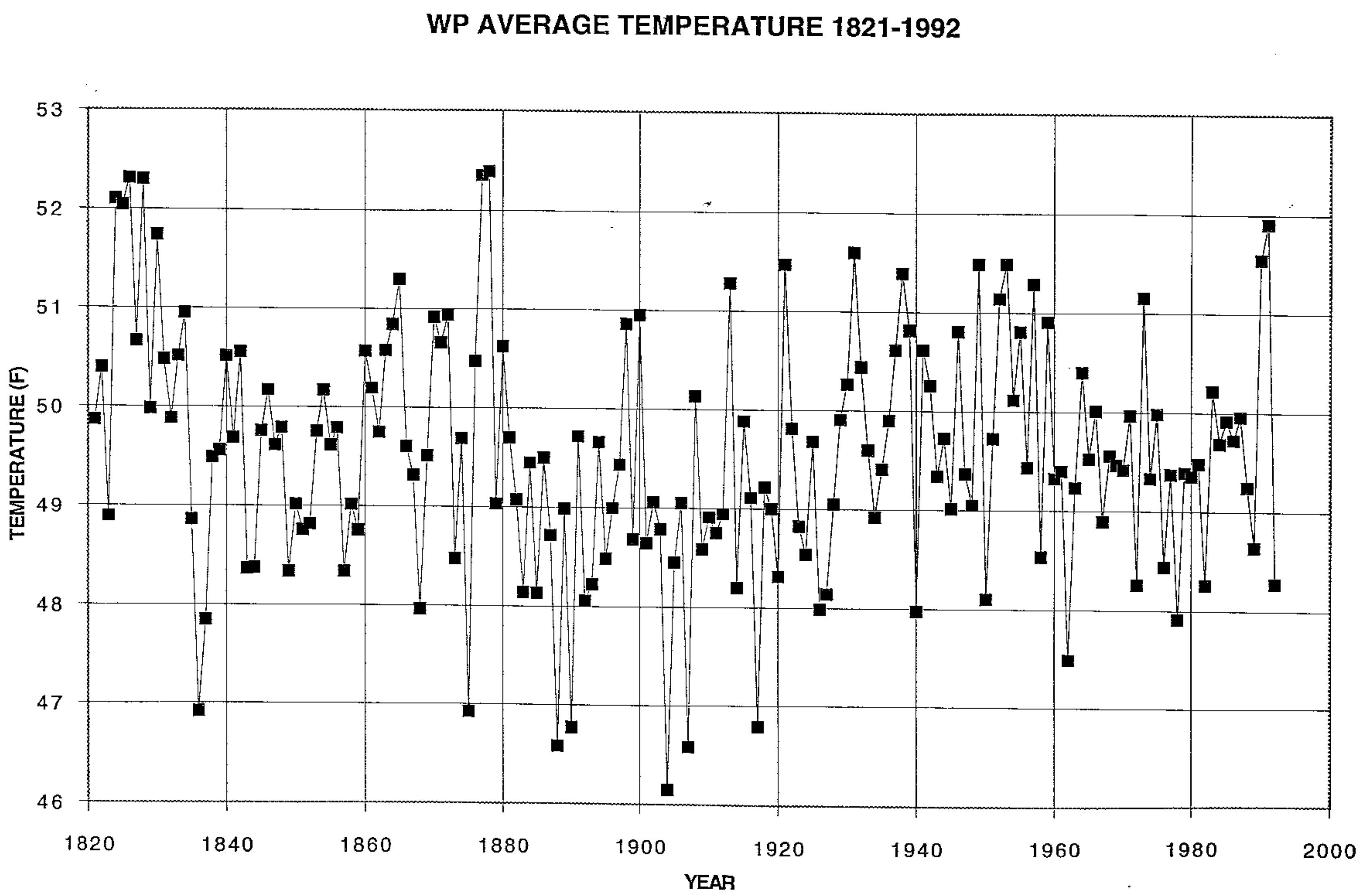
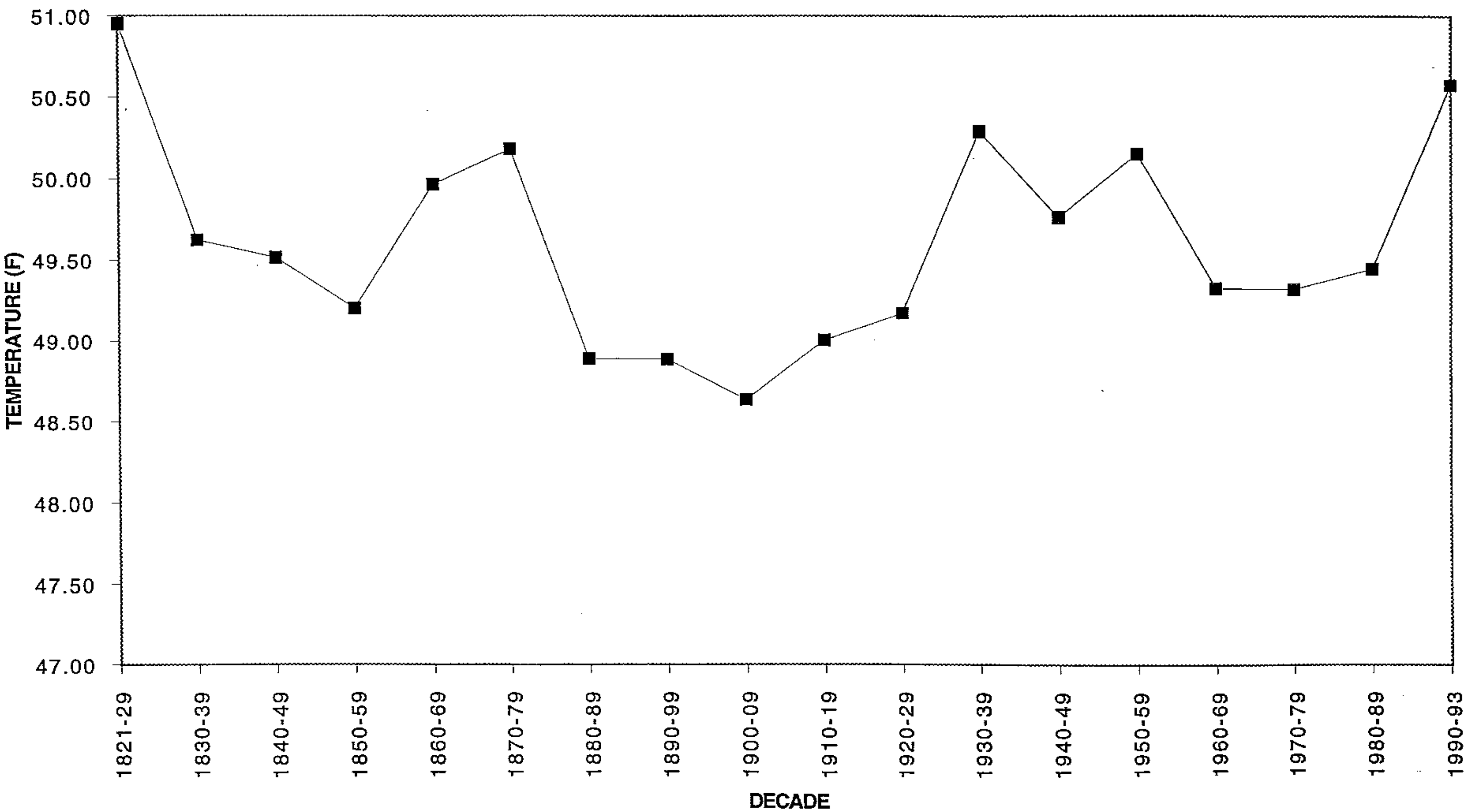

WP AVERAGE TEMPERATURE 1821-1992
TEMPERATURE (F)
53
52
51
50
49
48
47
46
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
YEAR

Figure 8

DECADE AVERAGE



Year	° F	Year	° F
1821-29	50.95	1910-19	49.01
1830-39	49.63	1920-29	49.18
1840-49	49.52	1930-39	50.30
1850-59	49.21	1940-49	49.76
1860-69	49.97	1950-59	50.16
1870-79	50.19	1960-69	49.33
1880-89	48.89	1970-79	49.32
1890-99	48.89	1980-89	49.45
1900-09	48.64	1990-93	50.58
AVERAGE	49.56		

Precipitation is of even greater importance to tree growth and carbon sequestration, as water is often an important limiting factor. Although total yearly precipitation rates are shown, of real concern is the precipitation that falls in the summer (June-August) months, when the trees are at the height of their growing season and the demand for water and nutrients reaches a maximum. The graphs show total yearly precipitation and summer precipitation. There was considerable variation in the period when forest growth was recorded, from a low total of less than 80 cm/yr in 1930, to over 175 cm/yr in 1983. The two decades prior to the records, 1910-29, also had very low rainfall, and this would affect the growth of young trees considerably. The average (1850-1992) annual precipitation was 117.5 cm/yr. There is no relationship between the deviations for summer precipitation and the annual. Some decades with high annual precipitation, such as 1950-59 and 1970-79 had below normal summer precipitation.

Table 14 documents the decade averages for both total annual and total summer precipitation. Trends over entire decades can be indicators of forest response. While one year of below average rainfall may not affect tree growth considerably, an entire decade of lower than normal can be much more easily correlated with growth rates and responses. The deviation from the average (117.5) for the entire decade is also shown.

Table 14 - Precipitation: Decade Average & Deviation (cm)

	JAN-DEC	YEARLY DEVIATION	SUMMER	SUMMER DEVIATION
1850-59	122.62	5.08	33.94	2.67
1860-69	111.82	-5.72	34.21	2.94
1870-79	106.70	-10.84	31.20	-0.07
1880-89	120.90	3.36	33.63	2.36
1890-99	120.33	2.79	32.66	1.39
1900-09	124.89	7.35	32.27	1.00
1910-19	114.55	-2.99	28.31	-2.96
1920-29	106.27	-11.27	26.30	-4.97
1930-39	109.48	-8.06	30.22	-1.05
1940-49	114.68	-2.86	30.22	-1.05
1950-59	131.30	13.76	30.10	-1.17
1960-69	109.51	-8.03	29.90	-1.37
1970-79	132.47	14.93	29.66	-1.61
1980-89	120.10	2.56	33.50	2.23
1990-92	117.38	-0.16	36.73	5.46
ANNUAL AVG	117.54		31.27	

There was below average annual and summer rainfall in the period 1910-49, which would sufficiently affect tree growth when the plots began to be measured. The years spanning 1920-39 had particularly low rainfall. There then followed alternating decades of high and low precipitation. The decades 1950-59 and 1970-79 had annual rainfall above average (13.76 cm and 14.93 cm respectively), although the summer months had less rainfall than would be expected (thus the rain fell in greater amounts during the time in

