MINERAL NUTRITION OF YELLOW-POPLAR (LIRIODENDRON TULIPIFERA L.)

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ABSTRACT

MINERAL NUTRITION OF YELLOW-POPLAR
(LIRIODENDRON TULIPIFERA L.)

by Raymond Francis Finn

Yellow-poplar (Liriodendron tulipifera L.) is an important timber tree species that occurs over a wide geographical range in the United States. It is one of the most commonly planted tree species in the hardwood region of the United States. However, yellow-poplar plantations and other hardwood plantations usually have not grown and developed satisfactorily. Part of this failure has been ascribed to the inadequacy of available soil nutrients.

It is desirable, therefore, to have a standard which can be used to judge the adequacy of available soil nutrients. Foliar chemical analyses offer a possible means of providing this standard. To use foliar analyses for diagnostic purposes, the relationships between nutrient concentration, growth or yield, and foliar concentration must be established. This information is not available for yellow-poplar. In 1960, experiments were initiated to supply the needed information.

A sand-culture technique was used to establish the relationships between solution nutrient concentrations, growth, and foliar nutrient concentrations. Nitrogen,

phosphorus, potassium, and calcium solution nutrient concentrations were varied; all other nutrients were maintained at a fixed concentration.

Deficiency symptoms induced by omitting nitrogen, phosphorus, potassium, and calcium singly and in combinations from the nutrient solutions were studied in a sand-culture medium.

Fertilizers were applied to sand, sandy-loam, and clay-loam soils in pots containing yellow-poplar seedlings. Nitrogen, phosphorus, potassium, and calcium were applied to the soils at several rates, singly and in combination. The effects on growth and foliar nutrient concentrations resulting from the application of fertilizers were observed.

Since mycorrhizae are known to affect the inorganic nutrition and growth of forest tree species, an experiment was designed to determine to what degree mycorrhizae are important in the inorganic nutrition of yellow-poplar seedlings growing on a sand and a sandy-loam soil.

The results from the first experiment in which the solution concentrations of N, P, K, and Ca were varied indicate that there is a significant positive relationship between solution nutrient concentration and foliar nutrient concentration. The relationship in some cases is linear and in others is defined by a second order polynomial equation. Growth was significantly related to N, P, and Ca solution concentrations, and hence, to foliar

concentration. The relationship between solution potassium concentration and growth was not statistically significant.

The omission of N, P, or K from the cultural solutions resulted in the death of the seedlings. The omission of calcium, however, did not retard growth. Fast-growing seedlings produced more severe deficiency symptoms than slower growing seedlings. The omission of N + P or N + K or higher order combinations of these three elements produced less severe symptoms than when one of the three elements was omitted.

When two or more elements were omitted from the basic nutrient solution, the foliar deficiency symptoms were generally characteristic of the symptoms produced by the omission of only one element. Thus, when nitrogen and phosphorus, simultaneously, were omitted from the basic solution, a characteristic nitrogen deficiency symptom was produced.

Foliar analyses indicated an increase in inorganic nutrient uptake following fertilization. Growth response to fertilization was not great. The most consistent response was associated with the phosphorus fertilizer applied to the sandy-loam soil. Soil texture and associated soil physical factors played a more dominant role in growth than fertilization.

The adequacy of available soil N, P, K, and Ca was indicated by the small growth response to fertilization.

Foliar analyses indicated only a slight deficiency of available N, P, K, or Ca.

Seedlings in soil inoculated with organic material from a yellow-poplar stand grew no better than those in uninoculated soil. There was no evidence of the formation of mycorrhizae. It is suggested that this result may be due to the use of inoculum in which the fungi were not active; and hence, did not invade the seedling roots.

The main findings of this study are that a solution nutrient concentration of a single varied element can be identified for maximum growth. Foliar nutrient concentration is correlated with solution nutrient concentration. Therefore, a foliar nutrient concentration can be identified which coincides with maximum growth. However, maximum growth values determined separately in the N, P, K, and Ca series differ by as much as seventy percent. This appears to be caused by the strong ion antagonism between N, P, K, and Ca. This antagonism is reflected in different foliar concentrations for elements which have the same solution concentration in two or more of the series.

It is, therefore, doubtful that foliar nutrient concentration derived from single element studies will be very useful as a standard for estimating the adequacy of soil nutrients. Apparently, there is a range of foliar percentage combinations of elements that are correlated with essentially the same amount of growth.

MINERAL NUTRITION OF YELLOW-POPLAR (LIRIODENDRON TULIPIFERA L.)

By

Raymond Francis Finn

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CHAPTER I

INTRODUCTION

Inorganic nutrition of forest tree species in the
States has reached a level of practical importance
nitant with the advent of the intensification of
practices which evolved during the past decade or

This is a result of the recognition by foresters
oils may not have a sufficient supply of some of the
ial inorganic nutrients to meet the tree's require-
for satisfactory growth and development. Foresters
ecognize that application of inorganic fertilizers to
nutrient deficiencies in plantations is a practical
l practice. It is now commonplace to fertilize hard-
antations. In the West a large timber company re-
fertilized thousands of acres of coniferous plan-
; and in the South, pulp companies are fertilizing
creages of planted cottonwood. Europeans have
ed forest fertilization for many decades. Efficient
ective fertilization of hardwood plantations is
ly important, since many hardwood species are in
pply. They often are planted on sites which may
kedly in their capacity to supply all the essential

ients in amounts required for the fastest growth and
elopment.

The major problem of efficient and effective ferti-
tion is the determination of the kind and amount of
ilizers to apply to achieve the maximum growth response
a particular species on a specific site. This entails
iled knowledge of the tree's ability to absorb and
ize nutrients from the soil. Field fertilizer studies
ucted on an emperical basis have yielded very little
rmation on the nutrient requirements of forest tree
ies.

Soil factors that affect the growth and development
rees exert their influence through interactions with
other and with the tree. Therefore, it is extremely
cult, if not impossible, to isolate the independent
t of a single soil factor on the growth of a tree.
his reason, field fertilization trials have yielded
fundamental information on the nutrient requirements
est tree species. It is important, however, to know
dependent effect of single soil factors before inter-
effects can be clearly understood.

An approach to the solution of the nutrition problem
grow seedlings under uniform environmental conditions.
dlings are grown on chemically inert quartz sand.
t solutions are prepared, using distilled water,
ntain all the essential elements at fixed, non-
; concentrations except the concentration of the

ent under study. The concentration of the element
study is varied from deficiency levels to concen-
ions beyond the optimum level where growth is depressed.
these data it is possible to describe the mathematical
ionship between yield and the concentration of the
d element.

This relationship cannot be used directly for inter-
ng the nutrient status of field-grown seedlings or
because the concentration of available soil nutrients
be determined directly.

Available soil nutrient concentrations can be esti-
by analyzing the leaves of soil-grown seedlings.
results can then be compared to foliar nutrient con-
tions obtained from the controlled experiments. The
ve quantitative availabilities can then be employed
dict the probable growth response to fertilization.

In 1959 and 1960, investigations were started to
he nitrogen, phosphorus, potassium, and calcium
on of yellow-poplar seedlings. Specifically, the
were designed to: (1) determine the relationship
yield and nutrient concentration; (2) determine
ationship between nutrient concentration and foliar
concentration; (3) induce nutrient deficiency
at low nutrient concentrations; (4) determine the
ship between yield and fertilized representative
ndy-loam, and clay-loam soils; and (5) determine
ct of mycorrhizae on yield and nutrient uptake.

Yellow-poplar was selected for study because it is
mportant timber species distributed over a large geo-
hical area, and is one of the most widely planted tree
ies. The wood is in demand for furniture, doors,
ow sashes, and musical instruments. The root system
sually deep and profusely branched. Fertility seems
e an important factor in the growth of this species,
g classified by Mitchell and Chandler (1939) as a
rogen-demanding" species. The specific nutrient re-
ements of yellow-poplar have not been determined. This
rmation is required for evaluating the adequacy of soil
ent availability required for satisfactory growth and
opment.

CHAPTER II

STATEMENT AND SCOPE OF THE PROBLEM

Mineral nutrition of forest tree species is receiving sed attention from foresters. In the past, their s were concentrated on coniferous species almost to clusion of hardwood species. The increasing impor- of hardwoods in the forest economy has focused at- on the need for information that will assist land s to grow quality trees on the shortest rotation e. Adequate nutrition of the growing trees is a equisite for satisfactory growth and development. tudies have shown that yellow-poplar, a very im- timber species, grows best on well-drained, moist lth a thick upper organic-enriched mineral horizon 1945). McCarthy (1933), however, states that, "the e of chemical composition of the soil on growth of oplar is apparently slight." Mitchell (1939), (1933), Finn (1953), and Finn and White (1966) hat the chemical composition of the soil has a ignificant effect on the growth of yellow-poplar. llow-poplar is planted on a wide variety of sites e of the most important hardwood species used in tion and afforestation. Consequently, a knowledge

s nutrient requirements would greatly aid the forest
nd manager in selecting sites best suited to the
ent requirements of the species.

Nitrogen, phosphorus, potassium, and calcium are the
nts most likely to be deficient on sites planted with
w-poplar. This study was designed to investigate the
K, and Ca requirements of yellow-poplar in sand-
ent culture medium and to describe induced foliar
iency symptoms. It was also designed to study the
t of N, P, K, and Ca fertilizers on yellow-poplar
ings planted in pots containing sand, sandy-loam, and
loam soil. And lastly, the study included an investi-
n to determine the effect of mycorrhizae on the growth
llow-poplar seedlings planted in two forest soils.

CHAPTER III

REVIEW OF LITERATURE

General

Forest tree nutrition was ignored by most foresters
United States until the third decade of this cen-
About this time, a small group of foresters with
ng in soils and physiology initiated studies de-
to increase knowledge of the nutrient needs of
s species, factors that affect mineral nutrition of
trees, and methods of diagnosing nutrient require-

The Harvard Forest symposium on forest tree physi-
n 1957 summarized the work to that date and it was
ed in book form by the editor, Thimann (1957). The
ricultural Station (1957) sponsored a symposium
n the same year which covered the important topics
ral translocation in forest trees, mineral nutrient
ment of forest trees, techniques and analyses of
issue, mycorrhizae and light.
her important summaries of work on mineral nutrition
t trees were provided by Leyton (1958), Duke Uni-
(1959) symposium and by Gessel (1962).

Kozlowski (1956) edited a bibliography of forest tree
ology, and White and Leaf (1956) compiled a complete
bibliography with abstracts on the use of fertilizers
mendments in forestry. A compilation of the general
iques of using solution and sand culture methods in
tion studies was provided by Hewitt (1952).

Most of the work on the mineral nutrition of forest
species has been directed toward conifers and this
as been ably documented in a voluminous literature.
latively few studies that have dealt with hardwood
s will be the subject of review in the following
sions.

Site-Fertility

Fertility is one of the important factors of site
it exerts a profound influence on growth and develop-
However, it is only one of a host of factors.
and White (1956) have emphasized the necessity
idering all site factors and to identify those
dominant influence. Some factors like physiography
perature cannot be manipulated; but others including
soil moisture, and fertility can be changed by
thinning, irrigation, or fertilization (Kramer and
ki, 1960; Mitchell and Chandler, 1939; Rudolph,

rowth is a complex process that results from the
ted interaction effects of environment and genetic

tial. Growth probably never reaches the maximum set
e limit of genetic potential. One or more factors
always be limiting. This is so, because the numerous
ndent factors would all have to be at optimum in
ation with each other, which is unlikely. For ex-
using N, P, K, and Ca at five levels in all combi-
s, 4^5 (1024) combinations would be required to
ish an optimum concentration of these elements in
ation.

The response that can be expected when the deficiency
limiting factor is corrected is given by Mitscherlich
statement, "the increase in a crop produced by a
crement of a deficiency factor is proportional to
rement of that factor from the maximum" (Bray, 1954).
whenever a factor approaches a minimum its relative
becomes very great (Spurr, 1964).

Field Fertilization of Hardwoods

rly foresters generally emphasized the role of water
growth to the almost total exclusion of nutrients as
tant factor in site quality (Wilde, 1958). Many
s were convinced that sufficient nutrients were
in all soils for satisfactory growth. This belief
changed by numerous field fertilizer trials which
onstrated an increase in growth of trees following
tion.

In Iowa, McComb (1940) fertilized seedling black
and green ash growing on an acid, infertile glacial
Neither species responded much to nitrogen, but the
se to phosphorus was "tremendous." Denuyl (1944)
btained a marked increase in height of black locust
ng application of a complete fertilizer (2-12-6) at
e of one tablespoon per tree. First year response
ow-poplar seedlings on a Georgia stream bottom was
rked (McAlpine,1959). The increased height growth
e of yellow-poplar to phosphorus fertilization con-
through the fourth year. Yellow-poplar in south-
Michigan growing on a light soil and showing nutri-
iciency symptoms responded to fertilization signifi-
in increased height and diameter growth. Increased
rate was still evident at the last measurement which
d at the end of five growing seasons (Finn and White,

ny species of hardwood trees in New York increased
growth following an application of nitrogen ferti-
Mitchell and Chandler, 1939).
nt (1947) fertilized several species of coniferous
woods. The growth of pine, spruces, and red oak
ersely affected by lime, but sugar maple and white
benefitted by it. Hybrid poplar growth response
gen and to lime was highly significant. Chapman
und a delay of one year in height growth response
-poplar to nitrogen fertilizer. He also found

he greatest height growth response resulted from
40 and 100 pound applications of nitrogen. Hannah
nke (1964) concluded from soil pot studies in south-
liana that phosphorus may be one factor limiting
of planted hardwoods on abandoned old fields.
cComb (1949) grew seedling green ash, American elm,
, and black locust in gray-brown podzolic forest
and prairie Clarion, Tama, and O'Neill soils.
as a marked differential growth response by species
ilizers. Black locust did not respond to nitrogen
zation, but did respond to phosphorus fertilization.
C horizon soil with residual total nitrogen at 600
per acre, the response of American elm to added nitro-
acre responses were small or nil. Phosphorus was
be consistently and significantly deficient on
soil only. On O'Neill soil, red oak showed a marked
wth response to phosphorus fertilization. Potassium
deficient on O'Neill or Clarion soils.
d oak was the only species with ectotrophic mycor-
nd was least tolerant to high soil pH. Green ash
most tolerant of the four species to alkaline soil.
e examples that have been cited indicate that some
e deficient in one or more inorganic nutrient ele-
lative to a particular species.
neral coverage of the practical aspects of forest
ilization have been provided among others by
1959), Mayer-Krapoll (1956), and Wilde (1958, 1961).

Plots containing a mixture of red oak and red maple
ertilized with rock phosphate. The results showed
remely high correlation between rate of fertilization
liar concentration. However, the phosphorus concen-
n of the maple leaves was 100 per cent greater than
osphorus concentration of the red oak leaves (Mitchell
n, 1935).

The mineral composition of leaves may be influenced
cent stands (Schomaker and Rudolph, 1964). An adja-
xed hardwood stand contributed litter higher in
ts than the litter found on an area of poor growth.
rients from the contributed litter resulted in
nutrient content of the leaves of yellow-poplar grow-
re the litter from the adjacent stand was deposited.
ner nutrient content of the yellow-poplar leaves was
ed with greater diameter and height growth (Scho-
d Rudolph, 1964). Black locust may favorably affect
th of associated species by increasing soil nitrogen.
oplar, black walnut, and black cherry in mixture
ck locust had higher foliar nitrogen concentrations
n grown without black locust. The trees planted in
with black locust also grew faster in diameter and
han trees without black locust (Finn, 1953).