Figure 9

WP ANNUAL PRECIPITATION 1850-1992

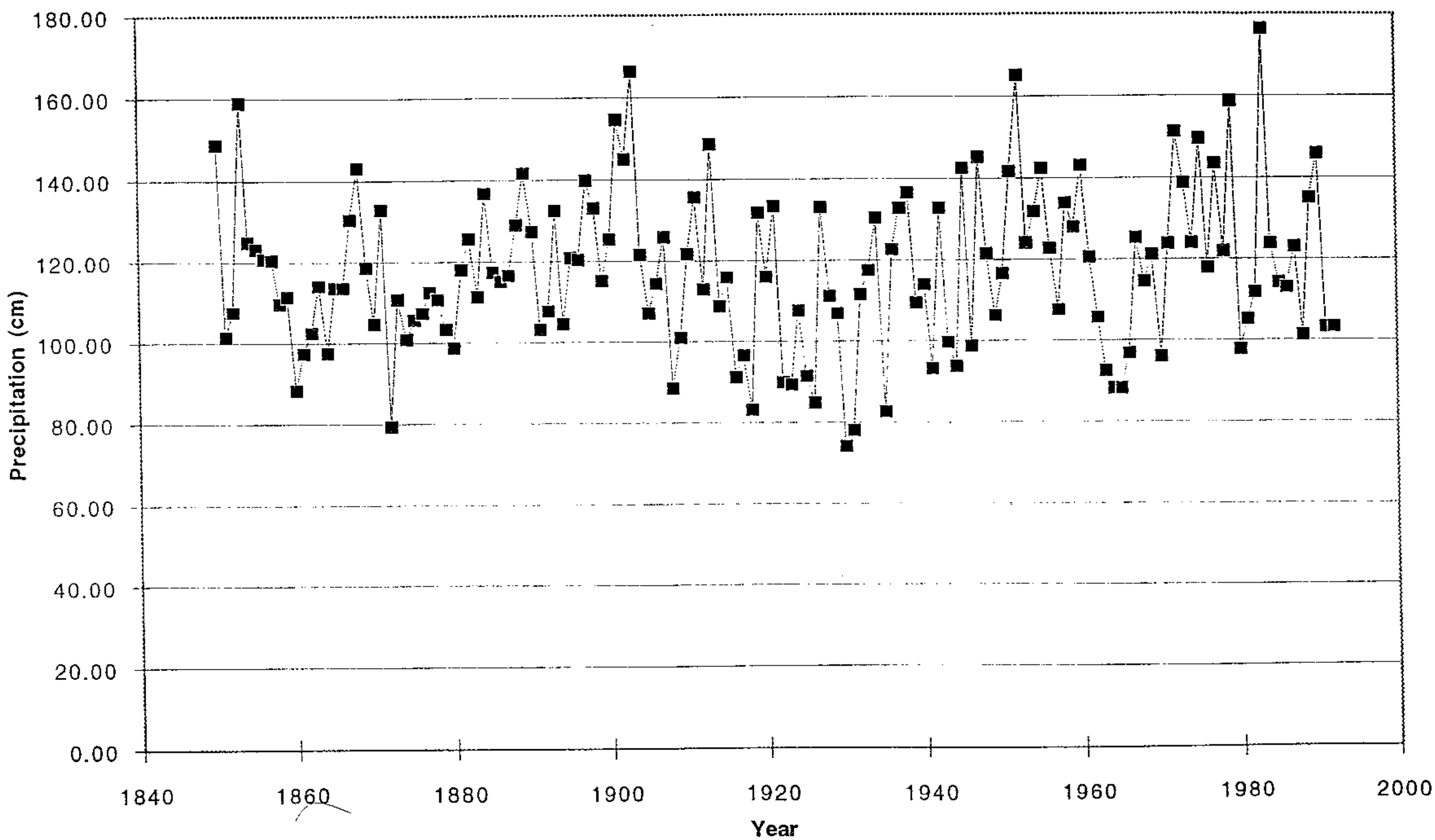
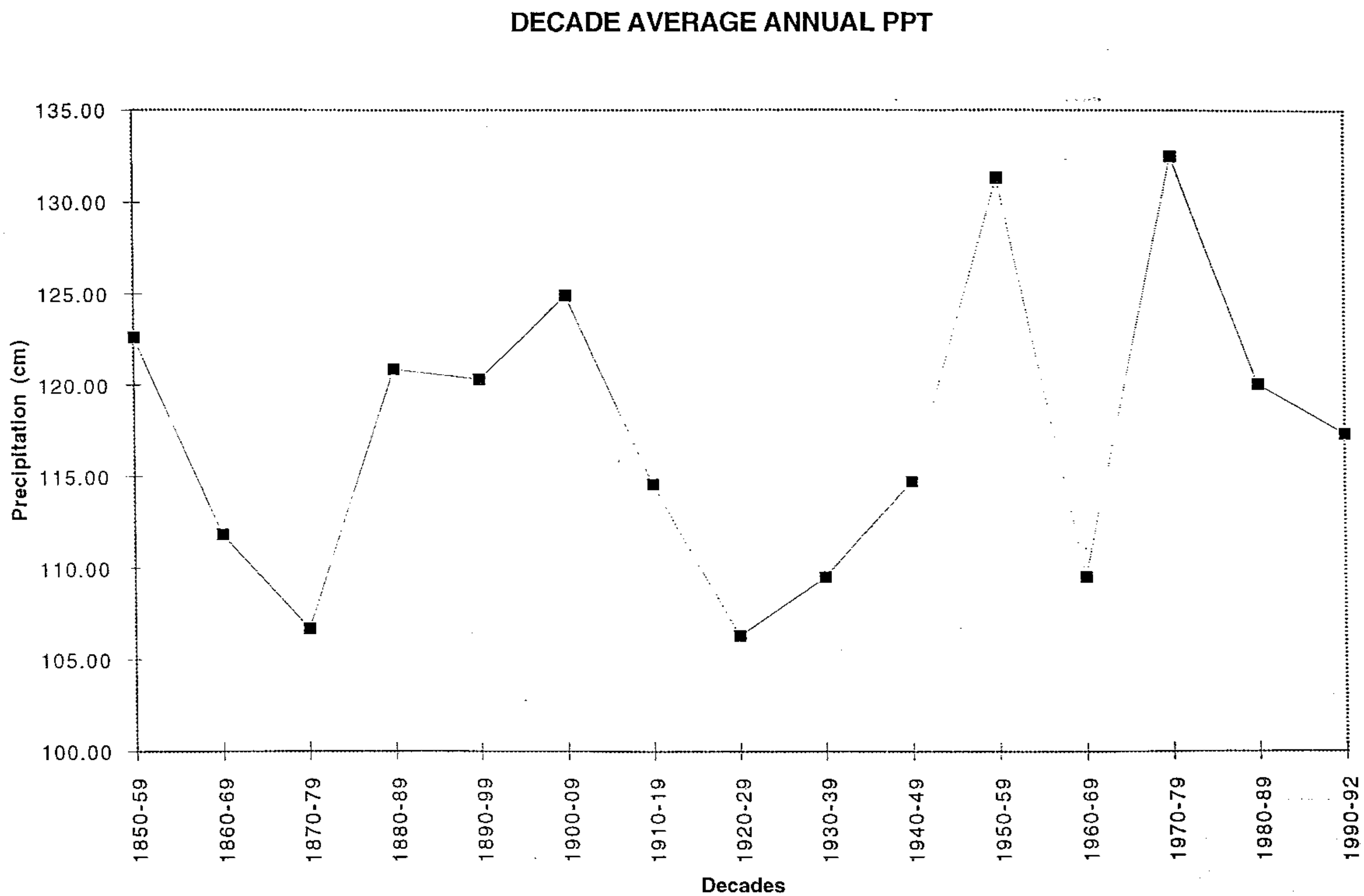


Figure 10



DECADE AVERAGE ANNUAL PPT
135.00
130.00
125.00
120.00
115.00
110.00
105.00
100.00
Precipitation (cm)
1850-59
1860-69
1870-79
1880-89
1890-99
1900-09
1910-19
1920-29
1930-39
1940-49
1950-59
1960-69
1970-79
1980-89
1990-92
Decades

Figure 11

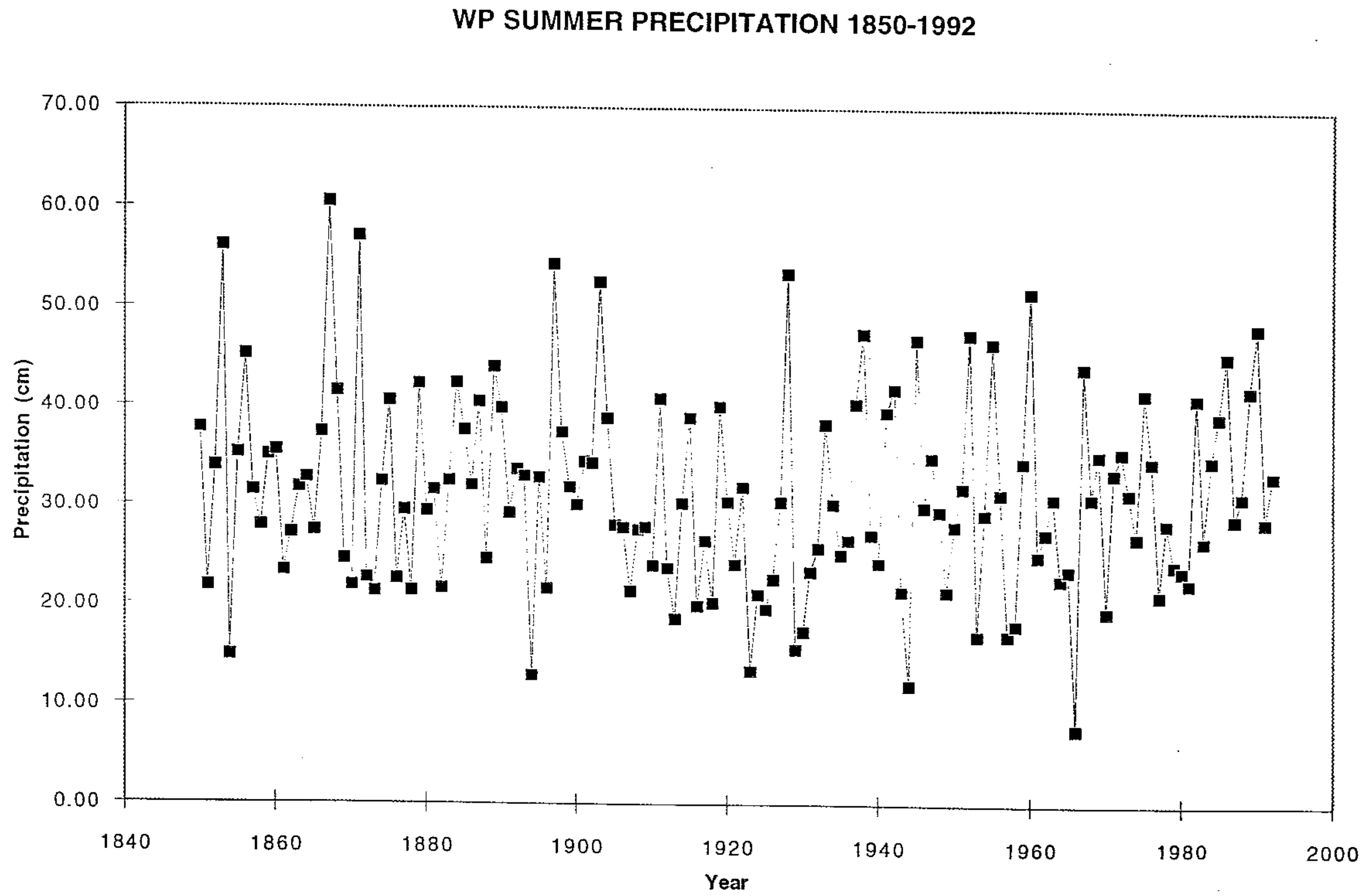
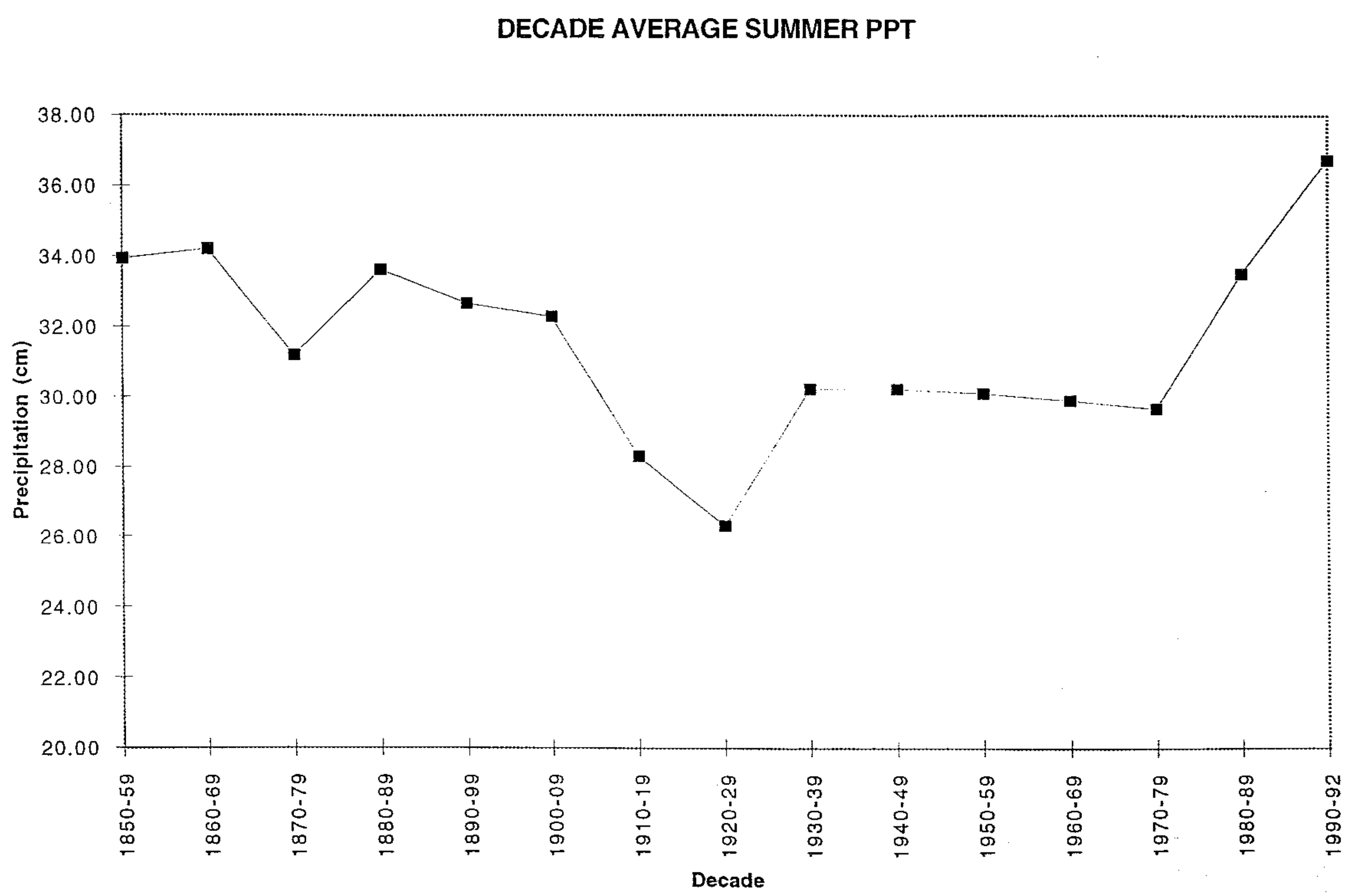

WP SUMMER PRECIPITATION 1850-1992
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Precipitation (cm)
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year

Figure 12


DECADE AVERAGE SUMMER PPT
38.00
36.00
34.00
32.00
30.00
28.00
26.00
24.00
22.00
20.00
Precipitation (cm)
1850-59
1860-69
1870-79
1880-89
1890-99
1900-09
1910-19
1920-29
1930-39
1940-49
1950-59
1960-69
1970-79
1980-89
1990-92
Decade

the year when growth is less affected). There was also another significant dry period in 1960-69, with 8.03 cm annual precipitation below average. Overall, the trend for summer precipitation shows a decrease, with the exception of 1980-92. Whether this is an indication of future decreases in precipitation for the Northeast U.S. remains to be seen, or perhaps the trend will continue to moisten, as has been experienced the past decade. The extremely high precipitation rates for the 1990's must be regarded cautiously, as a two year period can significantly alter the average compared to an entire decade.

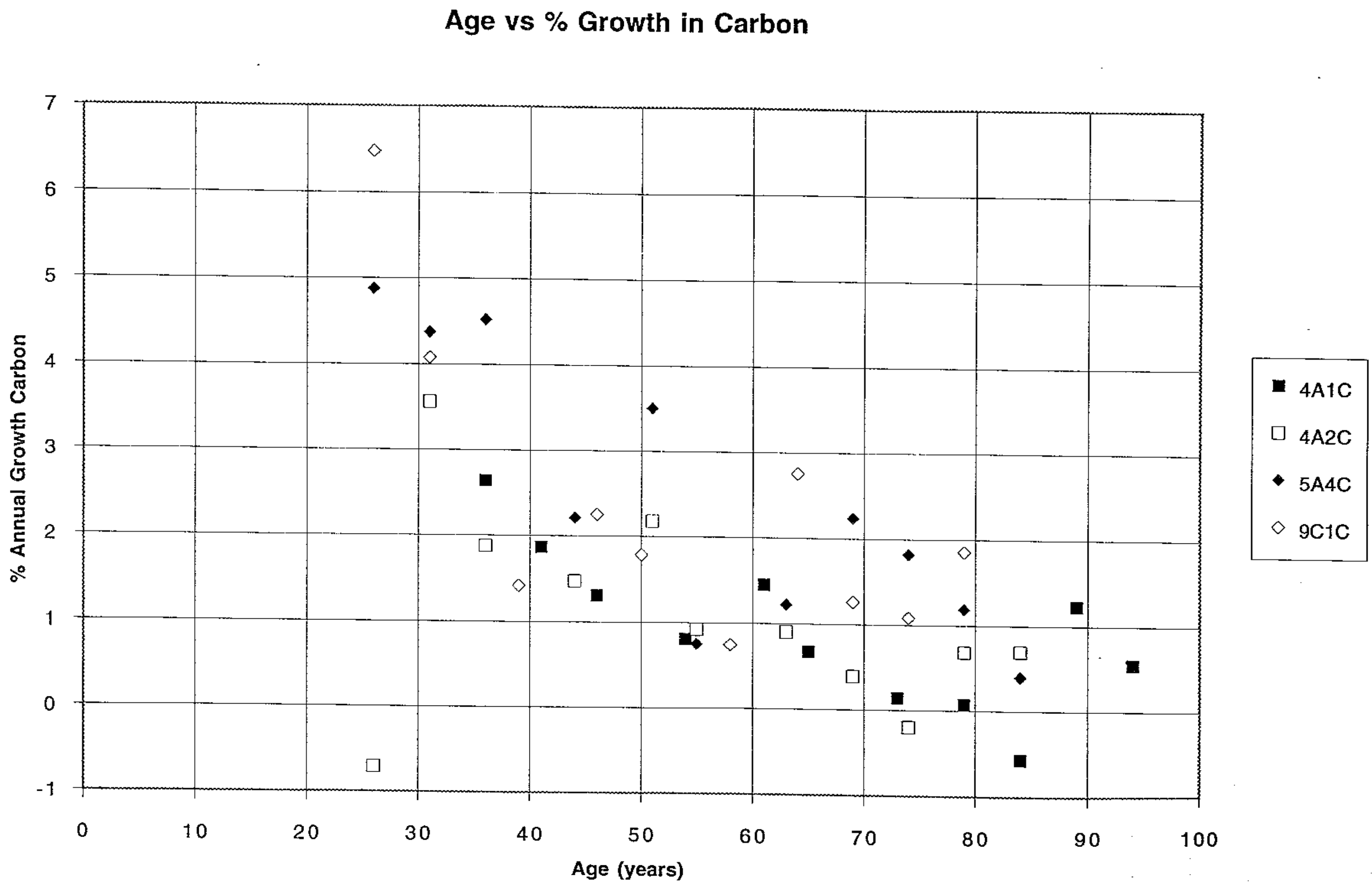
Discussion

I. Differences in Carbon Sequestration Among Plots

The stand age of the respective plots, species composition, and microhabitat differences, as well as external environmental factors, determine the differences in total above ground carbon. From 1931 to present the plots have demonstrated a wide range of carbon sequestration rates and changes in their growth. A history of past use of the BRF area can also shed light on why plots have different carbon values. During the 19th century, the area was frequently clearcut in 30-40 year rotations, with little thought to forest regeneration. Agriculture, not extensively practiced on the rather marginal soils, was limited to dairying and fruit production. The lumber from the clearing went to the charcoal industry. There were repeated fires, which seriously damaged the soils (except in moister cove areas, like 4a1c) by depleting the humus layer and leaf-litter deposits. The frequent fires and clear cutting also encouraged the growth of less valuable species like red maple and chestnut oak (Tyron, 1930). An overview of growth patterns and plot response follows.

Plot 4a1c, Arthur's Brook, was the best established in terms of basal area and total above ground carbon (henceforth referred to as merely carbon) at the time of plot laying. It is the oldest plot in respect to stand age, with the last clearcutting occurring approximately in 1900 (Tyron, 1930). Its high carbon content, both in the early history of the plot and presently, is due partially to the high density of trees, and their distribution among the larger size classes. 4a1c had the second highest density in 1931, while having the most representatives in the second (10-20 cm) size class and tying (with 4a2c) for the 20-30 cm class. In 1994, it still contained the most carbon (110 metric tons/ha), although 4a1c had lower basal area than 5a4c (30.6 m^2 and 30.8 m^2 respectively). 4a1c contains many species which have denser wood (see table 5) and thus store more carbon proportional to their basal area. These species include sugar maple, and black and yellow birch. The relative numbers of black birch and sugar maple have remained constant over the years (10% and 30-35%), whereas yellow birch has doubled, thus increasing the carbon content of 4a1c more than if other species grew there. Importantly, 4a1c has had the most favorable growing conditions, with middle elevation (355 m) and abundant water, as Arthur's Brook runs through it. As stated earlier, 4a1c's soils may have been more protected from the effects of past abuses. These factors, along with the large, healthy trees, which have made 4a1c's

Figure 13


Age vs % Growth in Carbon
7
6
5
4
3
2
1
0
-1
% Annual Growth Carbon
0
10
20
30
40
50
60
70
80
90
100
Age (years)
4A1C
4A2C
5A4C
9C1C

carbon values the highest. However, due to its maturity, 4a1c has not shown the tremendous growth of other plots. It has averaged 1.18% annual growth, and has experienced a slow, steady decrease. Maturing forests naturally show slowing growth, and eventually at approximately 175 years of age NE deciduous forests reach a carbon productivity (above ground) steady state (EPA, 1993). If plot 4a1c has been regrowing for 95 years (Tyron, 1930), it will reach a stasis in respect to carbon storage within the next 75 years. However, with its slower growth rates, it could conceivably be overtaken by other plots, especially 5a4c, in total above ground carbon.

Plot 4a2c, although it started with the second highest carbon value in 1931, currently contains the least (73.3 t/ha). Presently similar to 9c1c in carbon content, it has a completely different character in regard to density and size class distribution. 4a2c has 50% more trees, but the majority are in the smallest size class which do not contribute to carbon values as much. 4a2c has also shown an increase in those species with lower carbon values, being red maple (from 1931 to 1994, a 20% to 35% increase) and red oak (11% to 24%). 4a2c has shown the lowest growth over the past decade, which will continue to decrease based on maturation of the ecosystem, and competition for nutrients and light among these small, densely spaced trees. In general the growing conditions in this area are more difficult. It is located at a higher elevation (370 m) than 4a1c and 5a4c, on a slight slope with rocky terrain, within a tract of land that underwent frequent clearcuttings (Tyron, 1930). There is also considerable competition from the underbrush, as the laurel growth is very prolific, and thus competes with the younger, smaller trees for light and water.

Plot 5a4c has demonstrated the greatest growth of all the plots. It has averaged 4.63% annual growth, which has allowed the carbon content to more than triple to 101.5 t/ha. Although 5a4c contains equivalent stem densities to both 4a1c and 9c1c, it resembles the former much more in carbon values. 5a4c has the greatest basal area of any plot currently, but does contain less carbon than 4a1c. 5a4c has more trees in the largest size category (30+ cm), but is underrepresented in the second and third largest category (10-20, 20-30 cm) than 4a1c. 5a4c also has fewer of the "denser" species than 4a1c. In 1994 it contained primarily red oak and species of the "other" category, although from 1931 to the present the percent of black birch, a denser species, increased to 17%. Throughout its history, 5a4c has demonstrated remarkable growth, being aided by its low elevation (320 m) and deeper soils.