Other Effects of Fertilization

rtilization may affect plant processes other than
Increased seed production by beech and basswood

chieved by applying basalt or diabase rock dusts to
reduced in productivity as a result of degradation
c,1956).

Agricultural workers protect alfalfa against frost
e by applying potassium fertilizer. Yellow-poplar
s in southwestern Michigan suffered less mortality
frost damage during a hard freeze in May when foliar
ntrations of potassium were relatively high (White and
1964). Six coniferous species and two hardwood species
in sand cultures containing no potassium and in solu-
containing potassium were exposed to low temperatures.
pecies except one showed more cold resistance with
amounts of potassium in the nutrient solution. High
c pressure was related to the supply of large amounts
Sato and Muto,1951). Jack pine seedlings grown under
imum nitrogen supply of 200-250 ppm were as drought
ant as seedlings growing in a soil deficient in nitro-
However, increasing the supply of nitrogen above the
n level resulted in lower drought resistance (Bensend,

In northern Wisconsin, Kopitke (1941) grew white and
ruce, and white pine seedlings in quartz sand cultures
sandy nursery soils. Application of potash ferti-
promoted the accumulation of simple and invert sugar
seedling tissue, increased total solid content and
pressure, and lowered the freezing point of the ex-
sap. These changes indicate a marked improvement

ability of nursery or planting stock to withstand
injury.

Loblolly pine fertilized with nitrogen showed an in-
in height and diameter growth, a decrease in wood
, decrease in proportion of summerwood, decrease in
wall thickness and fiber length and no change in
width. These changes are beneficial for some pro-
nd detrimental for others (Posey, 1965).

pH and Nutrients

ilde (1954) supports Aslander's (1952) contention
n the presence of a sufficient supply of available
ts the concentration of H ions in the soil is of
mportance to the growth of plants. Examples are
f acidophile plants, Tsuga, (Abies balsamea (L.)
(Picea mariana (Mill.) B.S.P.), and basophile
yellow-poplar, and Platanus spp., which in suitable
ients grow well on alkaline (pH 7.3-8.0) and strongly
4.6) soils respectively. Auten (1945) found no
between yellow-poplar site index and pH for any
within the range of conditions encountered in his

study in Iowa evaluated the effect of soil acidity
ients on the growth of one-year-old black locust
n ash. Four acidity levels were maintained: 4.3,
7.7, and three fertility treatments: no nitrogen,
and potassium, nitrogen, phorphorus, and potassium.

end of five months, seedlings of both species grew
regardless of pH when no fertilizer was added. Both
s showed a tremendous response to NPK fertilizer at
levels and no response to nitrogen or potassium indi-
that phosphorus was most limiting. Both species grew
pH 4.3 when phosphorus was added and growth decreased
alues increased. When phosphorus was omitted growth
species increased up to pH 6.9 but decreased at pH
reen ash developed almost as well at the alkaline pH
ther pH levels but black locust grew poorly at pH 7.7.
and Kapel (1942) interpreted the results largely in
phosphate availability. The fact that best growth
at pH 4.3 is attributed to the relatively high base
on and the apparently adequate quantities of indi-
important bases.

Residual Effect of Fertilizers

number of fertilized plots in the Black Rock Forest,
were resampled four to five years after fertilizer
s were applied. The leaf samples were analyzed for
phosphorus, or potassium. The following results
rved: (1) plots fertilized with sodium nitrate-
sulphate showed a significant decrease in available
(2) plots fertilized with an organic fertilizer
od) showed a significant increase in available
(3) rock phosphate plots, a decrease in available
; and (4) potassium availability increased slightly

ots fertilized with potassium chloride (Finn, 1942).
and Finn (1966) found the residual effect of ferti-
on growth of yellow-poplar to be evident five years
application. Although the effect was decreasing, it
ly would continue for an additional number of years.
fect of fertilizer on growth of a mixed plantation of
nd hardwoods in Belgium was still apparent forty years
the fertilizer was applied (Delevoy, 1946).

Soil Moisture and Nutrients

lice (1944) found little correlation between mineral
by twenty tree species and precipitation as such, but
uptake was correlated with ground water table.
oisture withdrawal was found by Smika et al. (1961)
ease at all soil depths with the addition of ammonium
fertilizers to range soils. Moisture extraction was
ly correlated with fertilization rates. Early re-
dicated that fertilization stimulated root growth
ture use in the subsoil. Eck and Fanning (1961)
the uptake of nitrogen and phosphorus in relation to
placement under different soil moisture regimes.
y conditions uptake of phosphorus ceased when the
ched the vicinity of the wilting point but nitrogen
parently continued. Nitrogen absorption increased
h of placement under dry conditions. On the wet
hosphorus increased with depth of placement; hence,

increasing soil moisture. Nitrogen uptake was not
ted by depth of placement under this moisture condition.
Varying moisture, under laboratory conditions, from
to one hundred percent of the moisture equivalent
ound by Burns and Barber (1961) to have no effect on
elease of non-exchangeable potassium except in one
The higher the temperature the greater was the rate
lease of non-exchangeable potassium. Hacskaylo (1960)
igated the water requirements of white pine, black
, and sweet gum. He defined water requirement as the
e amount of water taken up by plants in any given
, per gram weight of dry matter produced. He found
enerally, mineral deficient trees require more water
it dry weight produced that non-deficient trees. The
of efficiency in water utilization was black locust,
gum, and white pine. Water requirements were different
es with different nutrient deficiencies. For example,
er requirements for the "complete" series and -P, -K,
o, and -S series were similar. The remaining series,
, -Mg, -Fe, -B, -Zn, and -Mn all had higher water
ments than the other series. The water requirement
"complete" series was 368.25 ml. and 596.00 ml. for
series.

Light and Nutrients

e relationship between nutrient requirements and
tensity of American ash was investigated by

bauer (1932). He concluded that if the supply of nutri-
was sufficient to satisfy the needs of the plant, the
um light requirement was not lowered by increasing the
ent supply. However, positive growth response to in-
ed concentration of nutrients could be obtained at
light intensities.

Interactions Among Nutrients

Seedling growth of Sugi in relation to different concen-
ns of potassium applied in combination with nitrogen,
orus, and calcium was investigated by Furukawa (1963).
rmal seedling growth he concluded that a potassium
tration above 100 ppm was necessary. Nitrogen and
orus uptake were depressed as the uptake of potassium
seedlings increased.

Ingestad's (1962) work on the nutrition of pine, spruce,
rch is very complete and includes comments on ion anta-
In birch, he found ion antagonism effects of NH_4 on
, magnesium, and potassium. He also found potassium
listic to calcium and magnesium especially in birch.
was antagonistic to magnesium in pine and spruce and
gnesium to potassium and calcium. However, the vari-
in the percentages of the unvaried affected elements
ally small according to Ingestad. Interactions be-
he uptake of nitrogen, phosphorus, and potassium were
d by Finn and White (1966) in a plantation yellow-
fertilization study. The data indicate that an

ase of soil nitrogen increases phosphorus uptake and
a large increase in soil potassium decreases nitrogen
e. A small increase in soil potassium increases nit-
uptake. It was also apparent that the interaction
t on growth of the nutrients applied in combination
ifferent in some instances from the additive effects
e elements applied singly.

Mycorrhizae-Hardwoods

Much attention has been given to the mycorrhizae re-
ship in coniferous species for the past forty years,
e importance of this relationship in the nutrition of
rous species has been demonstrated in many studies.
(1936), Mitchell et al. (1937), Kessel (1927), McComb
, Rayner and Neilson-Jones (1944), Bjorkman (1942),
s (1958), and many others have contributed to the know-
of the function and mechanism of mycorrhizae in the
l nutrition of conifers. Almost without exception,
s recognized that the mycorrhizal relationship benefits
e, and that their presence usually results in in-
growth.

ardwood tree species have received relatively little
on; and consequently, the mechanism and function of
izae in hardwood species is uncertain. The few
that have been conducted on hardwood mycorrhizae
the most part only preliminary. Some mention of

rhizae in relation to hardwoods is made by Henry (1932), gall (1914), McComb (1949), Trappe (1962), Dominik).

Clark (1964) grew yellow-poplar in pots containing rom adjacent areas with different vegetative covers. ils were sterilized with methyl bromide and some were lated" with plugs of soil from a forested area. He that seedlings in the sterilized soil were consistently r than seedlings grown in the inoculated soil. Micro- sections of the roots of seedlings growing in the ated soil showed that the roots contained endotrophic izae, while those from the sterilized soil were non- izal. Moose (1957) working with cuttings from apple howed cuttings infected with an endotroph were ly larger than uninfected cuttings.

n New Zealand the roots of a species of Cornaceae in- ted by Baylis (1959) exhibited endotrophic mycorrhizae. gs with mycorrhizal roots were larger after one to rs than non-mycorrhizal seedlings grown in sterilized

minik (1958) identified the type or types of mycor- ound on a number of species of hardwoods occurring e natural vegetation growing on a slag heap in and describes the anatomy of the mycorrhizae. e present state of knowledge of hardwood mycotrophy fficiently advanced to provide definitive answers portant problems, but the available evidence seems

indicate that endrotrophic, like ectotrophic mycorrhizae,
rt a positive effect on growth and probably on nutrient
ake.

Evaluation of Soil Fertility

. Analyses

The various methods that have been used to obtain a
ure of soil fertility have been summarized and described
itchell (1934). Direct chemical analyses of the soil or
extract, as well as indirect biological methods, have
employed to obtain a measure of soil fertility. The
ogical method consists of growing plants in a soil for
rtain period, and then using the weight of the plants or
nutrient content as an index of soil fertility.
Direct chemical analyses of the soil occassionally are
factory for an element; but the results for nitrogen
enerally inconsistent in relation to nitrogen values
termined by the biological method. However, some other
tigators including Gessel (1962), Wilde and Patzer
) have attempted to use direct soil chemical analyses
aluate soil fertility. Schomaker (1964), studying
-poplar in Michigan, concluded that soil analyses
ot suitable for evaluating soil fertility. He did
correlation between growth and phosphorus content
subsoil, but no correlation with growth was found
il nitrogen and potassium. Heiberg and White (1951)
ed soil and foliar analyses successfully to identify

assium deficiency and to use the information in pre-
ing a treatment for its correction. The deficiency
red in young coniferous plantations on sandy soils in
ern New York. Strong correlations were found between
r potassium and growth response and between soil and
r content of potassium. Positive relationships between
r nitrogen, soil nitrogen supply, and growth were de-
ed by Mitchell and Chandler (1939) for a number of
ood species in New York.

The principal reasons why direct chemical analyses of
il are generally unsatisfactory for estimating soil
ity is the failure of chemical extraction methods to
tely duplicate the tree's nutrient extractive mechan-
and to the complexity introduced into nutrient ab-
on in the presence of mycorrhizae.

Soil analyses are a useful adjunct to foliar analyses
ermining whether deficiencies are due to a lack of
ment in the soil or to unavailability resulting from
sence as an insoluble compound or in being fixed or
within the space lattices of the clay crystal.

Analyses

oliar analyses have been used successfully by many
in the field of plant nutrition. Mitchell (1936)
foliar analyses in studies on the nutritional
f forest tree species. Kenworthy (1950) adapted
od for diagnosing nutrient-element problems in

uit trees. Goodall and Gregory (1947) reviewed the
erature on this subject and indicated the nutrient
ncentrations associated with plants showing symptoms of
iciency or excess.

This method of assessing soil fertility has been adopted
r the relatively simpler and more direct soil analyses
hods because foliar concentrations indicate the level of
ilability of soil nutrients with greater precision and
lability than soil analyses do. Since nutrients in the
ves have been extracted from the soil by the roots, it is
ical that no other method of extracting soil nutrients can
tly duplicate the extractive action of the roots. Also,
ient uptake in roots is dependent on active transport,
h involves an expenditure of energy by the plant as well
n purely surface physical phenomenon and other physical
es. Many workers have shown that the foliar concentration
lements is a good indicator of the level of availability
ne elements in the soil. However, the chemical compo-
on of the leaves varies with a number of factors, in-
ng their position in the crown, physiological age of
eaves, incidence of insect or disease damage to the
s, species of plant, availability and concentration of
lements in the soil.

Leaf sampling can be standardized to hold most of
factors constant. This standardization permits mean-
l comparisons to be made of foliar nutrient concen-
ons obtained through use of foliar analyses.

ntially, foliar analyses are used to evaluate the level
vailability and concentration of soil nutrients. This
be done when leaf sampling is standardized.

Foliar analyses have been used by many workers to
te abnormal leaf color to nutrient deficiencies. For
ple, Fowells and Krauss (1959) nitrogen deficiency
oms; Mitchell and Chandler (1939) phosphorus deficiency
oms; Lunt (1947) calcium deficiency symptoms; Stone
) magnesium deficiency symptoms; Wallace (1961) em-
d tissue analyses and color photographs to relate ab-
l leaf color to nutrient deficiencies occurring in
cultivated plants, including some fruit trees. Ashby
) described induced nutrient deficiency symptoms in
ood (Tilia americana L.).

Mitchell and Chanler (1939) found a high degree of
ation between the nitrogen concentration of yellow-
leaves and nitrogen supply. Also, the leaves of
-poplar from trees receiving high nitrogen supply
econd only to basswood in nitrogen concentration.
ound that an increase of 180 pounds in the nitrogen
resulted in a 250 per cent increase in radial incre-
and that the radial increment increase was linear.
oncluded that a further increase in nitrogen supply
robably result in still greater radial growth rates.

CHAPTER IV

METHODS AND PROCEDURES

Sand Culture Experiments

iners and Sand

A sand nutrient culture technique was employed to the effect on growth of varying the nitrogen, phospho- potassium, and calcium solution concentration. The ntration of each of the four elements was varied ately. The concentration of all other elements, ex- he one being varied, was maintained at a fixed con- ation. The sand nutrient culture technique was used dy the visible foliar deficiency symptoms. The ms were induced by omitting nitrogen, phosphorus, ium, and calcium singly and in combination from a complete nutrient solution. For the first study, allon glazed crocks were used. These contained 10 of quartz gravel (1/8"-1/4") and 35 pounds of Ottawa silica sand. A one-inch glass tube extended from the the gravel through the fine sand to one-inch above nd in the crock. A one-gallon glass amber jug was ed by a rubber tube to the crock at a drain hole ove the bottom of the crock. Solution was applied

the crocks by pouring the jug solution into the glass
es. After pouring, a pinch clamp on the rubber hose
released and the solution was allowed to drain back
o the jug. The same procedure was used in the deficiency
eriment, except that three-gallon crocks were used con-
ning 7.5 pounds of quartz gravel and 26.25 pounds of
wa white silica sand.

ure Solution

The basic nutrient solution in the growth study con-
ed of the following elements with the concentration
essed as parts per million: nitrogen 300, phosphorus
potassium 319, calcium 364, sulfur 232, iron 3.4,
esium 176, boron 0.5, manganese 0.5. Nitrogen, phospho-
potassium, and calcium concentrations were varied
ly in separate studies. Six liters of the appropriate
tion were added to each pot to saturate the sand, after
the pinch clamp was released allowing the solution to
into the reservoir jug. After complete drainage, the
ion level in the reservoir jug was permanently marked
line. To replace water lost by evapo-transpiration,
lled water was added to bring the level of the solution
e line on the jug. This procedure maintained the concen-
on at a constant strength. Solutions in the growth study
changed twice during the course of the investigation to
ce nutrients absorbed by the seedlings.

Figure 1.--General view of the fertilizer and sand nutrient culture experiments (August 5, 1960).

Figure 2.--The arrangement of pots and nutrient reservoir glass jugs used in the sand-culture nutrient studies. Jugs are below the bench. Solutions were hand-poured through the glass tubes shown in the middle of the pots.