Plot 9c1c, being last clearcut in 1915 (Tyron, 1930), is the youngest plot in terms of stand age. It started with the lowest biomass, although it has demonstrated sufficiently strong growth (3.84% annual) as to surpass 4a2c, which initially had 50% more carbon. 9c1c also started with the lowest density of any plot, although now it is comparable with 4a1c and 5a4c. The increase in carbon on 9c1c is due to the shift from the two smaller size classes to the two larger. However, counteracting this is the increase in the species with the lowest biomass values, the red maple, which have increased from 15% to 43%. In general, plot 9c1c still has great potential to sequester considerable more carbon, as more trees continue to mature and grow into larger size classes, such as seen on 4a1c and 5a4c. This potential is most evident in that 9c1c has shown the strongest growth of all plots in the most recent decades.

II. Plot Growth in Response to Climate Variability

The plots' overall trends in annual growth can best be explained when correlated with meteorological variables. These can explain past trends, as well as aid in making future predictions. The plots responded most strongly to annual precipitation deviations, showing stronger growth when there was above average annual rainfall, and conversely weak growth in periods of drought. The deviations in summer precipitation had lesser effect, although one would expect greater sensitivity to decreased precipitation during the growing period in the summer months.

Table 15 - Precipitation & Deviation

	total ppt (cm)	total deviation	summer ppt (cm)	summer deviation
1931-36	107.0	-12.3	28.3	-3.1
1937-41	117.1	-2.2	35.8	4.4
1942-46	118.7	-0.6	30.5	-1.0
1947-54	131.4	12.1	29.9	-1.5
1955-61	128.2	8.9	32.0	0.6
1962-65	93.6	-25.7	26.1	-5.3
1966-73	120.9	1.6	29.7	-1.7
1974-79	135.8	16.5	29.5	-1.9
1980-84	122.9	3.6	29.7	-1.7
1985-89	117.3	-2.0	37.3	5.9
1990-92	117.4	-1.9	36.7	5.3
avg 1931-92	119.1		31.4	

Plot 4a1c showed the least response to climatic influences, as demonstrated by its relatively unaffected gradual decline in growth.

Figure 14a

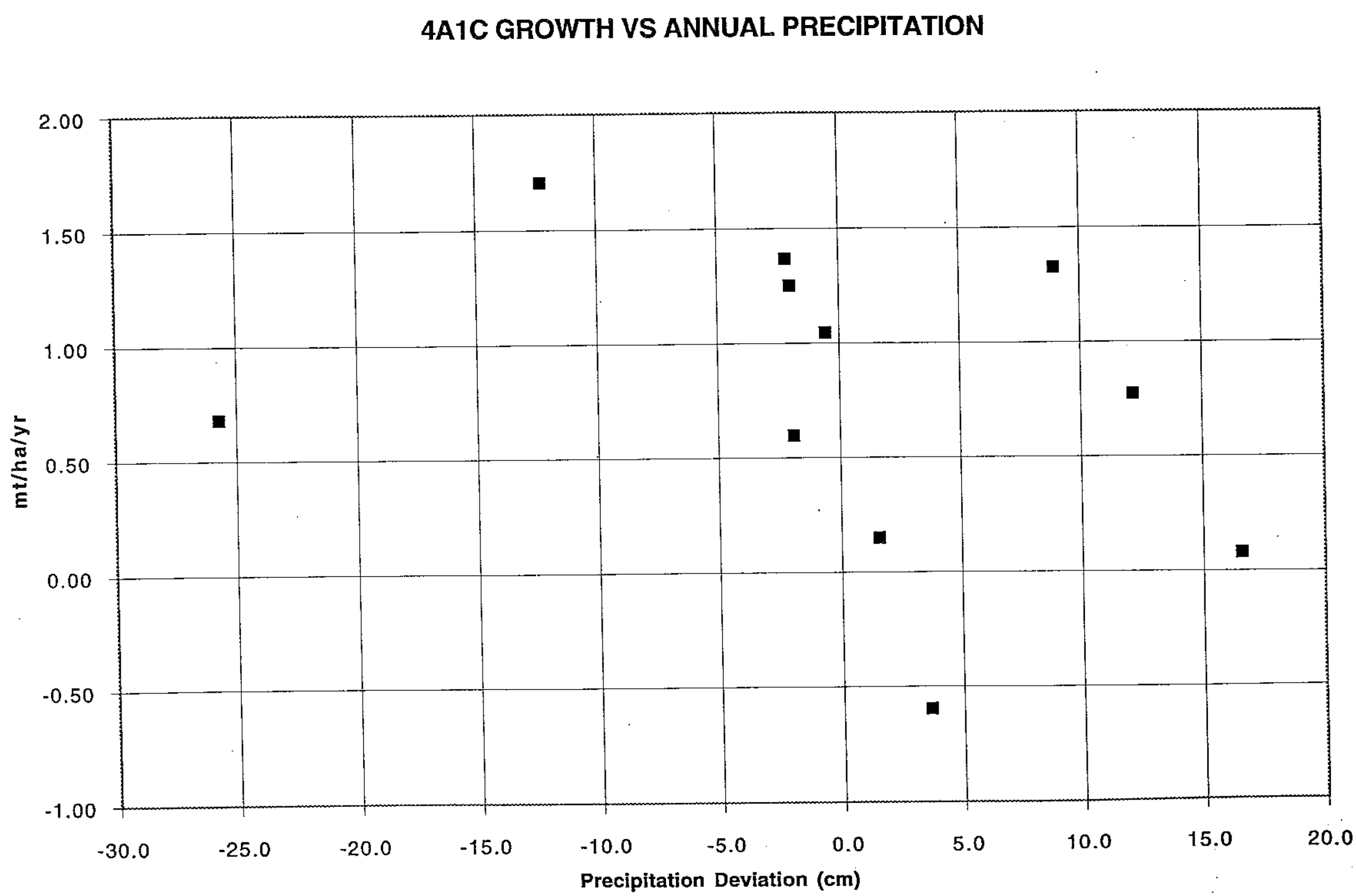

4A1C GROWTH VS ANNUAL PRECIPITATION
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
mt/ha/yr
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0
Precipitation Deviation (cm)

Figure 14b

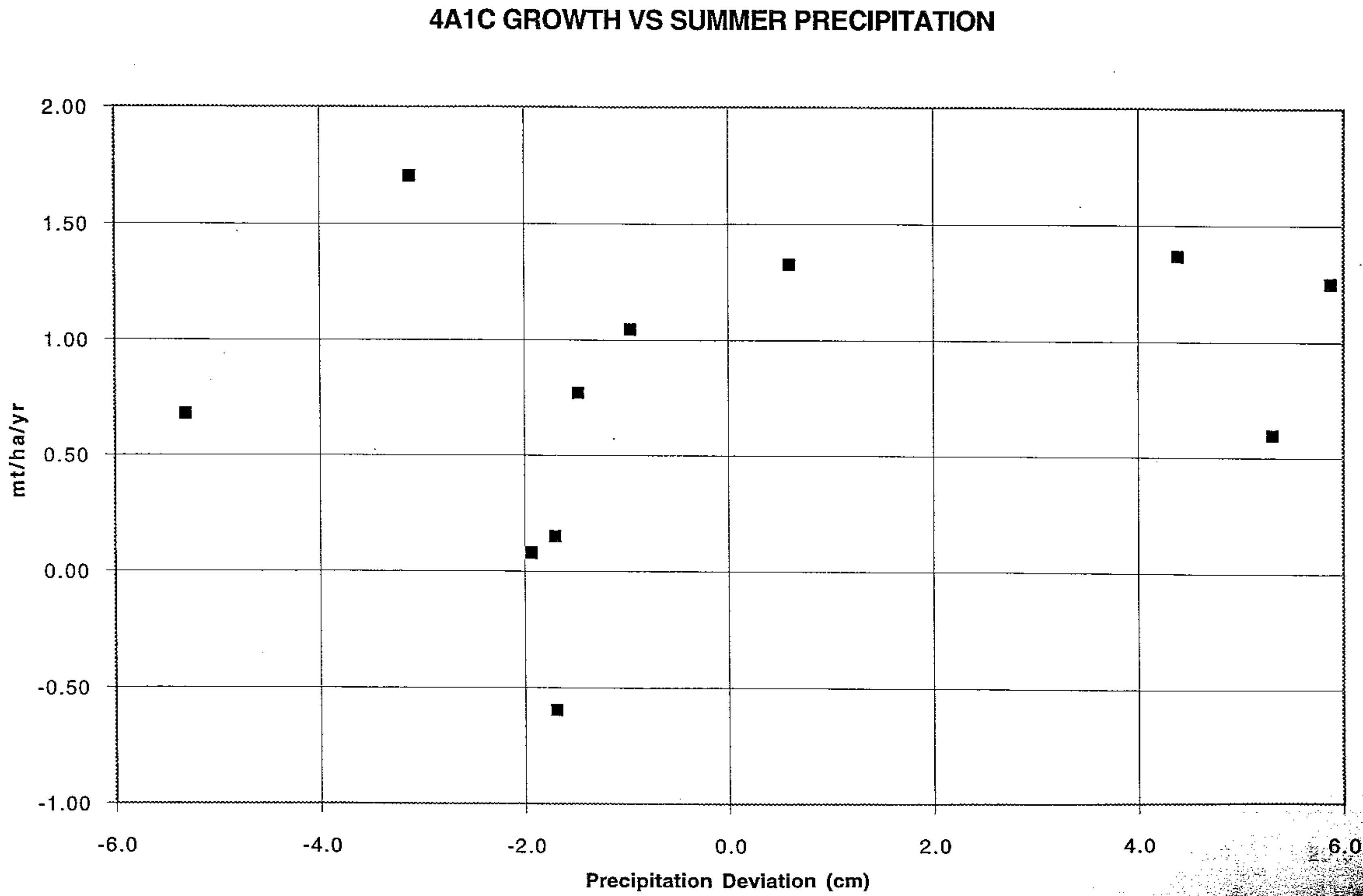

4A1C GROWTH VS SUMMER PRECIPITATION
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
mt/ha/yr
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
Precipitation Deviation (cm)

Figure 14c

4A2C GROWTH VS ANNUAL PRECIPITATION

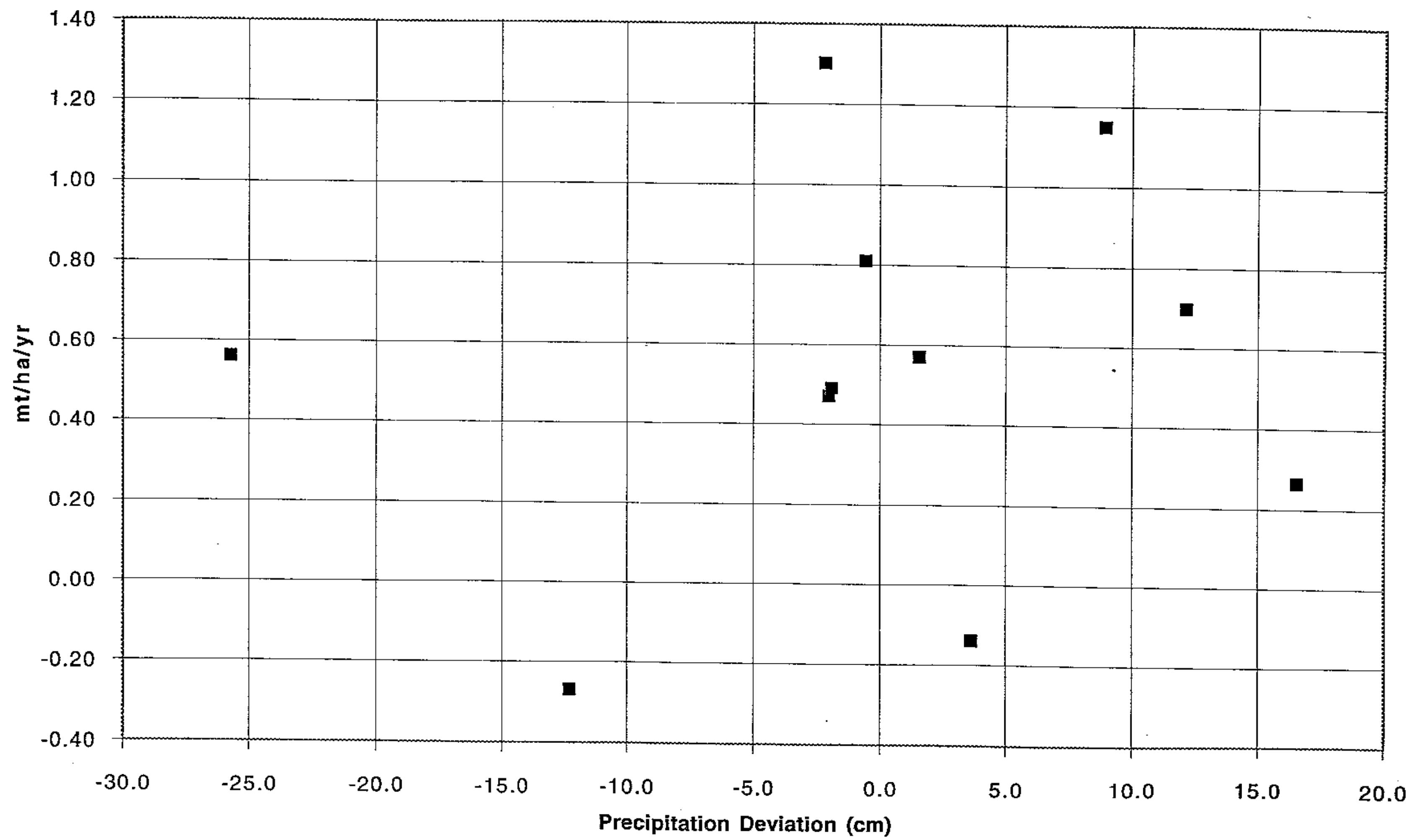


Figure 14d

4A2C GROWTH VS SUMMER PRECIPITATION

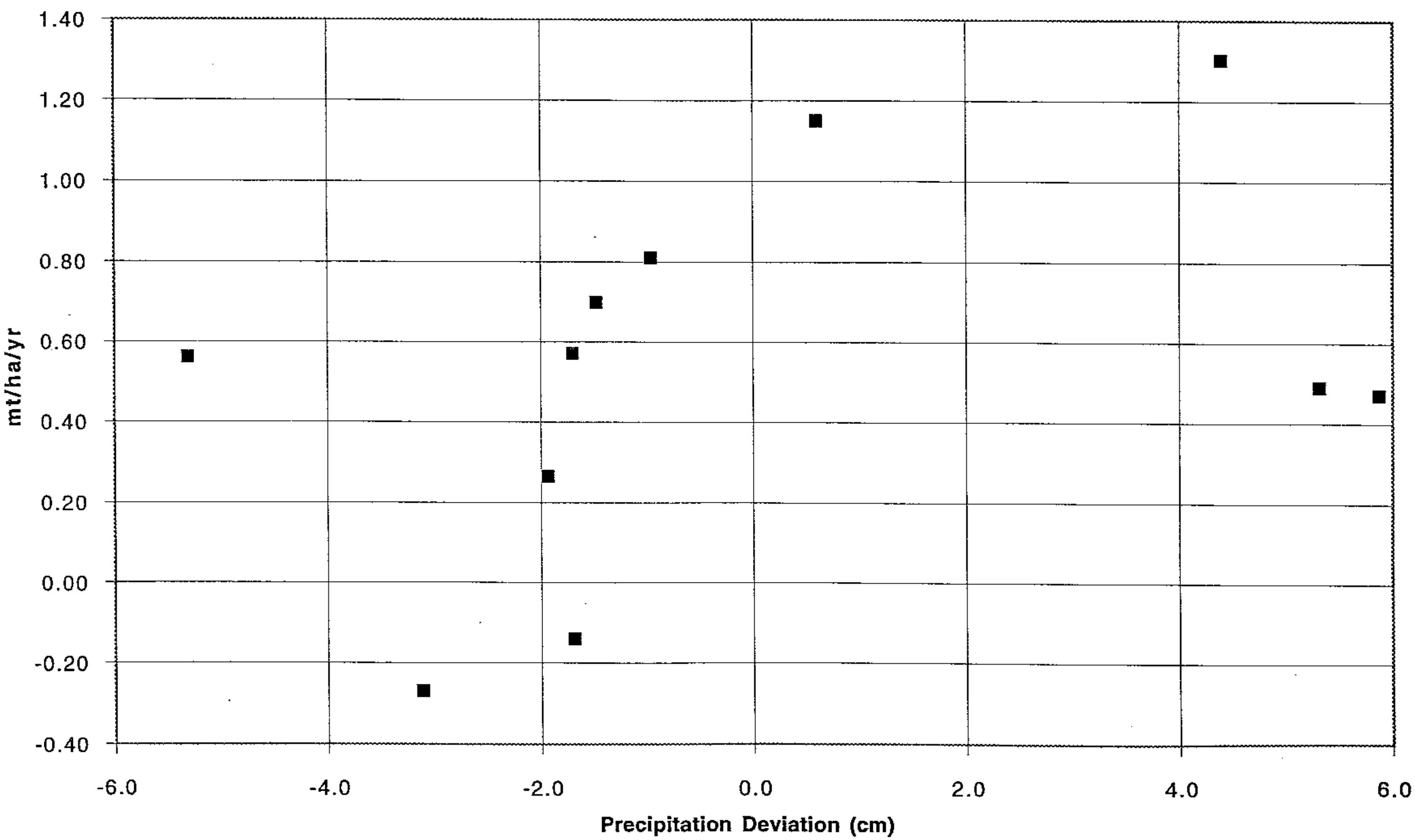


Figure 14e

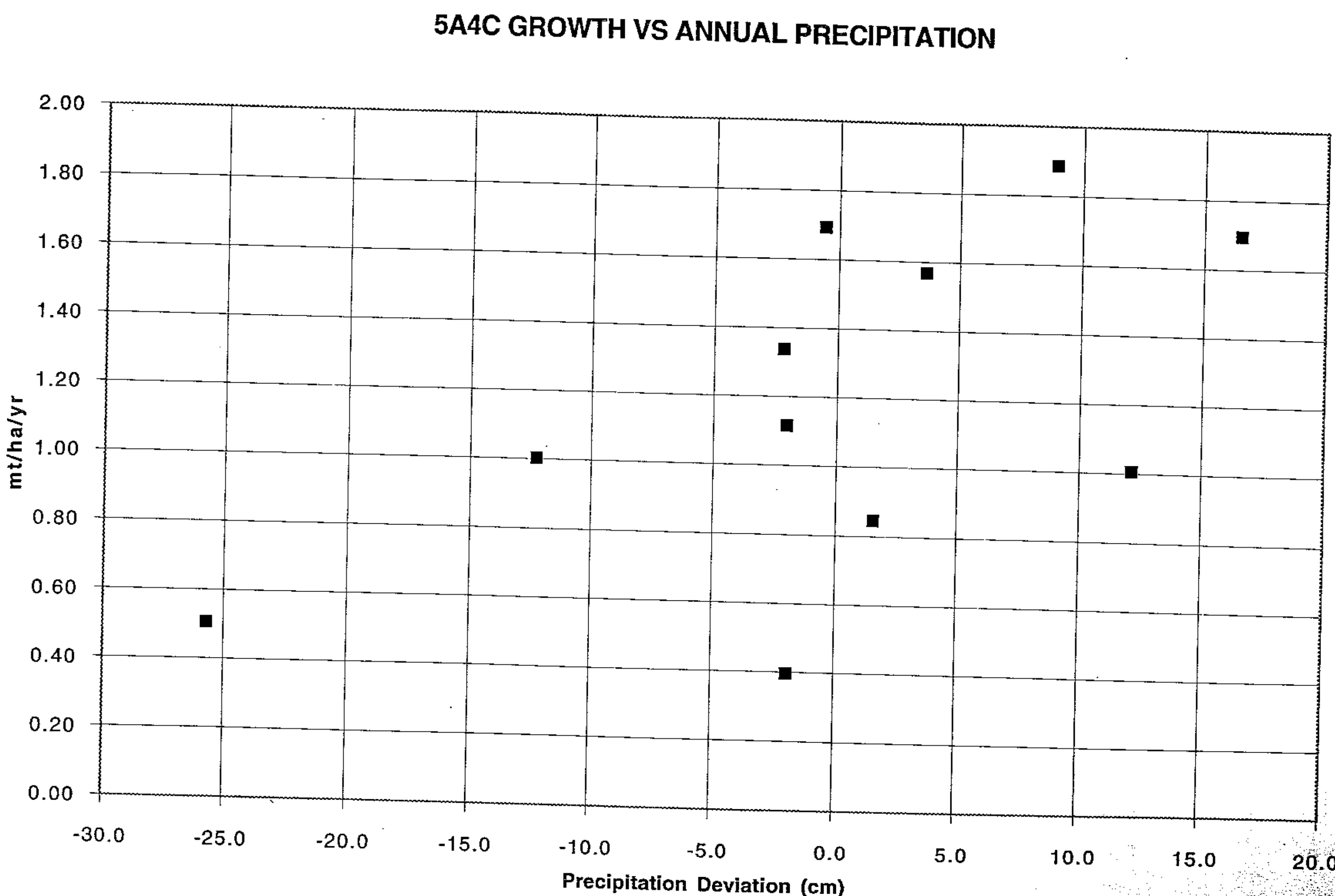

5A4C GROWTH VS ANNUAL PRECIPITATION
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
mt/ha/yr
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0
Precipitation Deviation (cm)

Figure 14f

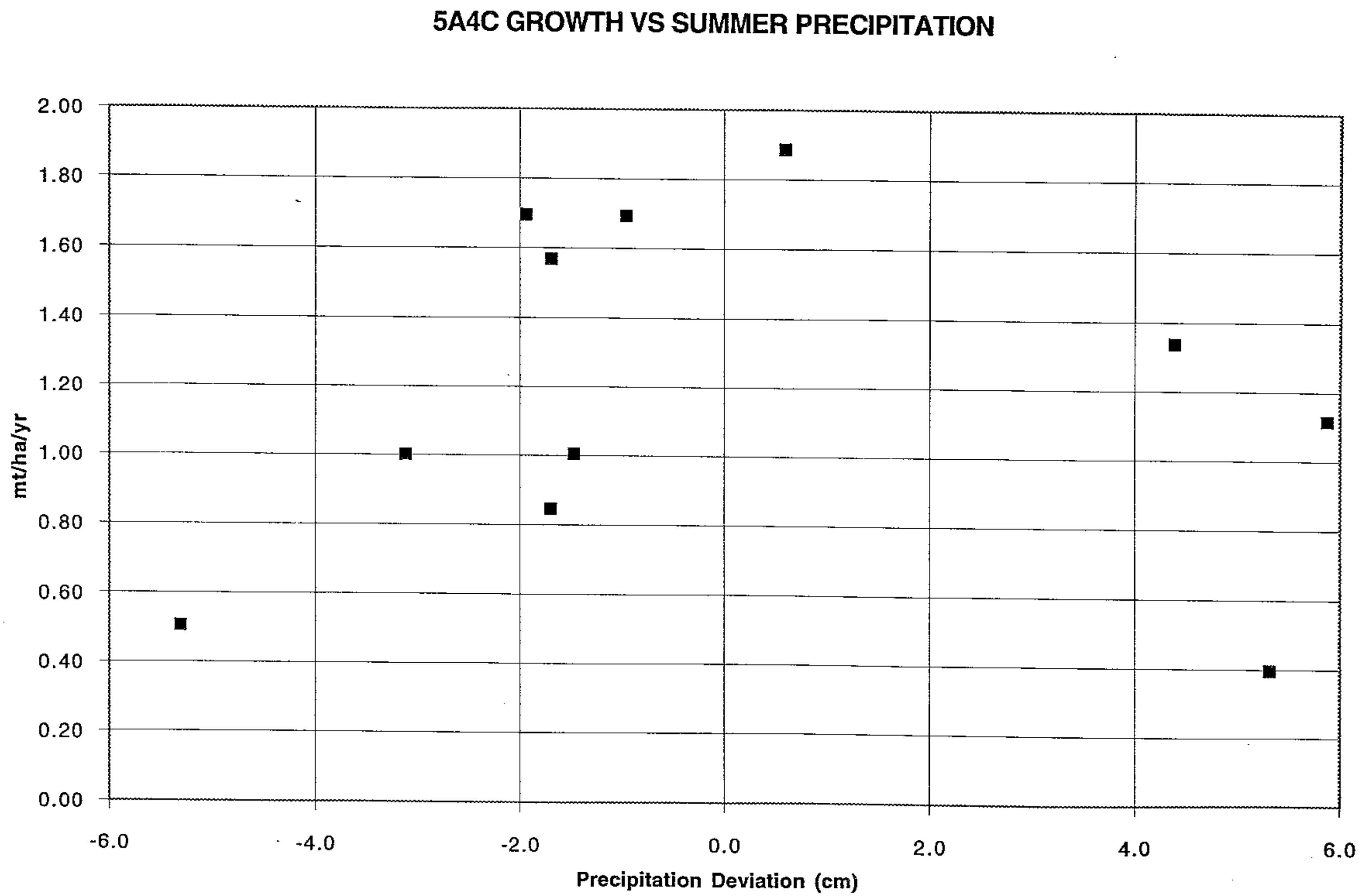

5A4C GROWTH VS SUMMER PRECIPITATION
mt/ha/yr
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
Precipitation Deviation (cm)