The concentrations of the nutrient solutions were dually increased over several weeks until full strength reached in order to avoid too rapid a change in concention with consequent injury to the seedlings.

The basic procedure of adding nutrients to pots in deficiency study was the same as that used in the growth dy. However, only five liters of solution were applied the deficiency study because the crocks (3 gals.) were ller than those used in the growth study. Smaller crocks e used because they were just as suitable as the larger cks for inducing deficiency symptoms, and required less erials and solution. The concentrations of the elements in the deficiency study were as follows: nitrogen and phorus 300 ppm, potassium and calcium 200 ppm, sulfur ppm, magnesium 176 ppm, iron 3.7 ppm, boron 0.5 ppm, anese 0.5 ppm. The concentrations stated are for the ents, not their salts.

lings

All seedlings used in the four experiments conducted 960 were essentially the same. Seed was collected from ld growth stand on Michigan State University's Russ st in southwestern Michigan in the fall of 1959. The was stored moist in polyethylene bags on February 1, at 40° F. The seed was planted on April 5, in 18 containing brick sand to a depth of 1/4- to 1/2-inch,

d covered with burlap and subsequently kept moist with
stilled water. First germination occurred on April 25.

Seedlings planted in each study were straight, approxi-
ely the same length, having one or two secondary leaves,
one to four lateral roots.

In the growth experiment, the seedlings were planted
the pots on May 18 and 19. Seedlings were planted in
deficiency experiment on May 19, in the fertilizer
eriment on June 9 and 10, and in the mycorrhizae experi-
t on July 26.

The seedlings used in the 1959 deficiency experiment
e collected from the same source as those used in the
) experiment, but were sowed in the fall of 1958, in
Bogue Nursery. They were lifted from the nursery and
ted in the pots on July 22, 1959. At the time of plant-
they were six weeks old and partially leafed out.

Soil Experiments

All soil used in the fertilizer and mycorrhizae experi-
s was obtained from Michigan State University's experi-
al forests. The Spinks sand and Conover sandy-loam were
urred from the Baker Woodlot near the main campus on June
the Bellfontaine clay-loam (B horizon) was collected
the Kellogg Forest. Some chemical and physical charac-
tics of these soils are shown in Appendix B.

These soils were chosen because yellow-poplar is idely planted on these and similar soils. The soils hosen for this experiment provide a range in texture from and to clay-loam and are expected to vary in fertility. ney were studied to learn if increasing certain soil nutri- nts would stimulate growth. The response would then be sed as a measure of the adequacy of the level of the supply f available nitrogen, phosphorus, potassium, and calcium.

The three soils were used in the fertilizer experiment t only the Spinks sand and Conover sandy-loam were used in e mycorrhizae study.

Each soil was thoroughly mixed before placing it in s container. The soil was placed in polyethylene bags d the bags were then placed in metal cans 9 1/2-inches in ameter and 12 1/2-inches tall.

rtilizers

Fertilizers applied in the soil experiment were reagent ade chemicals. Nitrogen was added as sodium nitrate, osphorus as phosphoric acid (H_3PO_4), potassium as potassium loride (KCl), and calcium as calcium chloride ($CaCl_2.6H_2O$). e appropriate amounts were dissolved in distilled water and e resulting solution was added to the pots as a single plication. No more additions were made during the experi- nt.

oculum and Sterilization

The inoculum for the mycorrhizae experiment was col-
ted on July 25, from the soil beneath a 12- to 15-inch
yellow-poplar growing in the Baker Woodlot. The inocu-
consisted of soil collected from six sample points from
upper six-inches of the A horizon. The soil from the
points was composited, placed in a polyethylene bag, and
t moist at room temperature.

One-half of the inoculum material was steam autoclaved
three hours at 15 psi and one-half of the soil was auto-
ved at 11 psi for eight hours.

The soil was placed in polyethylene bags which were
placed in #10 cans (6" dia. x 7" tall).

Inoculum, either sterilized or non-sterilized, was
d to the cans designated to receive this treatment by
ving a plug of soil approximately one-inch by five-inches
replacing the removed soil by a like plug of inoculum
rial.

Soil moisture in both the fertilizer and mycorrhizae
riments was maintained approximately at field capacity
dding distilled water to replace water losses.

Harvesting

Seedlings in the sand-nutrient culture experiment
harvested at the end of the first growing season be-
August 29 and September 8 and seedlings from the de-
ency study between September 9 and 14. Those from the

ertilizer study were harvested between October 7 and 10, nd seedlings from the mycorrhizae study between October 3 and November 1.

Seedlings growing in sand culture were removed from ne pots and carefully washed with a minimum of water to emove adhering sand particles from the roots. The same rocedure was followed for seedlings growing in soil and corrhizae experiments. The seedlings were allowed to y until the rinse water had evaporated. Leaves, petioles, ems, and roots were then weighed separately to obtain esh weights. Following oven-drying at 70°C for twenty-ur hours, seedling parts were reweighed and their weights corded.

Chemical Analyses of Seedling Parts

The oven-dried leaf parts were ground in a Wiley mill d stored in stoppered glass bottles.

Nitrogen was determined by a modified Kjeldahl method. assium was extracted from the ground material and the assium percentage was determined on a Beckman Model B ctrophotometer. All other elements were analyzed spectro-phically. Details of the methods used are given in endix A.

Experimental Design and Statistical Analyses

The treatments in the four experiments were arranged n a randomized block design. Blocks were oriented north-outh on the greenhouse benches, which is in the direction f the short axis of the greenhouse.

Each treatment in the two sand-nutrient culture experi-ents were replicated three times, and each pot contained ive seedlings. The three tallest were used in computing pot otals. This was done because some seedlings were shorter an others, and were shaded by the faster growing seedlings. the shorter seedlings had been used, nutrient effects would ve been confounded with light effects.

Treatments in the fertilizer experiment were replicated ice, and in the mycorrhizal experiment three times. Four edlings were grown in each can of the fertilizer experiment, t only two seedlings were grown in each can of the mycor-izal experiment because of the smaller sized can used. All edlings in each can were used to compute the treatment mean nce the seedlings were approximately uniform and did not ertop one another.

All data were initially analyzed by analysis of vari-e if the mean treatment differences were great enough to tify this.

The sand-nutrient growth experiment data were further lyzed be regression methods. The percentage of the ele-t in the leaves, milligrams of the element per leaf,

ven-dried weight of stems, roots, and leaves and stem ength were the dependent variables and external nutrient oncentration of the varied element was the independent ariable.

The model used for regression was a second order olynomial as follows:

$$y = a_0 + a_1x + a_2x^2$$

Separate regression equations were calculated for ach dependent variable in each of the four varied element eries. Tests of significance were made for the slope co- fficients, lack of fit of the data to the curve, and cor- elation coefficients.

CHAPTER V

RESULTS AND DISCUSSION

Sand Culture Growth Experiment

trogen Series

The mean oven-dried weights of stems, roots, and aves were greatest at 300 ppm solution nitrogen concen- ation. The dry weight of stems was greater than the dry ight of roots. The stem-to-root ratios were markedly fferent only at the 800 ppm level. At the 800 ppm level e ratio decreased markedly (Table 1).

BLE 1.--Nitrogen series. Yellow-poplar seedling weights D) and stem/root ratios.

edling Part	Nitrogen solution concentration (ppm)				
	100	200	300	400	800
	grams				
em	3.2	5.2	6.1	3.5	1.5
ot	2.2	3.5	4.4	2.1	2.2
m + Root	5.4	8.7	10.5	5.6	3.7
ves	0.61	0.66	0.72	0.69	0.55
ioles	0.05	0.09	0.07	0.10	0.04
dling	6.06	9.44	11.29	6.39	4.29
	ratio				
m wt. / t wt.	1.45	1.48	1.39	1.67	0.68

Fresh weights of stems and roots were also greatest the 300 ppm nitrogen concentration. The fresh weight roots, in contrast to the dry weight of roots, was eater than the fresh weight of stems at all concentrations. esh weight of leaves was constant between the 100 and 300 m level, but decreased at the two higher nitrogen concen- ations. In general, petiole fresh weight decreased as trogen concentration increased. Stem-to-root ratios on fresh weight basis were not markedly different over the 0-400 ppm range, but were much less at the 800 ppm level able 2).

BLE 2.--Nitrogen series. Yellow-poplar seedling weights resh) and stem/root ratios.

edling Part	Nitrogen solution concentration (ppm)				
	100	200	300	400	800
	grams				
em	10.2	17.3	21.3	9.4	4.9
ot	16.1	30.2	42.1	15.8	18.1
em + Root	26.3	47.5	63.4	25.2	23.0
ives	2.9	2.9	2.9	2.5	2.0
ioles	0.35	0.39	0.33	0.31	0.29
edling	29.6	50.8	66.6	28.0	25.3
	ratio				
$\frac{\text{m wt.}}{\text{t wt.}}$	0.63	0.57	0.50	0.59	0.27

The primary criterion used for evaluating the re- nse to change in nitrogen solution concentration was dry

ight. However, other indicative measurements were also
ed to aid in evaluating the growth response. It was
und that branches per stem, number of leaves per seedling,
d the size of leaves were also at maximum values at 300
m nitrogen (Table 3, see page 39).

The percent moisture of the stems and roots on an
en-dried basis was greatest at a solution nitrogen concen-
ation of 300 ppm (Table 4).

BLE 4.--Nitrogen series. Moisture percentages of yellow-
plar stems, roots, and leaves.

Nitrogen ncentration	Stem	Roots	Leaves
ppm	------- percent (ODW basis) ---------		
100	219	632	375
200	233	763	339
300	249	857	303
400	168	652	262
800	227	723	264

Root moisture percentages increased as nitrogen con-
ıtration increased from 100 to 300 ppm. Leaf moisture
'centages generally decreased as the solution nitrogen
.centration increased.

Roots had the highest moisture percentages, followed
decreasing order by leaves and stems. Length of roots
petioles were not much affected by changes in nitrogen

TABLE 3.--Nitrogen series. Yellow-poplar stem diameters, size and number of leaves.

Nitrogen Solution Concentration	Stem Dia. G.L.	Branches Per Stem	Leaves				
			Mature	Immature	Mature + Immature	Mature Leaf Thickness	Size of Mature Leaves
ppm	mm	number	---- number per seedling ---			mm	index*
100	7.3	4.9	3.8	9.5	13.3	0.28	39.7
200	9.1	6.8	6.1	17.9	24.0	0.24	40.1
300	9.0	7.6	10.3	18.8	29.1	0.24	47.5
400	7.6	4.5	7.3	12.1	19.4	0.23	42.8
800	6.9	2.7	8.5	7.1	15.6	0.31	33.8

*Product of widest width and center length of the blade in inches.

concentration. Changes in solution nitrogen concentration markedly affected stem length, especially in the 400-800 ppm range (Table 5). In this range, a marked reduction in stem length was observed.

TABLE 5.--Nitrogen series. Length of yellow-poplar stems, roots, and petioles.

Seedling Part	Nitrogen solution concentration (ppm)				
	100	200	300	400	800
	inches				
Stem	18.0	22.7	21.6	15.3	8.3
Roots	10.4	10.6	12.8	10.5	10.5
Petioles	3.8	3.7	3.6	3.6	3.4

The various seedling parts were analyzed for N, P, K, Ca, and other elements (Tables 6 and 7). The analyses were made for the purpose of relating (1) external nitrogen concentration to foliar nitrogen concentration, and (2) to identify the foliar nitrogen concentrations associated with both positive and negative growth responses.

These analyses showed that nitrogen percent of leaves stems, roots, and petioles increased as solution nitrogen concentration increased. However, the nitrogen content of the seedling parts was greatest at 300 ppm. The distribution of the total quantity of nitrogen (525.3 mgms) in a seedling, at the 300 ppm level, on a percentage basis is: leaves 60.4,

TABLE 6.--Nitrogen series. Nitrogen percent and content of yellow-poplar leaves, stems, roots, and petioles.

Seedling Part	Nitrogen solution concentration (ppm)				
	100	200	300	400	800
	Nitrogen percent (ODW)				
Leaves[1]	3.42	4.21	4.28	4.30	5.02
Stems	0.83	1.01	1.18	1.44	2.45
Roots	1.79	2.73	2.93	2.69	4.77
Petioles[1]	0.92	1.07	1.06	1.11	2.05
	Nitrogen content per seedling part (mgms)				
Leaf[1]	20.9	27.8	30.8	29.7	27.6
Stem	26.6	52.6	72.0	50.4	36.8
Root	39.3	95.5	128.9	56.4	105.0
Petiole[1]	0.5	1.0	0.7	1.1	0.8
	Total nitrogen content (mgms)				
Leaves[1]	79.4	169.6	317.2	216.8	234.6
Stem	26.6	52.6	72.0	50.4	36.8
Root	39.3	95.5	128.9	56.4	105.0
Petioles[1]	1.9	6.1	7.2	8.1	6.8
Seedling	147.2	232.8	525.3	331.7	383.2

[1]Only mature leaves were analyzed for nitrogen. The contribution of the small immature leaves are not included in the above values but their weights were small and their omission does not materially affect the relative numerical values presented.

TABLE 7.--Nitrogen series. Mineral percent composition and content of yellow-poplar leaves (ODW).

Element	Nitrogen solution concentration (ppm)				
	100	200	300	400	800
			Percent		
N	3.42	4.21	4.28	4.30	5.02
K	2.04	1.94	1.41	1.64	1.38
P	0.61	0.62	0.52	0.62	0.55
Ca	1.39	1.45	1.55	1.08	1.11
Mg	0.49	0.55	0.56	0.37	0.38
			Parts per million		
Mn	39	44	48	35	57
Fe	76	89	143	109	157
Cu	15	15	15	13	12
B	7	10	9	8	14
Zn	35	41	37	48	28
Mo	6	6	6	5	4
Al	37	43	56	67	48
			Content (mgms per leaf)		
N	20.9	27.8	30.8	29.7	27.6
K	12.4	12.8	10.2	11.3	7.6
P	3.7	4.1	3.7	4.3	3.0
Ca	8.5	9.6	11.2	7.4	6.1
Mg	3.0	3.6	4.0	2.6	2.1
Mn	0.024	0.029	0.034	0.024	0.031
Fe	0.046	0.059	0.103	0.075	0.086
Cu	0.009	0.010	0.011	0.009	0.007
B	0.004	0.007	0.006	0.006	0.008
Zn	0.021	0.027	0.027	0.033	0.015
Mo	0.004	0.004	0.004	0.003	0.002
Al	0.022	0.028	0.040	0.046	0.026

roots 24.5, stems 13.7, and petioles 1.4 percent. The same relative distribution of the percentage of the total quantity of nitrogen in the seedling parts was observed at the other solution nitrogen concentrations. However, the percentage of the total quantity of nitrogen in the stems decreased as the solution nitrogen concentration increased, whereas in the leaves it generally increased.

The effect of varying nitrogen concentration on the uptake of elements maintained at a fixed concentration in the nutrient solution is shown in Table 7. Potassium uptake on a percentage basis is seen to generally decrease as nitrogen concentration increased. However, on a quantity per leaf basis a marked decrease occurred only at the 800 ppm level of nitrogen. Neither the percentage nor the quantity of foliar phosphorus was significantly affected by increasing nitrogen concentration. Maximum calcium, magnesium, and iron foliar content occurred at the 300 ppm level of nitrogen concentration. Calcium and magnesium followed the trend of foliar nitrogen content; but, their percentage compositions were maximum at 300 ppm solution nitrogen concentration. Foliar iron percent increased in the same fashion as foliar nitrogen percent.