Figure 14g

9C1C GROWTH VS ANNUAL PRECIPITATION

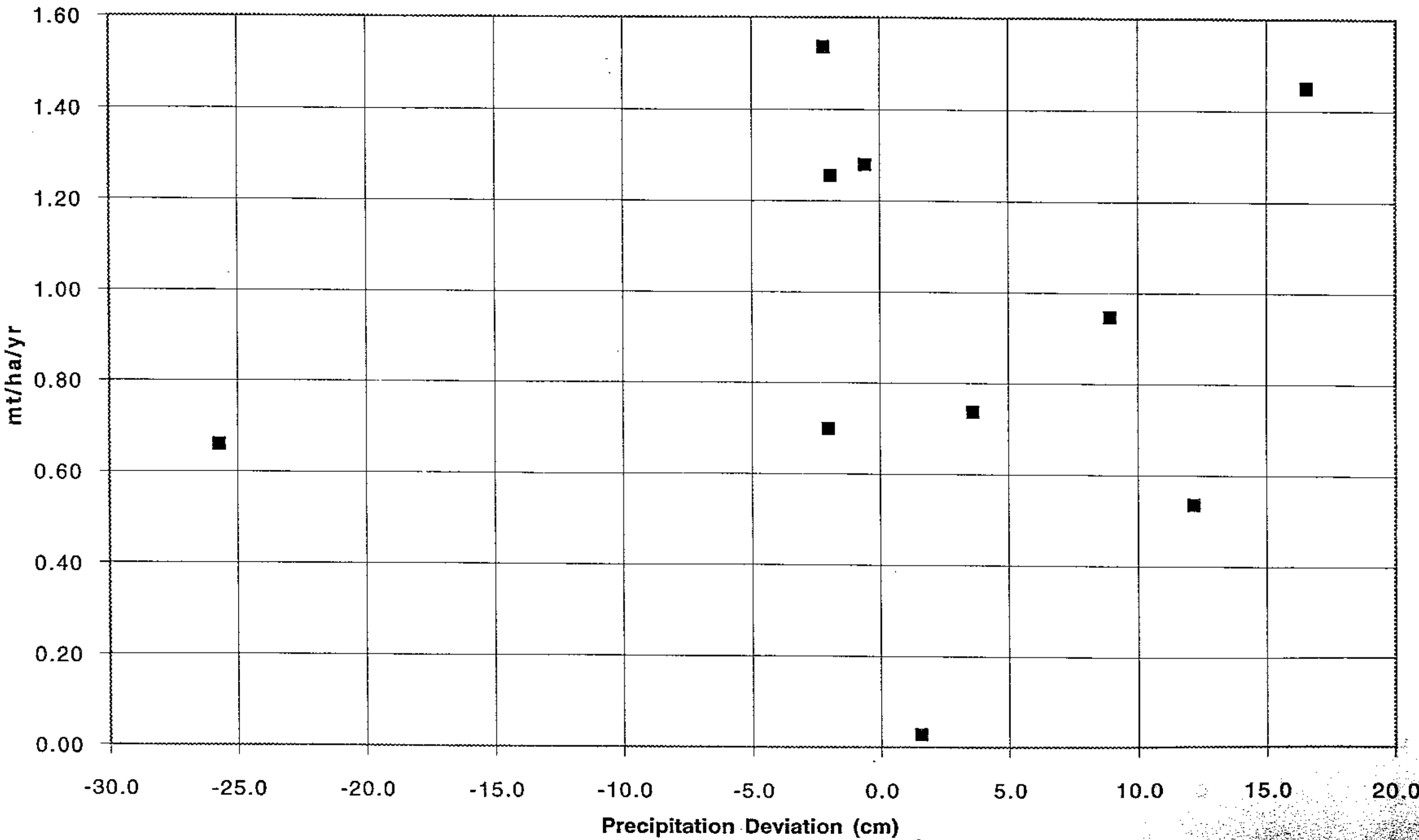
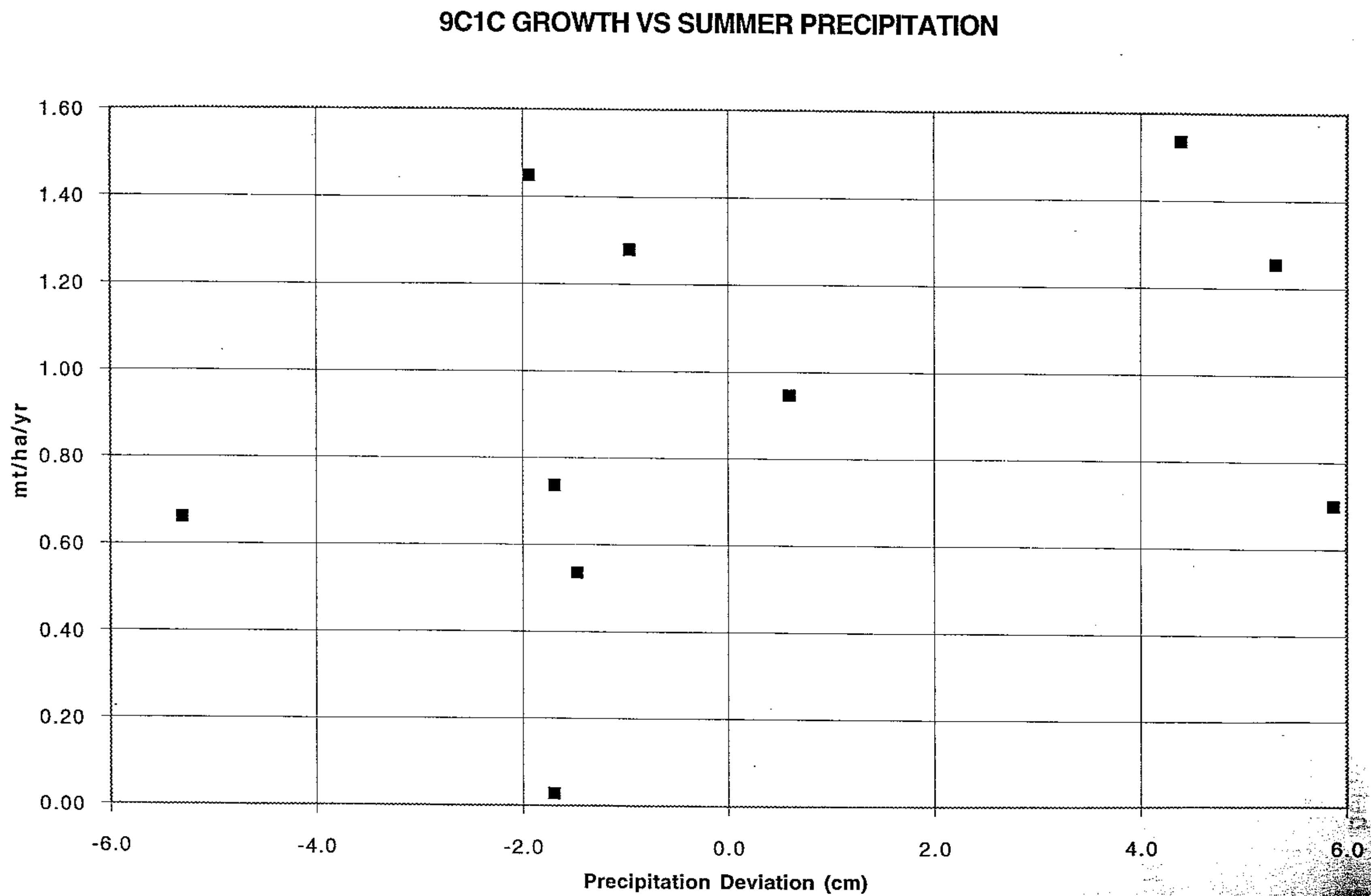


Figure 14h


9C1C GROWTH VS SUMMER PRECIPITATION
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
mt/ha/yr
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
Precipitation Deviation (cm)

Contrasting this to the sporadic peaks of 9c1c, one can assume that the older, better established trees of 4a1c are better protected against extremes than younger trees. 4a1c also has an optimal location next to Arthur's Brook, which supplies water at higher levels than what other plots receive. 4a1c continued to decline through 1954, and then showed increased annual growth in 1954-61. The period 1947-1961 had 10.5 cm above average annual precipitation. This is followed by a drought in 1962-65, when growth suffered on all plots, including 4a1c. Growth continued to decline, and this plot did not respond to the high rainfall during 1973-79 (18.8 cm above average). The peaks in growth in 1985-94 may be due to higher summer rainfall. As can be seen in graphs 12a-12h, which correlate annual growth (in additions of tons/ha/year) and deviations in annual and summer precipitation, 4a1c shows the least climatic response. For those years of average annual precipitation (or with little deviation), growth ranged from -0.6 tons/ha/yr to 1.37 tons/ha/yr. The period of highest growth correlated with years with -12 cm below average rainfall. Summer correlations are somewhat clearer, in that most high growth occurred during higher precipitation.

Plot 4a2c showed negative growth in 1936, due to the lower precipitation in 1931-41. As with 4a1c, growth increased after the high rainfall in 1947-61, only to fall drastically in the drought of the early 1960's. Growth continued to decline until 1983-94, when the increased summer rain caused stabilization of growth. In general, 4a2c showed stronger correlations between precipitation (especially summer) and growth, as can be seen in graphs 12a-12h.

Plot 5a4c echoes the general pattern of the two previous plots in gradual decreases in growth. 5a4c was not affected by the increased precipitation in the 1947-61; perhaps because the growth rates were already so high, and extra moisture would not have an additive effect. However, 5a4c was most affected of any plot by the drought of the following decade, as can be seen by the steep drop in growth. In the following years of 1973-79, it quickly recovered to the former trend in growth, and then has since been declining, unrelated to climate variables. In correlating growth and annual precipitation, 5a4c shows the strongest relationship. Above average growth (+1.19 tons C/ha/yr) occurred in years with strong positive or very slight (less than 3 cm) negative deviations in rainfall.

9c1c has demonstrated the most unpredictable growth in terms of correlation with climate. From 1936-54, the growth declined rapidly, although precipitation was not so severe in this period. 9c1c recovered slightly up to 1961, and then showed the smallest drop in growth from the drought (1962-65) of any plot. 9c1c's growth spurted during the high precipitation of the 1973-79, as it did again in 1989-94, due to increased summer precipitation of this time (5.5 cm above average). Overall 9c1c has shown the strongest growth of any plot in the past decade and half.