The objective of this experiment was to determine the nitrogen concentration which would produce maximum growth expressed as seedling dry weight. For the nitrogen series, the 300 ppm concentration resulted in the apparent greatest weight of stems, roots, and leaves. Also, the number of

branches per seedling, number of leaves per seedling, and the size of leaves was greatest at this concentration. In addition, the leaves, roots, and stems of seedlings grown at 300 ppm nitrogen contained the greatest amount of nitrogen, calcium, magnesium, and iron. It appears that the effect of increasing the nitrogen concentration is reflected in increased production of photosynthate resulting from an increased number and size of leaves. However, the model for describing the relationship between dry weight of stems and roots and external nitrogen concentration had a 12 percent probability that these values would be different in a repetition of the experiment (Table 8). Nevertheless, the weight of evidence seems to indicate that the 300 ppm level of nitrogen concentration is at or near the level required to maximize growth under the conditions of this experiment.

The lack of statistical significance at the conventional probability level, for the relationship between weight of stems and roots and external nitrogen concentration is due to the generally large variability associated with the growth of hardwoods and to the lack of adequate replication. The model did describe the relationship between external nitrogen concentration and foliar percent nitrogen, foliar nitrogen content, stem length, and leaf weight.

The relationship between solution nitrogen concentration and foliar percent nitrogen was linear. Also, the relationship for foliar content of nitrogen and solution nitrogen concentration was curvilinear as expected because the weight

TABLE 8.--Nitrogen series. Correlation and regression.

	Foliar N	Foliar N	Stem Weight	Root Weight	Stem Length
	percent	mgms/leaf	grams	grams	inches
		Correlation coefficients			
Foliar N mgms	N.S.				
Stem weight	N.S.	+.579*			
Root weight	N.S.	+.623**	+.750**		
Stem length	N.S.	N.S.	+.947**	+.629**	
Leaf weight	N.S.	+.687**	+.671**	+.739**	+.652**

Regression equations

$$Y \text{ (Foliar N percent)} = 3.1702 + 0.4427X - 0.0291X^{2**}$$

$$Y \text{ (Foliar N mgms)} = 17.4607 + 5.6596X - 0.5654X^{2**}$$

$$Y \text{ (Stem weight)} = 2.8241 + 1.1990X - 0.1727X^{2}$$

$$Y \text{ (Root weight)} = 2.1463 + 0.6520X - 0.0823X^{2}$$

$$Y \text{ (Stem length)} = 19.4407 + 0.9029X - 0.2917X^{2*}$$

$$Y \text{ (Leaf weight)} = 537.6912 + 83.6172X - 10.2861X^{2*}$$

The independent variable (X) is solution nitrogen concentration in ppm. Regression coefficients are coded in units of 100 ppm.

*Indicates statistical significance at the 5 percent level of probability.

**Indicates statistical significance at the 1 percent level of probability.

N.S. A lack of statistical significance at the 5 or 1 percent level of probability.

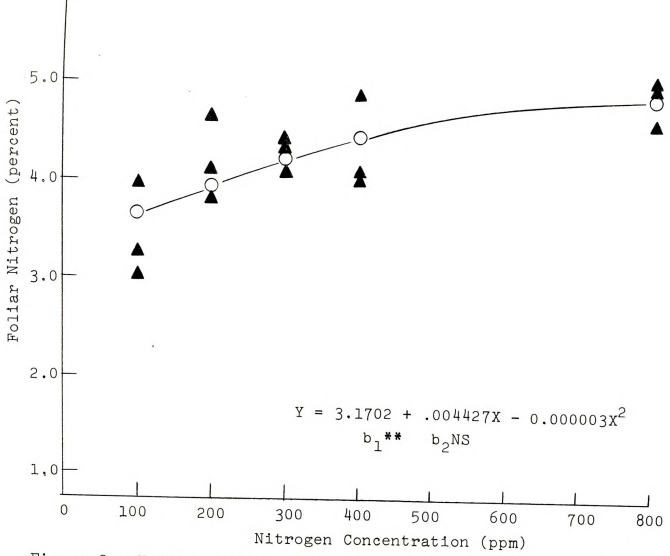

Figure 3.--Yellow-poplar growth experiment. Regression of foliar nitrogen percent on nitrogen solution concentration.

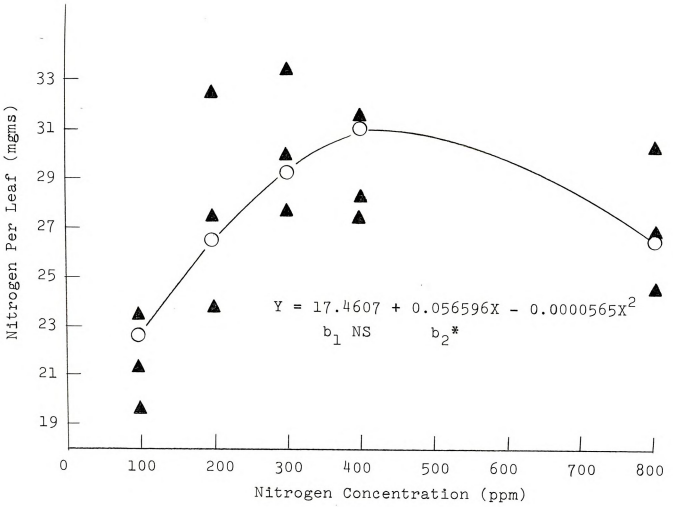

Figure 4.--Yellow-poplar growth experiment. Regression of foliar nitrogen content on nitrogen solution concentration.

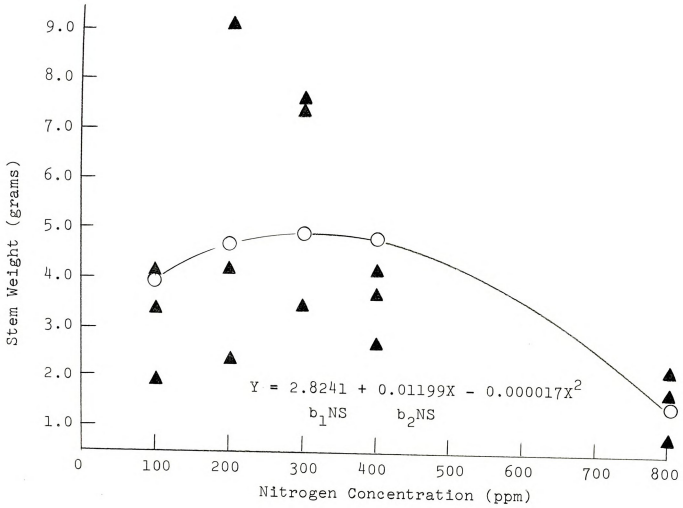

Fig. 5.--Yellow-poplar growth experiment. Regression of stem weight (OD) on nitrogen solution concentration.

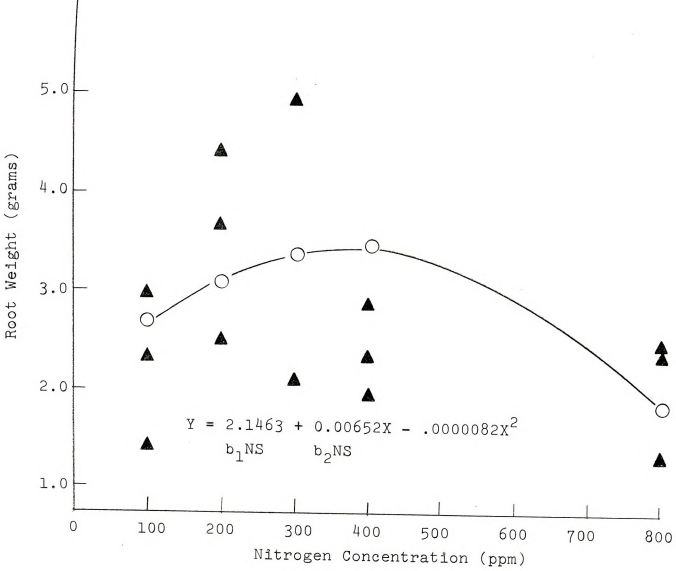

Figure 6.--Yellow-poplar growth experiment. Regression of root weight (OD) on nitrogen solution concentration.

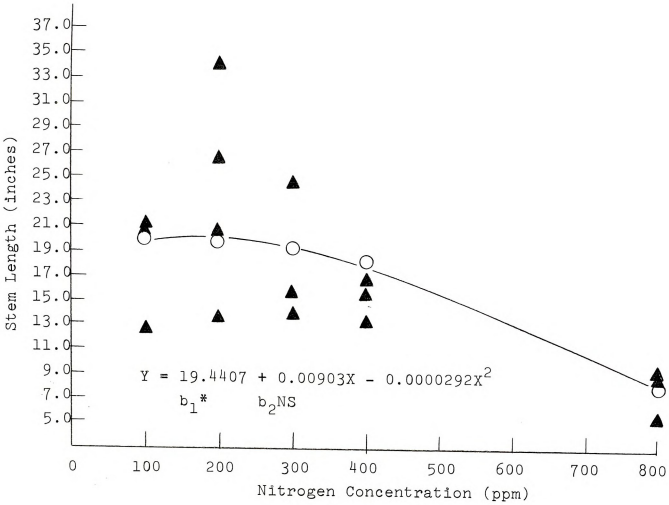

Figure 7.--Yellow-poplar growth experiment. Regression of stem length on nitrogen solution concentration.

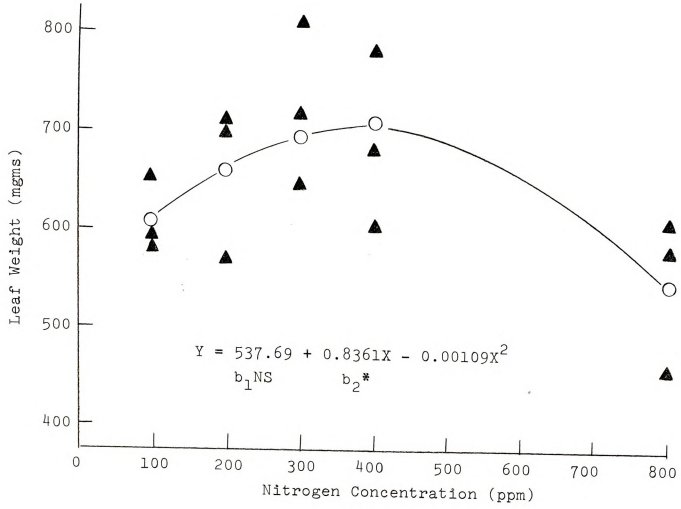

Figure 8.--Yellow-poplar growth experiment. Regression of leaf weight (OD) on nitrogen solution concentration.

of the leaves is less at concentrations of nitrogen higher and lower than 300 ppm. This is shown by the curvilinear relationship between weight of leaves and solution nitrogen concentration. There was a significant or highly significant correlation between foliar nitrogen content and stem weight, root weight, and leaf weight.

The effect of solution nitrogen concentration on the uptake of the elements not varied in this series in some cases is due to an actual increase and/or decrease in uptake of the element and to a dilution effect. The dilution effect resulting from increased growth without a corresponding increase in nutrient uptake, seems to indicate that foliar percentages alone are not truly indicative of the level of available nutrients. However, information on the foliar concentrations and content of all the nutrient elements, in conjunction with growth data, would provide a criterion for evaluating the level of available nutrients. But the question remains as to whether or not the results obtained is an artifact of the experimental methods and procedures used or is truly representative of the effect of nitrogen concentration per se on growth.

Phosphorus Series

The dry weights of stems and roots reached a maximum value at a phosphorus solution concentration of 50 ppm and decreased at higher concentrations. The dry weight of stems at all concentrations was greater than the dry weight of

roots. Petiole weights were the same over the entire range of concentrations. Leaf weights were about the same through the 200 ppm level, but were less at the 400 and 700 ppm concentrations.

Stem weight to root weight ratios showed a general increasing trend in relation to increasing phosphorus concentration. The percentage reduction in stem and root weights from the 50 ppm phosphorus level to the 700 ppm level was about the same, being 13.6 and 12.8 percent respectively. Hence, the adverse effect of the higher phosphorus level was to reduced stem and root weights proportionally. These data are shown in Table 9.

TABLE 9.--Phosphorus series. Yellow-poplar seedling weights (OD) and stem/root ratios.

Seedling Part	Phosphorus solution concentration (ppm)				
	50	100	200	400	700
	grams				
Stem	8.8	7.9	5.8	4.2	1.2
Root	6.2	6.1	4.0	2.7	0.8
Stem + Root	15.0	14.0	9.8	6.9	2.0
Leaves	1.0	1.0	1.0	0.8	0.4
Petioles	0.1	0.1	0.1	0.1	0.1
Seedling	16.1	15.1	10.9	7.8	2.5
	ratio				
$\frac{\text{Stem wt.}}{\text{Root wt.}}$	1.42	1.30	1.45	1.56	1.50

Figure 9.--Nitrogen series. Pots are arranged in order of increasing nitrogen concentration from left to right. Optimum growth (300 ppm N) pot fourth from left.

Figure 10.--Phosphorus series.--Pot arrangement same as in Figure 9. Optimum growth at 50 ppm second pot from left.

The fresh weights of stems, roots, and leaves decreased as the solution phosphorus concentration increased from 50 to 700 ppm (Table 10). The fresh weights of the roots were greater than the fresh weights of stems in contrast to the greater dry weight of stems than the dry weight of the roots. This difference is indicative of the greater succulence of the roots compared to the stems. Petiole fresh weights were constant except for a decrease at the 700 ppm level. However, there may be real differences in petiole weights at different phosphorus concentrations which were masked because weights were read to only the nearest 0.05 gram. The only noticeable change in fresh weight shoot-to-root ratios occurred at the highest phosphorus concentration, 700 ppm. At that level, the shoot/root ratio decreased markedly.

The moisture percentages of stems, roots, and leaves on an oven-dried weight basis are given in Table 11. The percentage moisture for the roots is greater than three times the moisture percentage of leaves and stems. There is no evident trend of variation in root moisture percentage with increasing solution phosphorus concentration. There is, however, a significant drop in moisture percentage of stems and leaves at the 700 ppm phosphorus concentration.

At 50 ppm phosphorus concentration, the number of branches per stem, number of leaves, both mature and immature, and size of mature leaves was greater than at other concentrations. Stem diameter for the 50 ppm phosphorus level

TABLE 10.--Phosphorus series. Yellow-poplar seedling weights (fresh) and stem/root ratios.

Seedling Part	Phosphorus solution concentration (ppm)				
	50	100	200	400	700
	grams				
Stem	30.4	27.3	19.9	12.9	2.8
Root	55.5	61.4	38.9	23.6	8.1
Stem + Root	85.9	88.7	58.8	36.5	10.9
Leaves	3.9	3.9	3.5	3.1	1.3
Petioles	0.4	0.4	0.4	0.4	0.2
Seedling	90.2	93.0	62.7	40.0	12.4
	ratio				
$\frac{\text{Stem wt.}}{\text{Root wt.}}$	0.55	0.44	0.51	0.55	0.34

TABLE 11.--Phosphorus series. Moisture percentages of yellow-poplar stems, roots, and leaves.

Seedling Part	Phosphorus solution concentration (ppm)				
	50	100	200	400	700
	percent (ODW basis)				
Stems	245	246	243	207	133
Roots	795	906	872	774	912
Leaves	290	290	250	288	225

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was slightly less than at the 100 ppm level. The stem diameters at the 50 and 100 ppm levels were greater than the diameters at higher phosphorus concentrations (Table 12).

While stem and root dry weights were greatest at 50 ppm phosphorus concentration, length of stems and roots was greatest at 100 ppm and 200 ppm respectively (Table 13). The size of leaves, however, was greatest at 50 ppm of solution phosphorus.

The distribution of phosphorus in the seedling parts is given in Table 14. Roots had the highest, and petioles the next highest percent phosphorus. The percent phosphorus of leaves and stems was essentially the same except at the highest phosphorus solution concentration. At the highest phosphorus concentration foliar percent phosphorus was much higher than for stems and equal to that of roots. Of the total quantity of phosphorus in a seedling, the roots contained the largest amount followed in order by stems, leaves, and petioles.

The percent phosphorus of the seedling parts generally increased as solution phosphorus concentration increased. The phosphorus content of the leaves generally increased as the concentrations of solution phosphorus increased. The stem content of phosphorus was about the same over the range of concentrations except for a sharp drop at 700 ppm level. Root content of phosphorus was maximum at 100 ppm and decreased at both lower and higher solution phosphorus concentrations.

TABLE 12.--Phosphorus series. Yellow-poplar stem diameters, size and number of leaves.

Phosphorus Solution Concentration	Stem Dia. G.L.	Branches Per Stem	Leaves				
			Mature	Immature	Mature + Immature	Mature Leaf Thickness	Size of Mature Leaves
ppm	mm	number	---- number per seedling ---			mm	index*
50	10.0	9.7	3.5	107	110	0.24	47.5
100	10.3	9.4	3.2	100	103	0.23	45.8
200	9.4	8.2	3.2	88	91	0.31	45.5
400	7.7	5.0	3.1	30	33	0.24	43.0
700	5.7	0.8	1.3	9	10	0.16	19.0

*Product of widest width and center length of the blade in inches.

TABLE 13.--Phosphorus series. Length of yellow-poplar stems, roots, and petioles.

Seedling Part	Phosphorus solution concentration (ppm)				
	50	100	200	400	700
	inches				
Stem	18.0	22.7	21.6	15.3	8.3
Roots	10.4	10.6	12.8	10.5	10.5
Petioles	3.8	3.7	3.6	3.6	3.4

TABLE 14.--Phosphorus series. Phosphorus percent and content of yellow-poplar leaves, stems, roots, and petioles.

Seedling Part	Phosphorus solution concentration (ppm)				
	50	100	200	400	700
	Phosphorus percent (ODW)				
Leaf[1]	0.34	0.47	0.52	0.65	1.43
Stem	0.34	0.39	0.53	0.69	0.65
Root	0.55	1.15	1.41	1.28	1.43
Petiole[1]	0.48	0.49	0.65	0.64	1.29
	Phosphorus content per seedling part (mgms)				
Leaf[1]	3.4	4.7	5.1	5.5	5.9
Stem	29.9	30.8	30.7	29.0	7.8
Root	34.1	70.2	56.4	34.6	11.0
Petiole[1]	0.6	0.6	0.8	0.7	0.8
	Total phosphorus content (mgms)				
Leaves[1]	11.9	11.8	16.6	20.2	18.6
Stem	29.9	30.8	30.7	29.0	7.8
Root	34.1	70.2	56.4	34.6	11.0
Petioles[1]	2.0	1.7	2.3	2.2	1.0
Seedling	77.9	114.5	106.0	86.0	38.4

[1]Only mature leaves were analyzed for phosphorus. The contribution of the small immature leaves are not included in the above values but their weights were small and their omission does not materially affect the relative numerical values presented.

The complete chemical analyses of leaves are summarized in Table 15. One of the salient features of this table is the high nitrogen percentages at the 200 and 400 ppm levels of solution phosphorus and the relatively high potassium percentages at the two lowest phosphorus levels. It should also be noted that foliar iron (ppm) decreases as solution phosphorus concentration increases. If these relationships are examined on a content per leaf basis, it is seen that nitrogen is constant over the first four phosphorus concentrations, but drops sharply at the 700 ppm level. However, in the case of potassium and iron there is a decrease not only in percentages but also in foliar content. For all elements except phosphorus, calcium, and boron there is a sharp drop in foliar content of these elements at the 700 ppm level of solution phosphorus.

The results of the statistical analyses of the phosphorus series data are given in Table 16. The correlation coefficients between foliar percent phosphorus and stem, root, and leaf weight are highly significant. The correlation between foliar phosphorus and stem length was also highly significant. However, foliar content of phosphorus was not correlated with any of the above measurements.

The regressions of stem, root, leaf weights, and stem lengths on solution phosphorus concentration were all significant or highly significant but the relationship was inversely linear. The regression of foliar percent phosphorus

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TABLE 15.--Phosphorus series. Mineral percent composition and content of yellow-poplar leaves (ODW).

Element	Phosphorus solution concentration (ppm)				
	50	100	200	400	700
			Percent		
N	3.88	3.84	4.06	4.16	3.74
K	2.00	2.01	1.70	1.67	1.76
P	0.34	0.47	0.52	0.65	1.43
Ca	0.88	1.06	0.84	0.69	0.77
Mg	0.54	0.57	0.43	0.38	0.40
			Parts per million		
Mn	28	26	29	31	32
Fe	163	103	128	110	92
Cu	14	15	14	13	16
B	6	5	6	10	15
Zn	65	40	44	46	46
Mo	4	5	4	3	3
Al	64	47	63	58	47
			Content (mgms per leaf)		
N	38.8	38.4	40.6	33.3	15.0
K	20.0	20.1	17.0	13.4	7.0
P	3.4	4.7	5.1	5.5	5.9
Ca	8.8	10.6	8.4	5.5	3.1
Mg	5.4	5.7	4.3	3.0	1.6
Mn	0.028	0.026	0.029	0.025	0.013
Fe	0.163	0.103	0.128	0.088	0.037
Cu	0.014	0.015	0.014	0.010	0.006
B	0.006	0.005	0.006	0.008	0.006
Zn	0.065	0.040	0.044	0.037	0.018
Mo	0.004	0.005	0.004	0.002	0.001
Al	0.064	0.047	0.063	0.046	0.019

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TABLE 16.--Phosphorus series. Correlation and regression.

	Foliar P	Foliar P	Stem Weight	Root Weight	Stem Length
	percent	mgms/leaf	grams	grams	inches
			Correlation coefficients		
Foliar P mgms	N.S.				
Stem weight	-.799**	N.S.			
Root weight	-.781**	N.S.	+.918**		
Stem length	-.848**	N.S.	+.910**	+.850**	
Leaf weight	-.839**	N.S.	+.737**	+.761**	+.796**

Regression equations

$$Y \text{ (Foliar P percent)} = 0.4099 - 0.0087X + 0.00572X^{2*}$$

$$Y \text{ (Foliar P mgms)} = 3.2624 + 0.5156X - 0.02784X^2$$

$$Y \text{ (Stem weight)} = 9.4955 - 0.8665X + 0.01999X^{2**}$$

$$Y \text{ (Root weight)} = 7.0709 - 0.7356X + 0.02056X^{2**}$$

$$Y \text{ (Stem length)} = 25.2742 - 0.8211X - 0.03461X^{2**}$$

$$Y \text{ (Leaf weight)} = 995.5532 + 10.2768X - 3.7063X^{2**}$$

The independent variable (X) is solution phosphorus concentration in ppm. Regression coefficients are coded in units of 50 ppm.

*Indicates statistical significance at the 5 percent level of probability.

**Indicates statistical significance at the 1 percent level of probability.

N.S. A lack of statistical significance at the 5 or 1 percent level of probability.

on solution phosphorus concentration followed the quadratic model and was highly significant.

It was anticipated that the optimum phosphorus concentration would be greater than 50 ppm, and that it would occur at about 100 or 200 ppm. If this had been the case, an optimum concentration could have been estimated from the calculated curve. However, the inverse relationship of growth (Figures 11 to 14) to solution phosphorus concentration over the range of concentrations studied precludes making an estimate of optimum phosphorus concentration from the curve. It is probable, however, that the optimum concentration for this series lies between 25-75 ppm solution phosphorus concentration.

Foliar phosphorus percent increased as solution phosphorus concentration increased. The increase followed a second order polynomial equation (Figure 15).

Optimum growth in the nitrogen series occurred at a nitrogen concentration of 300 ppm and a phosphorus concentration of 253 ppm. Optimum growth in the phosphorus series occurred at a solution nitrogen concentration of 300 ppm and phosphorus concentration of 50 ppm. However, optimum weight seedlings in the phosphorus series exceeded optimum weight seedlings in the nitrogen series by 40 percent. It should, however, be mentioned that in the nitrogen series the calcium concentration was 364 ppm and only 244 ppm in the phosphorus series. The higher calcium concentration in the nitrogen

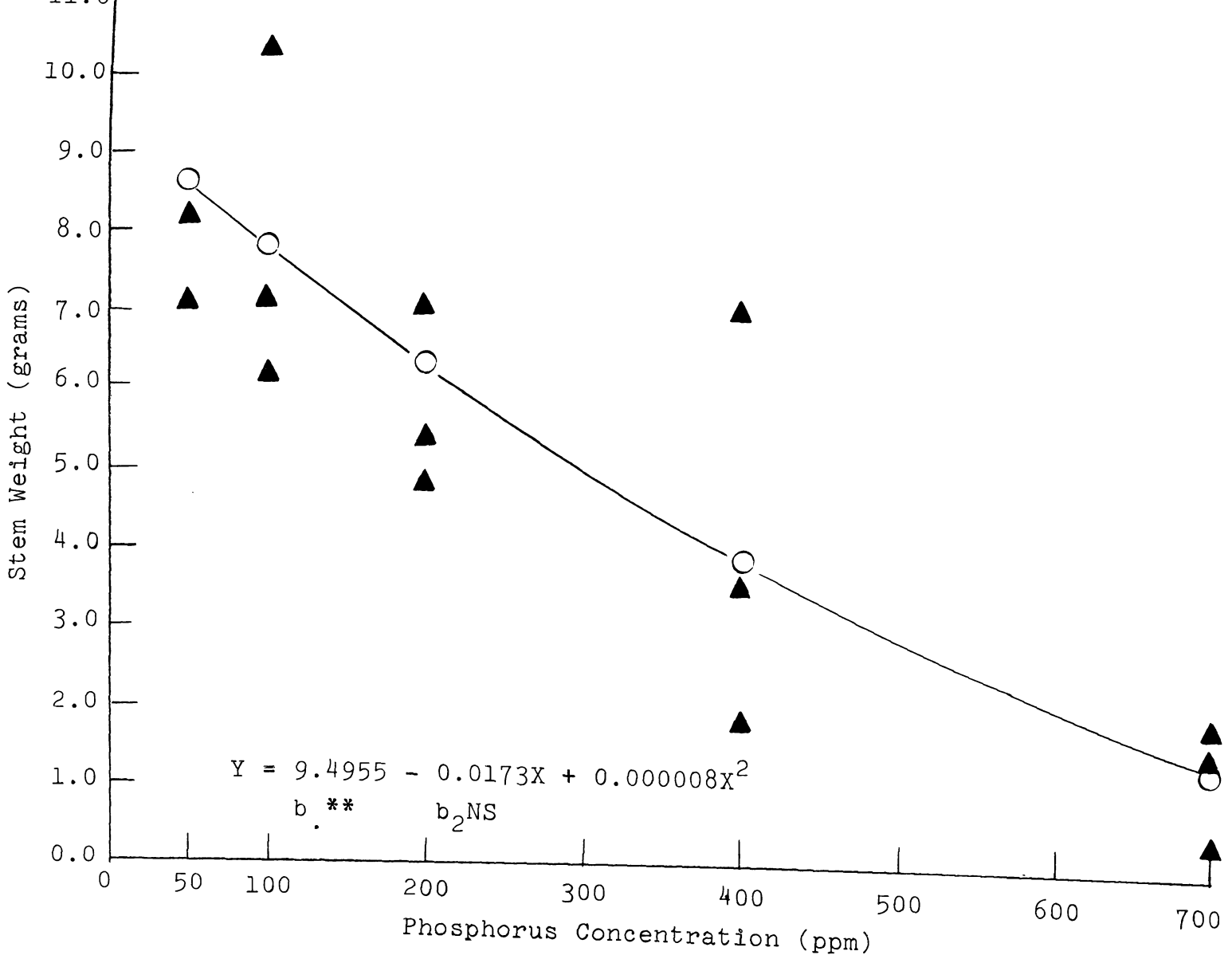

Figure 11.--Yellow-poplar growth experiment. Regression of stem weight (OD) on phosphorus solution concentration.

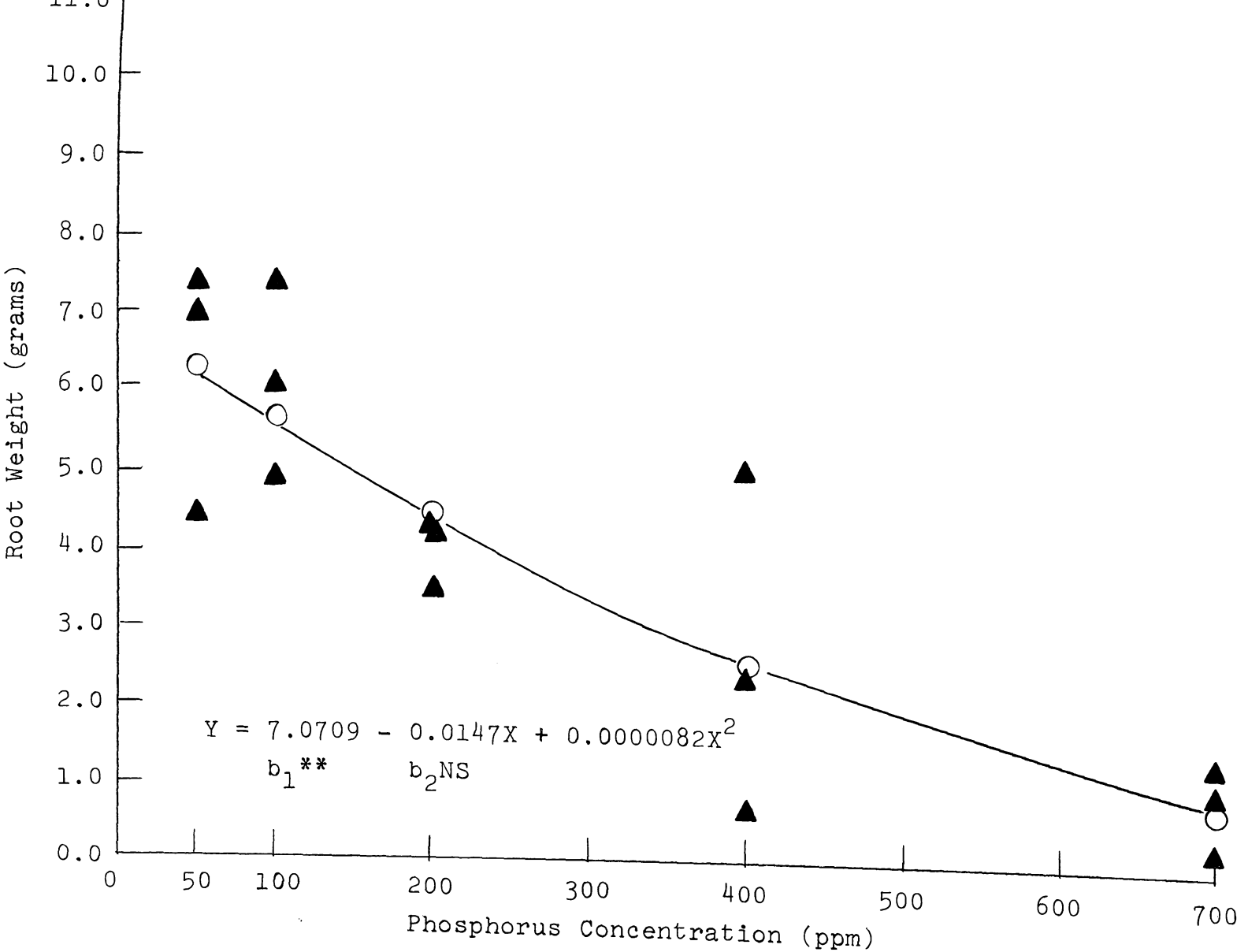

Figure 12.--Yellow-poplar growth experiment. Regression of root weight (OD) on phosphorus solution concentration.