III. Comparison to other NE Forests

My original predictions held that BRF would not sequester as much carbon as some other prominent Northeast forests. The forest is still relatively young (most plots are now roughly 80-95 years old). Furthermore, with its thin, rocky soils, the Hudson Highlands "...

may be classified as sub-marginal, ... with good soils limited to valley bottoms and coves" (Tyron, 1930).

The above ground carbon figures indicate that BRF has higher values than other forests comparable in geography and type, due to some optimal conditions in this area. The carbon figures used by the Forest Service and Department of Agriculture may also underestimate carbon sequestration in Northeast deciduous forests. BRF will be compared to figures used by the Forest Service in their computations in the General Technical Report (1992) (New York State forests, and for the two primary forest types that comprise BRF: maple-beech-birch and oak-hickory). BRF will also be compared to three experimental forest plots that have been the site of major biomass and forest ecology studies: Brookhaven, Long Island, Hubbard Brook, NH, and Smoky Mountains National Park, TN.

Although Brookhaven is closest in proximity to BRF, forest composition and growing conditions are different, consisting primarily of pitch pine and white oak. It is a young forest, which has undergone severe forest fires in the past, and thus contains small, unimpressive trees. It grows on poor, sandy soils, of the Long Island moraine. Average above ground biomass value is 32 tons C/ha (Whittaker & Woodwell, 1969).

The experimental forest at Hubbard Brook, New Hampshire (HBNH), is more similar in composition to BRF, and thus offers a better comparison. The primary species are sugar maple, American beech, and yellow birch, all species which are found in lesser concentrations at BRF. At higher elevations balsam fir and red spruce are prevalent. The soils are similar, a bouldery glacial till that becomes deeper at lower elevations. The HBNH data are useful in that the effects on biomass due to elevation changes can clearly be seen. The stands age in 1974 were from 83 to 124 years, thus roughly equivalent to BRF. At low (550-630 m), middle (630-710 m), and high (710-785 m) elevations, the respective carbon content is 80.5 metric tons/ha, 75.5 tons/ha, and 50.5 tons/ha. The forest is expected to climax with values of 350 tons/ha above ground biomass, or 175 tons carbon (Whittaker et al., 1974).

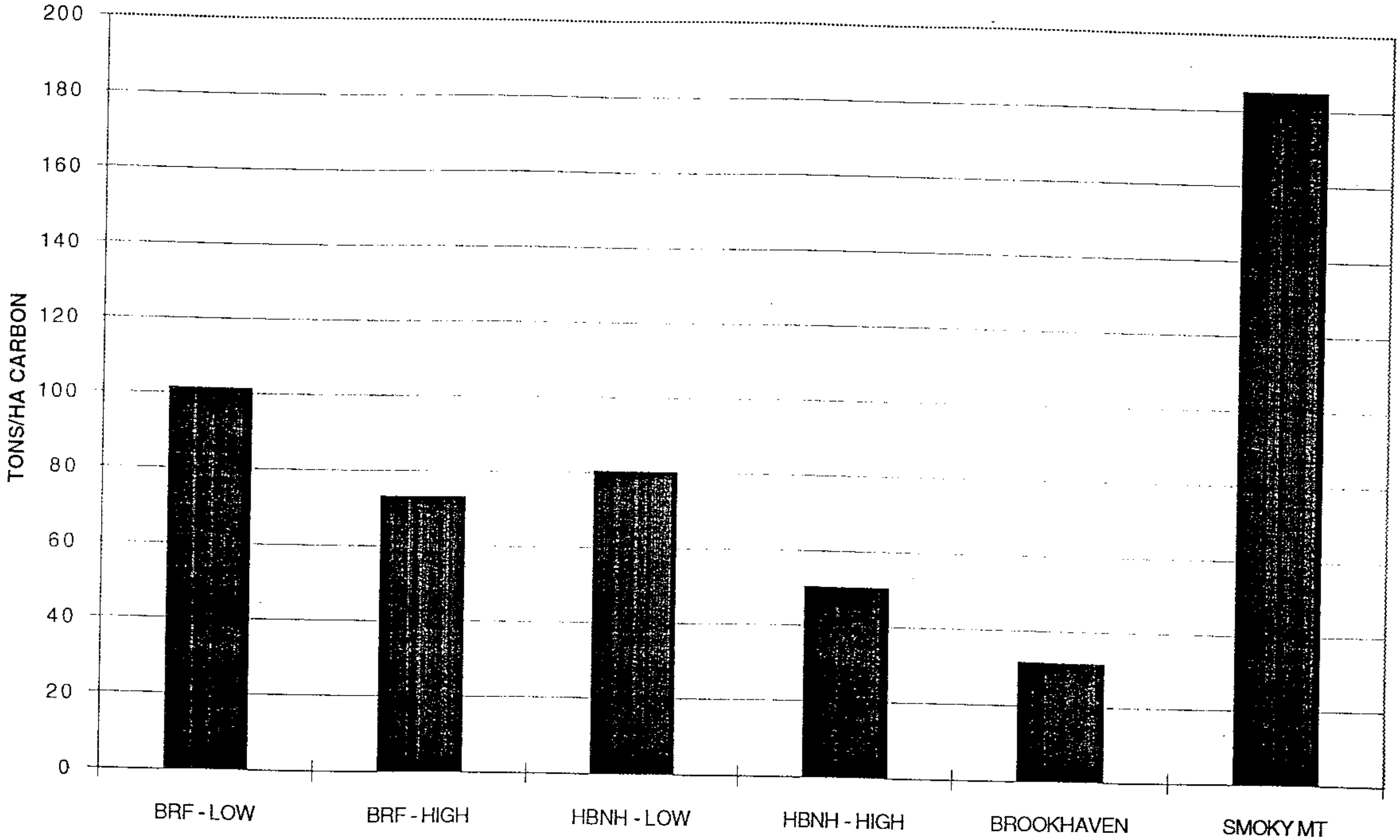
Further forest comparisons can be offered with the figures for the Great Smoky Mountains National Park. Although located in Tennessee, there are similarities in forest type. The oak-hickory forest has characteristics of BRF, although growing conditions are better in Tennessee, as is seen in the considerably more massive value of 185 t/ha carbon (Whittaker, 1966).

Table 16 - Above Ground Carbon Comparisons

Forest	Metric Tons C/ha
BRF: 4a1c	110
BRF: 4a2c	73.3
BRF: 5a4c	101.5
BRF: 9c1c	73.7
HBNH, low elevation	80.5
HBNH, middle elevation	75.5
HBNH, high elevation	50.5
Brookhaven	32
Smoky Mts. NP	185

As can be seen in the above table, the BRF plots 4a1c and 5a4c had considerably higher carbon figures than other forests in the Northeast. This can partially be explained in terms of species composition and the effects of geographical location, concerning elevation and climate, and their affects on the growing season. The

FOREST COMPARISONS



higher elevations of the White Mountains in NH can hinder growth, although the Smoky Mountains have equally high elevations. The figures in table 16 offer values for very specific ecosystems. This information is valuable because it has been calculated on an individual basis, and is very accurate for that type of forest at a certain age/level in succession. However, the very specificity of these data also limit its application to BRF comparisons and quantifications of the global carbon budget. Perhaps more useful are the generalized carbon values used for the Forest Service, which compute values for large geographic areas (such as New York State) and also specific forest types spanning the Northeast, such as the oak-hickory and maple-birch-beech forests. Discrepancies from these values also are useful in reassessing carbon figures for the global carbon budget, or at least the attempts of the U.S. to mediate emissions.

The above ground carbon values are derived by the USFS in a two-step process. First, the volume of standing stock lumber is calculated, and then these figures are multiplied by the specific gravity of the wood type, to determine biomass weight, which is then multiplied by the carbon conversion (0.498 for hardwoods) (Birdsey, 1992), which is similar to the 50% conversion used in my methods. Because these methods are tabulated for large areas, they are not nearly as accurate as the method used in the Hubbard Brook and Brookhaven forests, or at BRF, where individual trees are measured to compute carbon content. However, the use of these generalized figures is widespread among government agencies and scientists in computing the carbon budget.

In the USFS study all forest components were quantified: the trees, soils, understory, and forest floor. For New York State forests, trees contain 28.8% of the ecosystem carbon, with soils having 61%, forest floor 9.4%, and the understory 0.9%. Thus, for typical NY forests, accounting for the whole tree gives carbon values of 51.7 tons/ha, and accounting for only the above ground portion results in values of 42.9 tons/ha (boles, branches, and foliage being 83% and roots being 17%). Figures based on specific forest types give higher ranges. Oak-hickory forests on average have 52.1 tons/ha, while maple-beech-birch contain 47.5 tons/ha (Birdsey, 1992).

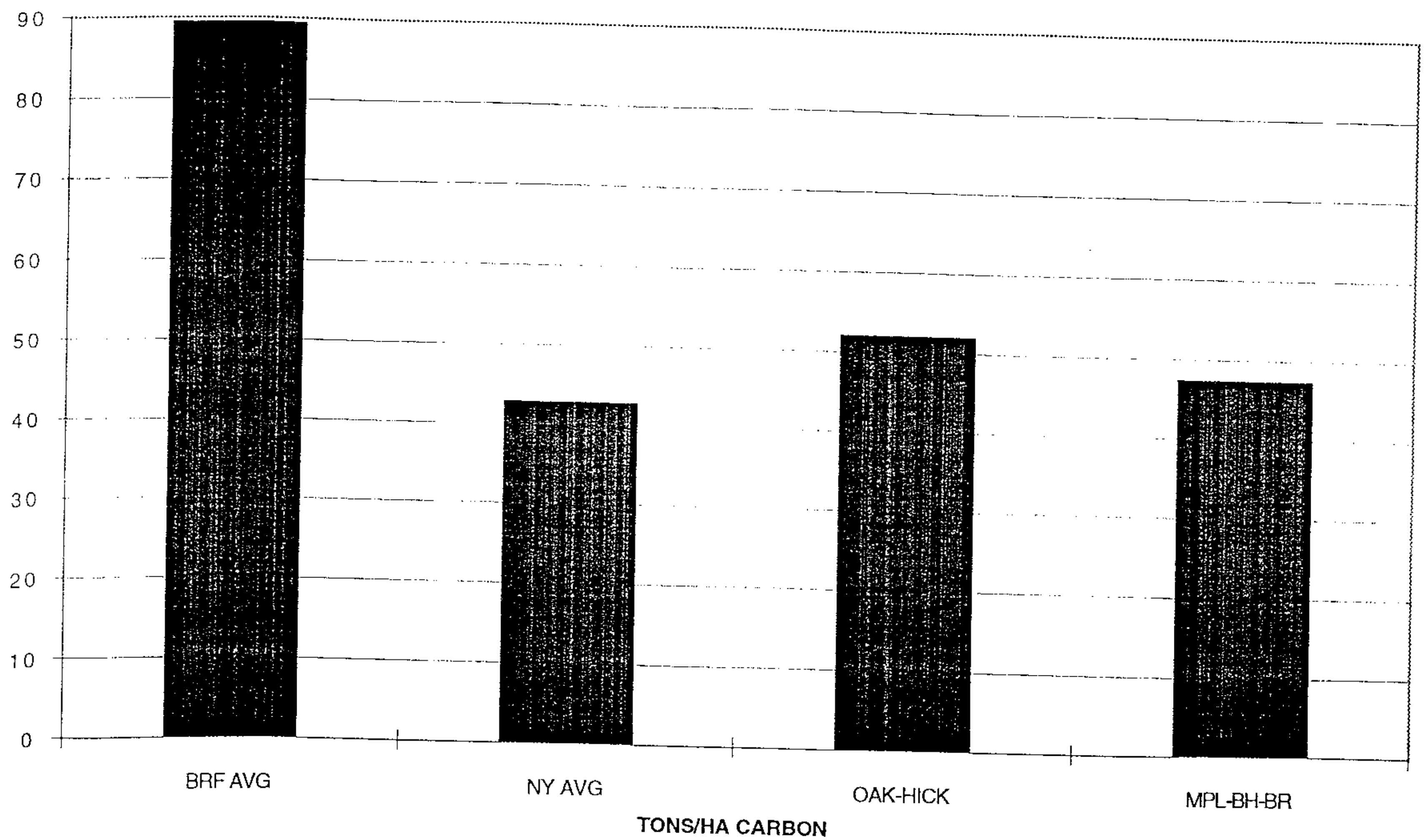
Table 17 - Carbon Value Comparisons

Forest:	**Metric Tons C/ha:**
BRF average*	89.6
NY average	42.9
NE Oak-hickory	52.1
NE Maple-beech-birch	47.5

* BRF average for the four plots 4a1c, 4a2c, 5a4c & 9c1c.