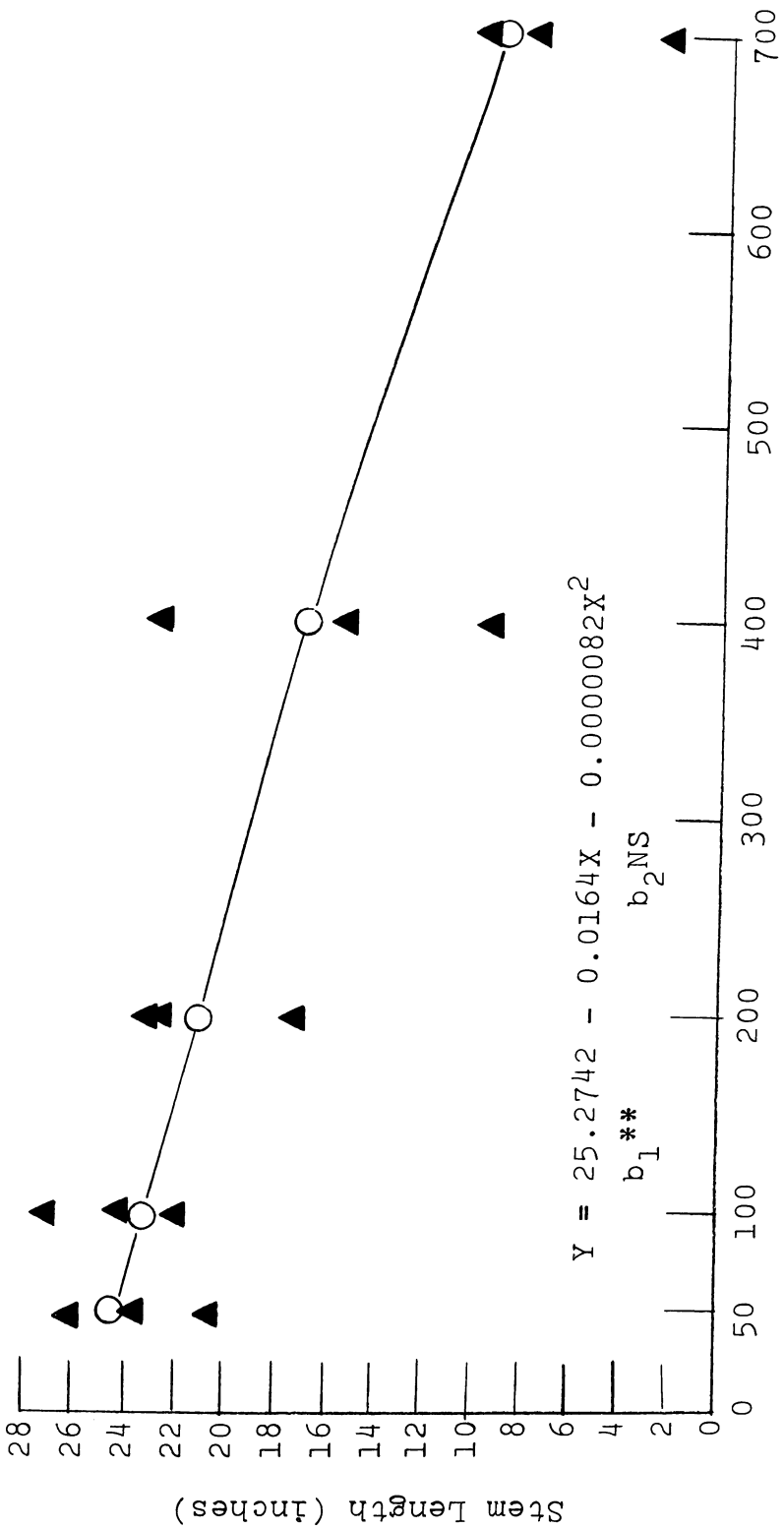

Figure 13.--Yellow-poplar growth experiment. Regression of stem length on phosphorus solution concentration.

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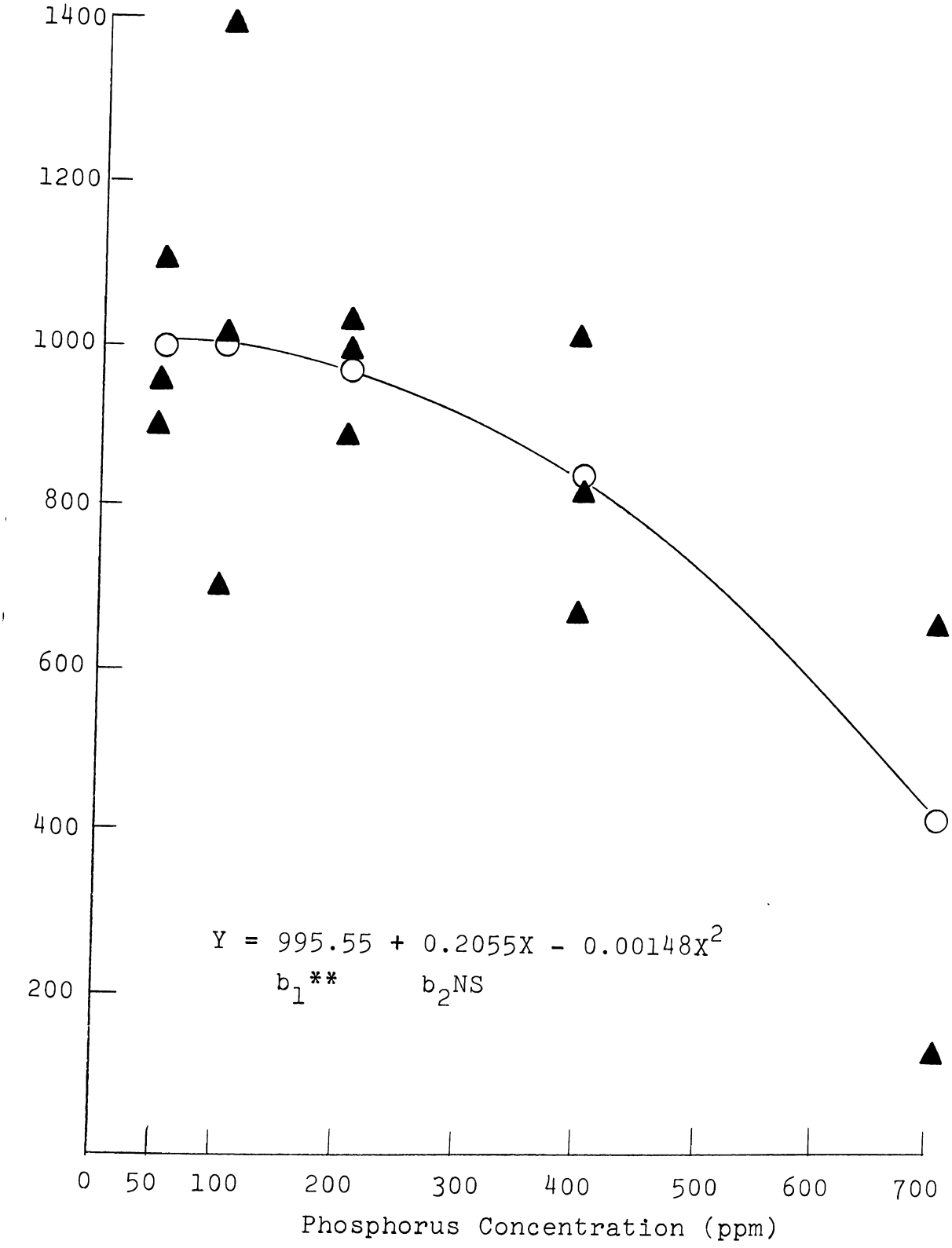

Figure 14.--Yellow-poplar growth experiment. Regression of leaf weight (OD) on phosphorus solution concentration.

Foliar Phosphorus (percent)

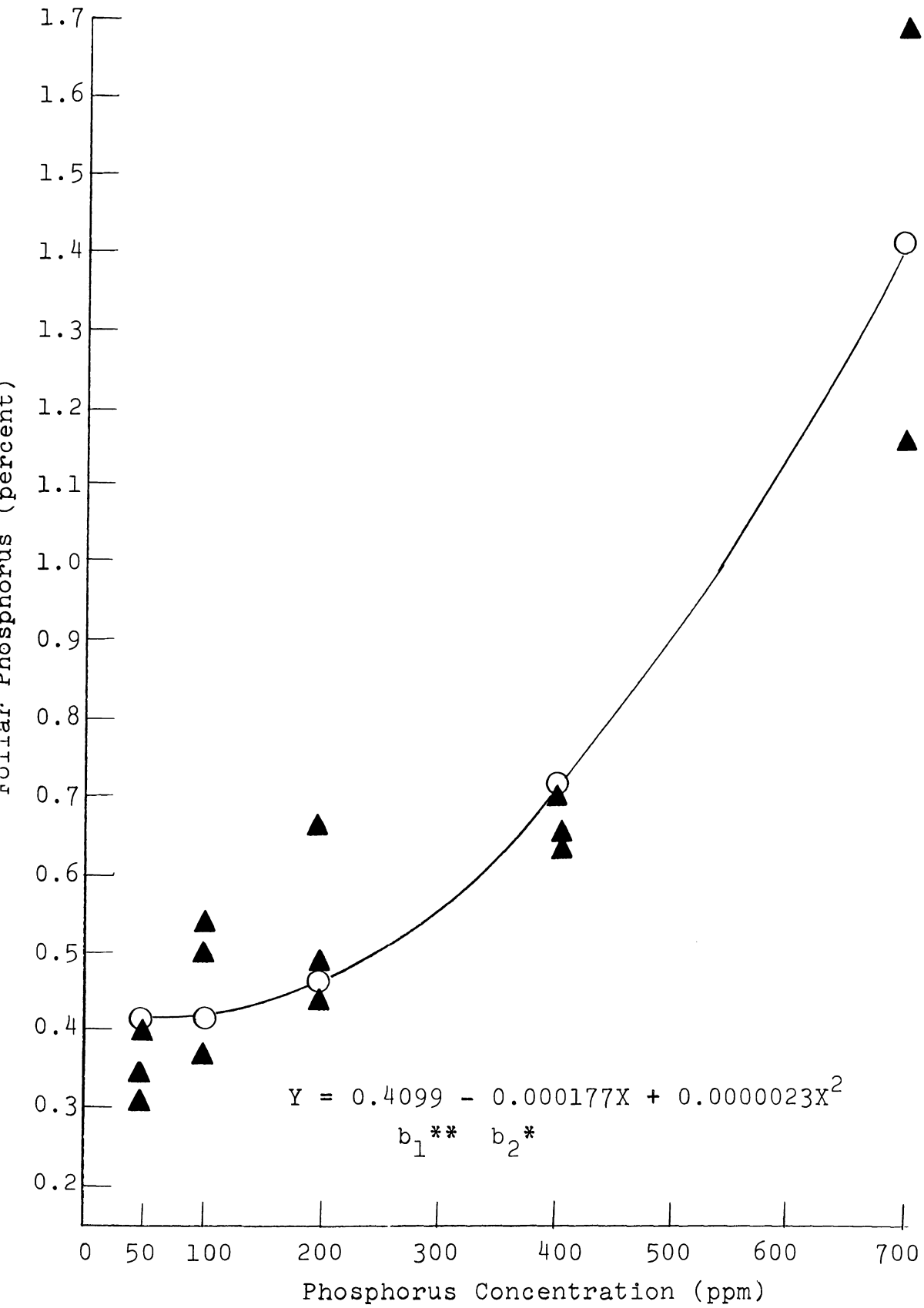

Figure 15.--Yellow-poplar growth experiment. Regression of foliar phosphorus percent on phosphorus solution concentration.

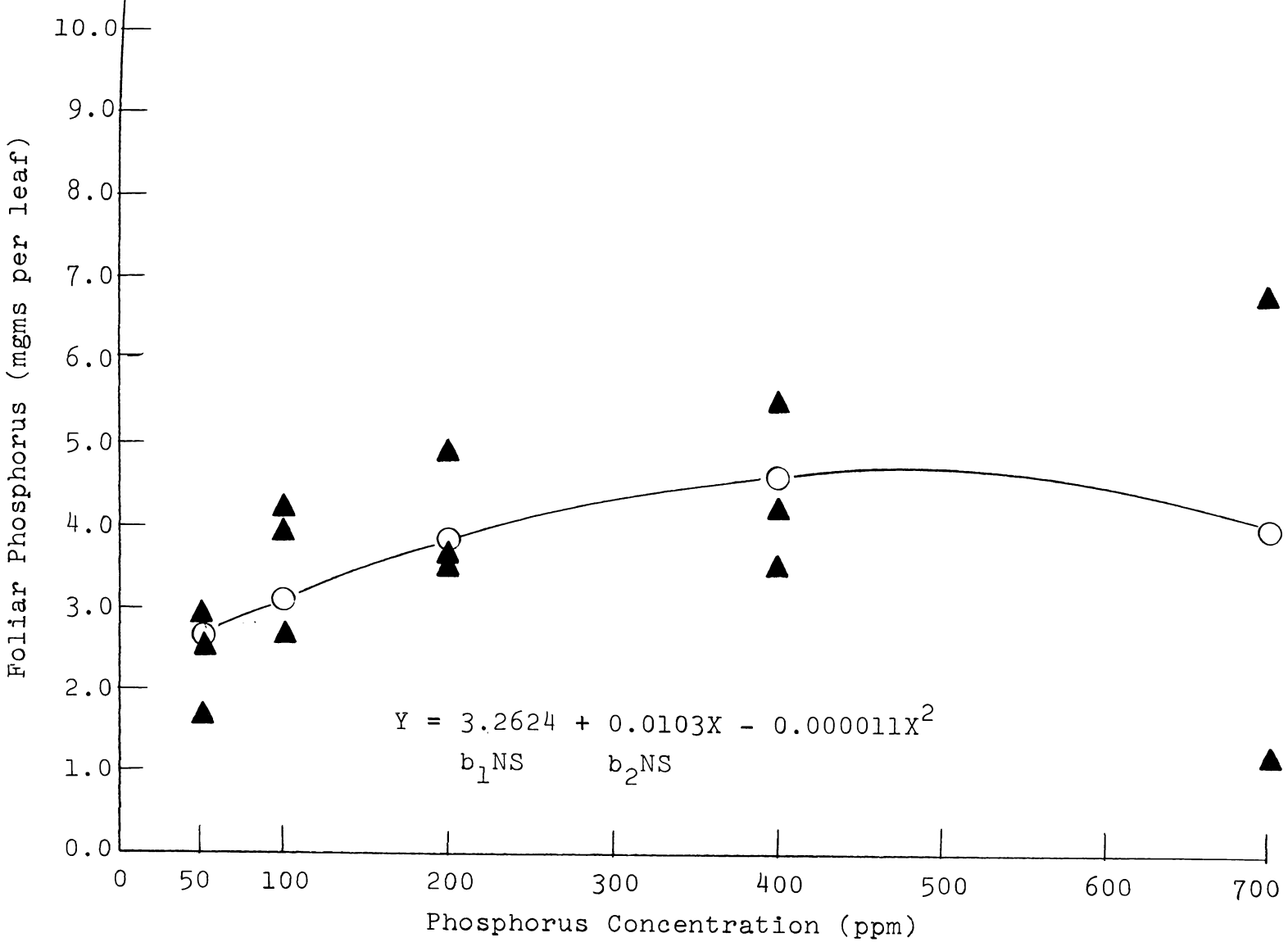

Figure 16.--Yellow-poplar growth experiment. Regression of foliar phosphorus content on phosphorus solution concentration.

series probably is partially responsible for the lighter seedling weights.

The marked decrease in iron uptake as phosphorus concentration increased may have resulted from a fixation of iron by the phosphorus in the form of ferric phosphate in the external solution. However, if this was the case there was no evidence of iron chlorosis. Therefore, it is unlikely that the reduction in growth was due to this cause. It is more probable that the increase in phosphorus concentration resulted in an unbalance between some of the other nutrient elements.

Potassium Series

The mean dry weights of stem and roots were largest at 400 ppm solution concentration of potassium (Table 17). Leaf and petiole weights varied but little over the range of potassium concentrations used.

Fresh weights of stems and roots (Table 18) paralleled the trend of dry weights. The maximum fresh weight of leaves and petioles also occurred at 400 ppm solution potassium concentration.

Stem diameter, number of branches per stem, total number of leaves per seedling, leaf thickness, and size of mature leaves were greatest at 400 ppm potassium solution concentration (Table 19).

Likewise, the length of stems, roots, and petioles reached their greatest length at 400 ppm concentration of potassium (Table 20).

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TABLE 17.--Potassium series. Yellow-poplar seedling weights (OD) and stem/root ratios.

Seedling Part	Potassium solution concentration (ppm)				
	50	100	200	400	800
	grams				
Stem	6.9	5.7	6.6	10.0	7.5
Roots	4.1	4.1	4.3	5.1	4.5
Stem + Roots	11.0	9.8	10.9	15.1	12.0
Leaves	1.0	1.1	0.9	1.1	1.0
Petioles	0.1	0.1	0.1	0.1	0.1
Seedling	12.1	11.0	11.9	16.3	13.1
	ratio				
Stem wt. / Root wt.	1.68	1.39	1.53	1.96	1.67

TABLE 18.--Potassium series. Yellow-poplar seedling weights (fresh) and stem/root ratios.

Seedling Part	Potassium solution concentration (ppm)				
	50	100	200	400	800
	grams				
Stem	14.0	11.0	13.7	22.2	15.4
Root	14.9	21.1	20.4	32.4	21.0
Stem + Root	28.9	32.1	34.1	54.6	36.4
Leaves	2.7	3.3	2.9	3.8	3.5
Petioles	0.3	0.4	0.4	0.5	0.4
Seedling	31.9	35.8	37.4	58.9	40.3
	ratio				
Stem wt. / Root wt.	0.9	0.5	0.7	0.7	0.7

TABLE 19.--Potassium series. Yellow-poplar stem diameters, size and number of leaves.

Potassium Solution Concentration	Stem Dia. G.L.	Branches Per Stem	Leaves				
			Mature	Immature	Mature + Immature	Mature Leaf Thickness	Size of Mature Leaves
ppm	mm	number	----- number per seedling ---			mm	index*
50	8.6	6.9	22.3	62.7	85.0	0.17	38.6
100	8.3	4.5	14.4	45.6	60.0	0.17	41.2
200	8.9	5.7	30.0	60.0	90.0	0.18	43.6
400	9.6	7.8	17.7	81.3	99.0	0.19	50.2
800	8.4	5.3	9.3	49.7	59.0	0.20	42.1

*Product of widest width and center length of the blade in inches.

TABLE 20.--Potassium series. Length of yellow-poplar stems, roots, and petioles.

Seedling Part	Potassium solution concentration (ppm)				
	50	100	200	400	800
	inches				
Stem	20.3	17.1	19.9	25.8	21.8
Root	10.1	10.5	10.7	11.4	10.9
Petioles	3.7	3.9	4.2	4.0	4.0

The moisture percentage of stems, roots, and leaves was maximum at 400 ppm potassium concentration. Roots contained the highest percentage of moisture followed by leaves and stems (Table 21).

TABLE 21.--Potassium series. Moisture percentages of yellow-poplar stems, roots, and leaves.

Seedling Part	Potassium solution concentration (ppm)				
	50	100	200	400	800
	percent (ODW basis)				
Stem	103	93	108	122	105
Roots	263	415	374	535	367
Leaves	170	200	222	336	250

The percentage of potassium in leaves, stems, roots, and petioles increased as potassium solution concentration increased. Roots had the highest percentage of potassium.

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Next in order were leaves and petioles, which had about the same percentage followed by stems which had the lowest percentage of potassium (Table 22).

The total content of potassium in the roots increased as potassium concentration increased. Leaves, stems, and petioles showed an increase up to 200 or 400 ppm potassium but showed a decrease at higher concentrations. The total potassium content on a seedling basis was larger at 400 ppm potassium concentration than at the other concentrations.

The results of the chemical analyses of leaves are presented in Table 23. Nitrogen percent and content were essentially unchanged over the range of solution potassium concentrations. Phosphorus percent and content were maximum at 50 ppm potassium, but did not vary consistently as potassium concentrations increased. There was a sharp drop in percent calcium and magnesium at the 800 ppm potassium concentration. But neither calcium nor magnesium content varied consistently as potassium solution concentration changed. Of the minor elements only iron percent and content were affected to a significant degree by changing potassium concentration. Both the percentage and content of iron at 800 ppm potassium was about twice as great as at the lower potassium concentrations.

The statistical analyses pertinent to the potassium series is given in Table 24. It will be noted that foliar potassium percent and content are significantly related to solution potassium concentration curvilinearly. However,

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TABLE 22.--Potassium series. Potassium percent and content of yellow-poplar leaves, stems, roots, and petioles.

Seedling Part	Potassium solution concentration (ppm)				
	50	100	200	400	800
	Potassium percent (ODW)				
Leaf[1]	0.59	0.99	1.29	2.09	2.73
Stem	0.44	0.62	0.96	1.00	1.51
Root	0.79	2.23	2.56	2.56	3.93
Petiole[1]	0.54	1.34	1.57	1.97	2.62
	Potassium content per seedling part (mgms)				
Leaf[1]	5.8	10.8	11.2	23.8	26.5
Stem	40.7	56.4	85.1	209.0	204.8
Root	32.4	91.4	110.1	134.1	176.8
Petiole[1]	0.5	1.5	2.2	2.6	2.6
	Total potassium content (mgms)				
Leaves[1]	129.3	155.5	336.0	421.3	246.4
Stem	40.7	56.4	85.1	209.0	204.8
Root	32.4	91.4	110.1	134.1	176.8
Petioles[1]	11.8	21.6	66.0	44.2	24.2
Seedling	214.2	324.9	597.2	808.6	652.2

[1]Only mature leaves were analyzed for potassium. The contribution of the small immature leaves are not included in the above values but their weights were small and their omission does not materially affect the relative numerical values presented.

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TABLE 23.--Potassium series. Mineral percent composition and content of yellow-poplar leaves (ODW).

Element	Potassium solution concentration (ppm)				
	50	100	200	400	800
			Percent		
N	3.72	3.75	3.72	3.54	3.95
K	0.59	0.99	1.29	2.09	2.73
P	0.78	0.59	0.48	0.46	0.52
Ca	1.04	0.99	1.08	0.95	0.84
Mg	0.56	0.45	0.43	0.48	0.39
			Parts per million		
Mn	25	27	33	25	31
Fe	120	147	129	99	265
Cu	13	14	15	18	14
B	8	7	8	5	7
Zn	86	53	45	59	68
Mo	5	5	5	5	4
Al	46	39	51	41	36
			Content (mgms per leaf)		
N	36.8	37.8	32.4	40.4	38.3
K	5.8	10.0	11.2	23.8	26.4
P	7.7	6.0	4.2	5.2	5.0
Ca	10.3	10.0	9.4	10.8	8.1
Mg	5.5	4.5	3.7	5.5	3.8
Mn	0.025	0.030	0.030	0.028	0.031
Fe	0.120	0.162	0.116	0.109	0.265
Cu	0.013	0.015	0.014	0.020	0.014
B	0.008	0.008	0.007	0.006	0.007
Zn	0.086	0.058	0.040	0.065	0.068
Mo	0.005	0.006	0.004	0.006	0.004
Al	0.046	0.043	0.046	0.045	0.036

TABLE 24.--Potassium series. Correlation and regression.

	Foliar K	Foliar K	Stem Weight	Root Weight	Stem Length
	percent	mgms/leaf	grams	grams	inches
			Correlation coefficients		
Foliar K mgms	+.973**				
Stem weight	N.S.	N.S.			
Root weight	N.S.	N.S.	+.693**		
Stem length	N.S.	N.S.	+.766**	N.S.	
Leaf weight	N.S.	N.S.	N.S.	N.S.	N.S.

Regression equations

$$Y \text{ (Foliar K percent)} = 0.3684 + 0.2776X^{**} - 0.0081X^{2*}$$

$$Y \text{ (Foliar K mgms)} = 2.6497 + 3.3058X^{**} - 0.1102X^{2*}$$

$$Y \text{ (Stem weight)} = 4.9392 + 0.8739X - 0.04415X^2$$

$$Y \text{ (Root weight)} = 3.6999 + 0.2550X - 0.01272X^2$$

$$Y \text{ (Stem length)} = 16.2764 + 1.6320X - 0.07950X^2$$

$$Y \text{ (Leaf weight)} = 968.1045 + 20.8760X - 1.2640X^2$$

The independent variable (X) is solution potassium concentration in ppm. Regression coefficients are coded in units of 50 ppm.

*Indicates statistical significance at the 5 percent level of probability.

**Indicates statistical significance at the 1 percent level of probability.

N.S. A lack of statistical significance at the 5 or 1 percent level of probability.

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neither weight of stem, roots, leaves, nor stem length were significantly related to solution potassium concentration. Nevertheless, all the evidence in terms of stem, root, and total seedling weight indicated that at 400 ppm solution potassium concentration growth was at a maximum. Additionally, stem diameter, number of branches per stem, number of leaves, leaf thickness, and size of mature leaves all are at their greatest value at 400 ppm solution potassium concentration.

The great variability of weight of stems and roots within a treatment is apparently an expression of the large variability in growth generally associated with hardwoods. Since there were only three replications of each treatment, and five seedlings per replication of which only three were used in computation, one large deviation in a treatment could have a large effect on the sum of deviations squared from regression. Increasing the number of replications would minimize this influence.

The conditions within a pot were essentially uniform. The seed was collected from a few trees in one stand and the resulting seedlings when planted were uniform in size and development and were uninjured. The differences in growth between seedlings within a pot could be ascribed to differences in seedling growth rate, differences in time at which vigorous growth occurred or differences due to adverse effects of competition within the pot. However, since all seedlings

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were subjected to the same environment within a pot, their reaction must be ascribed to genetic differences between the seedlings.

The objective of this study was to identify the concentration of potassium that would produce maximum growth and to relate this growth and concentration to the foliar percentage of potassium. In summary, growth seemed best at 400 ppm potassium concentration which corresponds to a foliar potassium percentage of 2.09. The evidence from this study in no way indicates that this high level of potassium would be required under a different combination of nutrient element concentrations. It should be pointed out that 64 percent of the total dry weight of the stems was attained at 50 ppm solution potassium concentration and that the remaining 36 percent increase in stem weight required an eightfold increase in solution potassium concentration (400 ppm). The same general relationships were true for root weight, stem length, and leaf weight.

Calcium Series

Maximum dry weight values for stems and roots occurred at a concentration of 50 ppm solution calcium concentration. This was the lowest concentration used in the series. Stem weights for all calcium concentrations were consistently greater than root weights. The dry weights of petioles and leaves and stem weight to root weight ratios did not follow a consistent trend in relation to solution calcium concentration (Table 25).

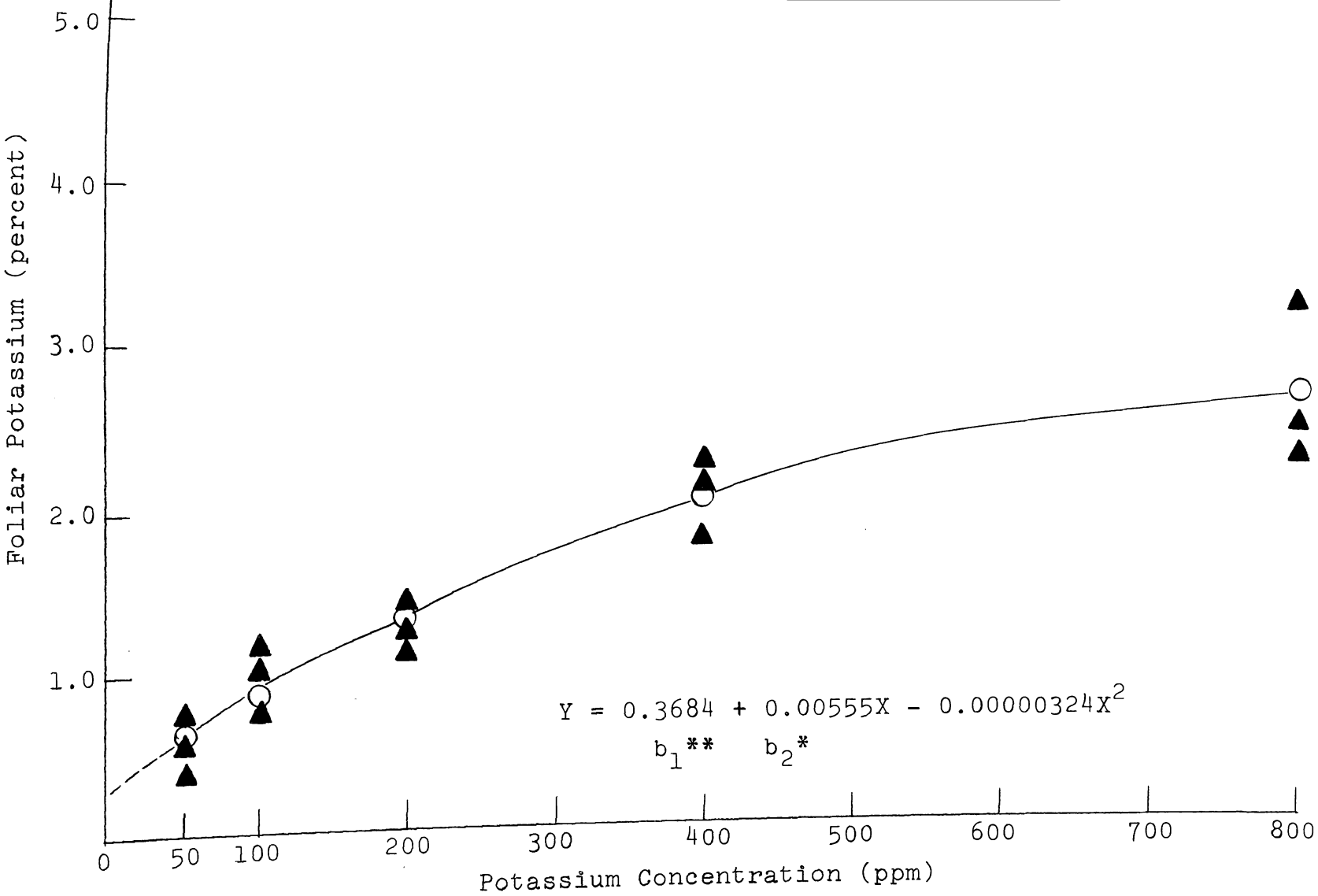

Figure 17.--Yellow poplar growth experiment. Regression of foliar potassium percent on potassium solution concentration.