Why is BRF more than double the "average" of New York, even though forests statewide have been regrowing from approximately the end of 19th century (Tyron, 1930)? BRF may be skewed because of the unusually high growth of 4a1c, with its stream location and diversity/size of trees. The New York average includes forests upstate that may experience more difficult growing conditions. However, because USFS data is based on a method that includes a great deal of approximation, credence must be given to BRF figures, which are 108% greater than NY figures, and 72% and 89% greater than the oak-hickory and maple-beech-birch forests respectively.

DATA COMPARISONS



IV. Future Growth

In general, one can expect BRF under natural conditions to reach a steady state in terms of above ground carbon storage (where added carbon in tree biomass is offset by lost carbon in respiration of trees and detritus) within 50 to 100 years (based on current plots' ages of 80-95 years (Tyron, 1930)). This is loosely calculated on the assumption of a 175 year steady state of NE maple-birch-beech forests (EPA, 1993). Overall, growth rates will decrease, and less carbon will be sequestered in live trees in the future than has been in the past 100 years. Rough estimates of future growth will be discussed, using past growth trends and predictions of climate change to help determine how BRF will respond.

Firstly, average biomass additions were calculated within plot "biomass classes". The plots' (in the time increments between measurements) annual additions in carbon were grouped together based on their present total carbon content (within biomass increments of 10 tons C/ha), and then averaged. As seen in table 18, plots with 60-99 tons carbon/ha showed consistent additions of carbon, ranging from averages of 0.85 to 1.38 tons C/ha/yr. Fast growth in smaller, younger plots declines once a certain point is reached, when trees reach maturity and grow slower, and also nutrients and light becomes scarcer. Once plots reached a threshold of 100 tons/ha, they only averaged additions of 0.49 tons C/ha/yr.

Table 18 - Annual Growth in Plot Biomass Classes

Biomass Class (tons carbon/ha):	Average Carbon Additions (mT/ha/yr)
60-69	.85
70-79	1.02
80-89	1.38
90-99	1.15
100+	.49

Based on the averages above, one can make rough predictions of short term growth of the different plots. Since both plots 4a1c and 5a4c currently contain over 100 tons C/ha, one would expect them to add no more than half a ton carbon annually, with perhaps greater decreases as they age. Because 4a2c and 9c1c both have less biomass (both contain roughly 73 tons C/ha) currently, they will likely continue to sequester more carbon over the next few decades, until they reach levels of 100+ tons C/ha, when growth will decrease to lower levels.

Although growth is expected to decline naturally as a factor of forest maturity, predictions effects of climate change could nonetheless have important implications for both growth and overall forest health. With a doubling of CO_2, GISS and GFDL models both predict lower soil moisture for the Northeast, 2.5-5% and 5+% lower respectively. There is less clarity on precipitation in general. Both models predict slight increases in precipitation, but with increased temperature, which would raise evaporation rates, and thus overall lowering soil moisture. There are discrepancies in seasonal distribution. For the Great Lakes area (the closest geographically to the Northeast), winter precipitation will increase 10-20 cm annually, but summer may either increase (under the GISS model) by

10 cm, or decrease (GFDL model) by 20 cm (EPA, 1989). Obviously, changes of this magnitude would have drastic effects on forest health and carbon content.

Lowering soil moisture basically has the same consequences as a decrease in precipitation to vegetation. As seen from climate history, BRF experienced two severe droughts, in 1962-65 and 1981-82 (EPA, 1990), in which growth rates on the majority of the plots decreased below "normal". However, the below negative deviations from average growth are also an artifact of natural forest maturation. As forests age, they grow at slower rates, and thus most growth for the later decades will be "below average", whereas earlier decades all will show "above average" growth.

Table 19 - Deviations in Precipitation and Growth (t/ha/yr)

Year	**Annual Ppt Dev. (cm)**	**Summer Ppt Dev. (cm)**	**4a1c* Dev.**	**4a2c* Dev.**	**5a4c* Dev.**	**9c1c* Dev.**
1931-36	-12.3	-3.1	0.94	-0.81	-0.19	
1937-41	-2.2	4.4	0.61	0.76	0.15	0.63
1942-46	-0.6	-1.0	0.29	0.27	0.50	0.37
1947-54	12.1	-1.5	0.01	0.16	-0.18	-0.37
1955-61	8.9	0.6	0.57	0.61	0.70	0.04
1962-65	**-25.7**	**-5.3**	**-0.08**	**0.02**	**-0.68**	**-0.25**
1966-73	1.6	-1.7	-0.61	0.03	-0.34	-0.88
1974-79	16.5	-1.9	-0.68	-0.27	0.51	0.54
1980-84	**3.6**	**-1.7**	**-1.36**	**-0.68**	**0.38**	**-0.17**
1985-89	-2.0	5.9	0.49	-0.07	-0.07	-0.21
1990-94**	-1.9	5.3	-0.16	-0.05	-0.79	0.34
Average Growth			**0.76**	**0.54**	**1.19**	**0.91**

* Deviation in growth (tons carbon/ha/yr) calculated by subtracting growth of time increment from average (1931-94).
** Precipitation data from 1990-92; growth data from 1990-94.

Increases in summer precipitation, as predicted by the models, would have positive influences on growth. Although the above table does not demonstrate increases in growth (due to forest maturation processes as stated earlier) in the years 1985-92, the positive deviations in summer precipitation in this time did increase growth rates. Figure 3 clearly shows an upswing in annual percentage growth for all plots except 5a4c for the past decade.

As shown by laboratory tests, trees under scenarios of doubled CO_2 also have higher water use efficiency, and thus might be less affected by changes in rainfall (Rogers et al., 1983). Increases in atmospheric CO_2 could have many other implications, both physiologically and ecologically, which will affect future forest growth. Young seedlings, including some species such as chestnut oak, show increased photosynthesis, and had considerably greater biomass in the first one or two years of life. Other species, such as red oak (Bunce, 1992), acclimated and their growth was not affected. Mature trees, when doing tree ring studies on those which have been growing since the Industrial Revolution, show mixed responses in growth (Luxmoore et al., 1993). Biomass allocation within the plant differs, in that under doubled CO_2 and limited nutrients and water, roots grow proportionally more than the stems (Bazzaz, 1990). This would particularly affect results from studies similar that of BRF, as only above ground carbon is being measured.

CO_2 increases can affect other environmental factors above the physiological level in plants. CO_2 has been shown to increase a plants' resistance to high levels of ozone and SO_2, and thus increases in pollution might not have drastic consequences on forest health

(Carlson et al., 1982; Coyne et al., 1977). Of greater importance are interspecific responses to CO_2. One study showed that species that were shade-tolerant, those being beech and sugar maple, grew considerably better at the expense of other species such as red oak and white pine (Bazzaz et al., 1990). Other models of GISS and GFDL show northward shifts in species due to rising temperatures caused by increased CO_2. Sugar maple and birch are expected to shift, whereas oak remains stable in the Northeast (EPA, 1990). These predictions could have consequences for BRF, if the sugar maple and birch shift out of the Hudson Highlands area, as these species are significant components of the forest community. If red oak is expected to remain stable, but not grow as well respectively under doubled CO_2, this would result in altered species composition, and perhaps tree death and biomass/carbon losses as the forest readjusts.

V. Adjustments to Carbon figures in Regional Areas

In the table 16, it is evident that the average BRF above ground carbon value (in metric tons/ha), is considerably higher than those values derived by the USFS using standing stock estimates of harvestable lumber. The average for New York State, 42.9 t/ha (whole tree values are 51.7, but only the 83% of above ground components of stem, branches, & foliage are counted), is only 48% of the values derived for BRF, which has characteristics of a typical forest for this area. According to General Technical Report WO-59 (1992), the states of New York, Connecticut, Rhode Island, and Massachusetts, all have forests with similar carbon contents (as well as being similar forest type ecologically, and spanning the same latitude & climate range), for a total area of 9.79 X 10^6 hectares, containing 424 million metric tons of above ground carbon total. This however may be a severe underestimation, when compared to BRF average values. If BRF values are extrapolated over the geographic area of these states, there are an additional 432.6 million metric tons (in above ground tree component alone) for which have not been accounted. This is 102% more than is currently believed to be held in trees in these states.

Although it is encouraging that forest growth in this regions has perhaps been stronger than estimated, the downside is that carbon sequestration will continue at lower rates than predicted by the USFS. Average New York forests are expected to accumulation 1.18 metric tons/ha of carbon annually, with the other states of Connecticut, Rhode Island, and Massachusetts ranging from 0.96 - 1.10 t/ha/yr. However, BRF has only averaged 0.65 t/ha/yr over the past five years.

Comparing BRF values to those used in global carbon cycle quantifications is of interest also. Ajtay et al. (1979) calculates mixed deciduous forest area to be 3 x 10^{12} m^2, containing a total of 37.8 x 10^{15} g carbon of living phytomass. This averages to 12.6 x 10^3 g C/m^2 (10.5 x 10^3 g/m^2 in the above ground component of biota). The BRF ranges of above ground carbon of 7.3 - 11 x 10^3 g C/m^2 (8.8 - 13.2 x 10^3 g C/m^2 for whole plant) are somewhat below those used by Ajtay et al. When extrapolated over the total land area of deciduous forests, the total carbon stored in living phytomass (both above and below ground portions) is calculated to be 26.4 - 39.6 x

10^{15} g C. The higher range goes above the values of Ajtay et al. because they use a lesser conversion ratio of carbon to dry biomass (0.45, whereas I used 0.5). Overall, my results show consistency of BRF data with those used in carbon cycle calculations.

Conclusion

In studying the past and present rates of above ground carbon storage at Black Rock Forest, one notices the high growth rates early in forest history, and a gradual decline up to present decades. There was considerable variation among plots over time, both in initial carbon and how rapidly it was sequestered. These variations were most strongly correlated with stand age, minor differences in the microhabitats, and precipitation deviations. Overall, trees showed the greatest response to increased precipitation, and to a lesser degree being located in optimal areas, either in lower elevations or by streams, where soil moisture was sufficient. As would be expected of forest maturation patterns, younger plots grew at higher rates than older ones. The current amount of above ground carbon at BRF is consistent with figures used by Atjay et al. (1979) in their global carbon cycle quantifications, although there was considerable variation among Northeast forests' biomass values. Thus one can conclude that BRF figures offer an appropriate average that can be extrapolated over greater land areas, and that BRF itself is a model ecosystem for better understanding the role of deciduous forests in the global carbon cycle.

Recommendations

The greatest gap in research includes having more comparisons available of different forests' biomass values. Both young communities and those that are better established need to be better studied, to understand how carbon sequestration rates change over time. Establishing long term plots in a variety of areas is advisable, as well as of course continuing to monitor those that already exist. Quantifying rates over time will be a crucial importance over the next 50 years, as many deciduous forests reach a stasis in respect to carbon storage, while CO_2 emissions will continue unabated. More knowledge is also needed in predicting forest response to climate change. Lastly, the soils and other below ground components are little understood, although they contain significant carbon, and are of crucial importance in quantifying the carbon cycle.

Acknowledgments

Many thanks and recognition to Dr. William Schuster, Director of the Black Rock Forest, for originally proposing this project and offering the facilities and Black Rock Forest itself to the study; and to my professors Stephanie Pfirman, who first informed me of the NIGEC Fellowship, and Jim Simpson, both of whom have offered invaluable guidance and advice since. Acknowledgment also to the National Institute of Global Environmental Change (NIGEC), for funding my work on this project through an undergraduate fellowship.

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