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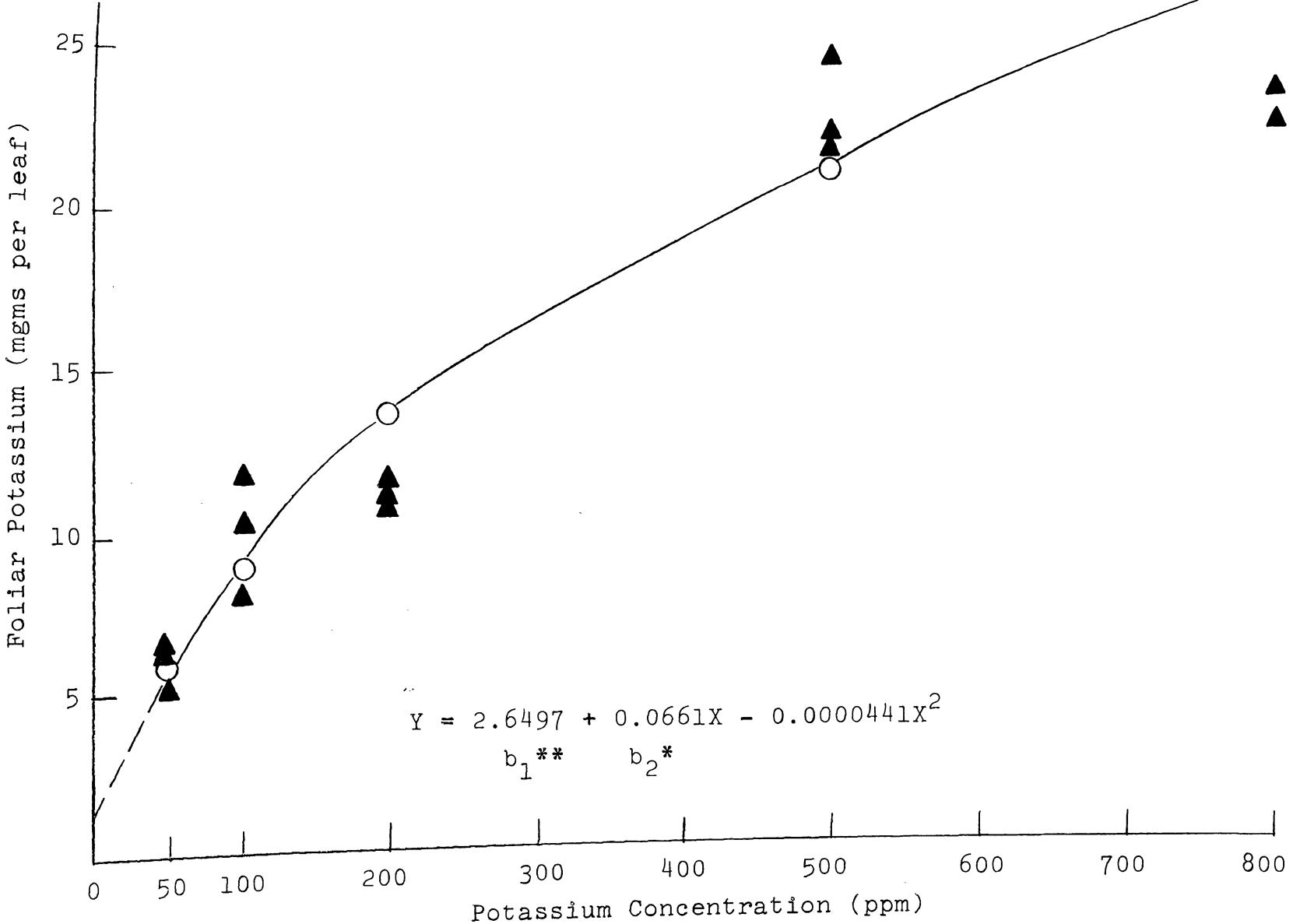

Figure 18.--Yellow-poplar growth experiment. Regression of foliar potassium content on potassium solution concentration.

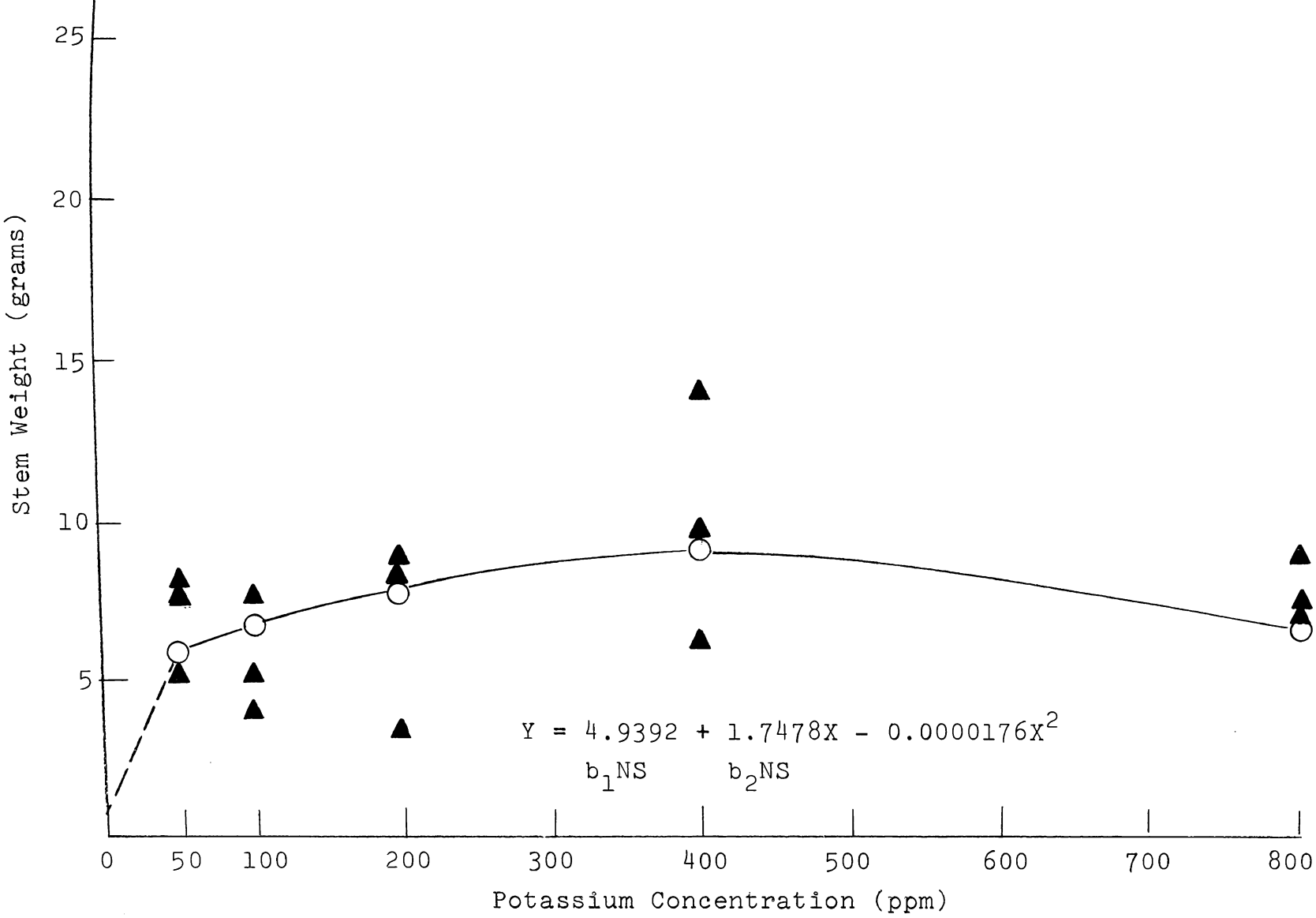

Figure 19.--Yellow-poplar growth experiment. Regression of stem weight (OD) on potassium solution concentration.

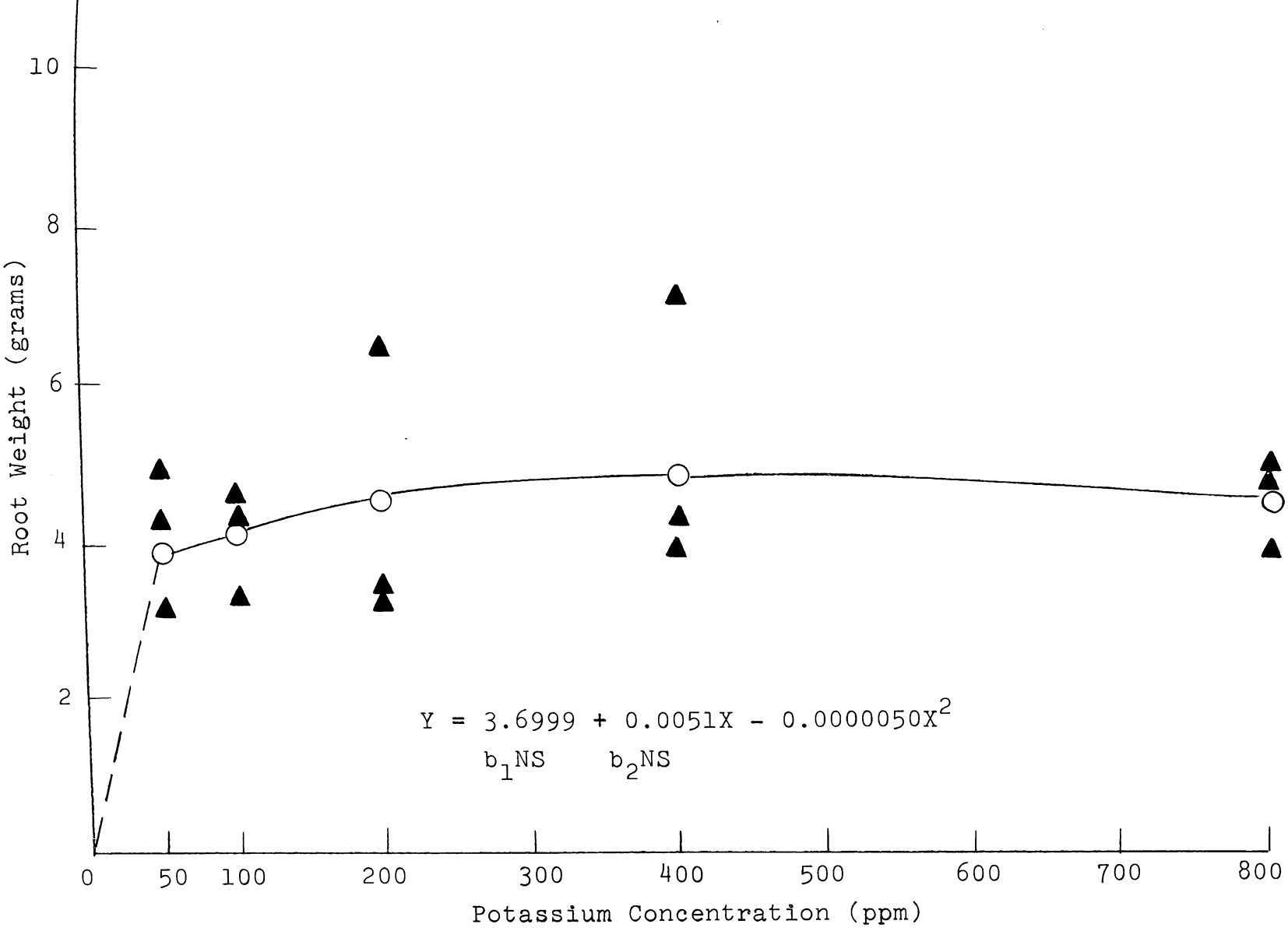

Figure 20.--Yellow-poplar growth experiment. Regression of root weight on potassium solution concentration.

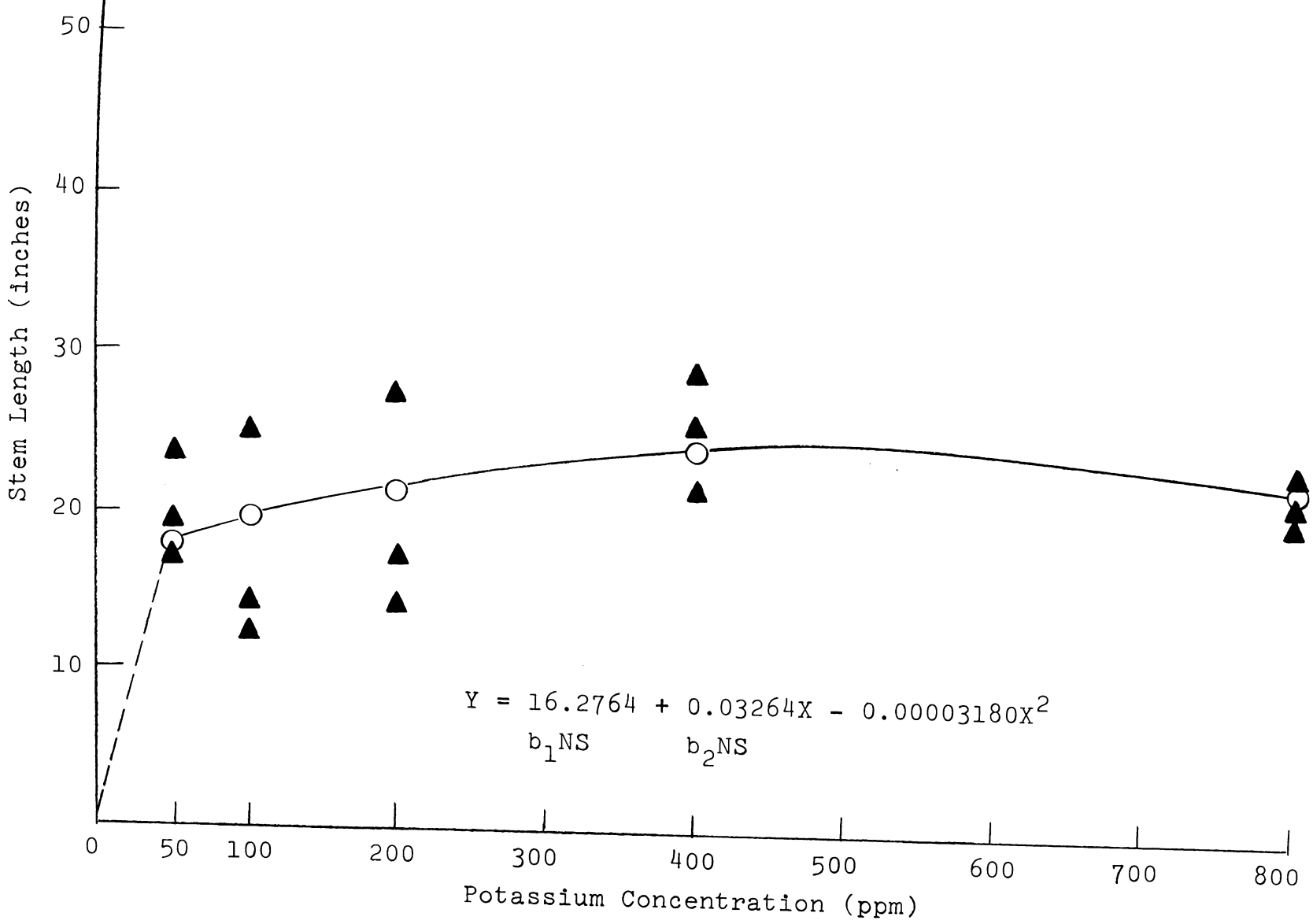

Figure 21.--Yellow-poplar growth experiment. Regression of stem length on potassium solution concentration.

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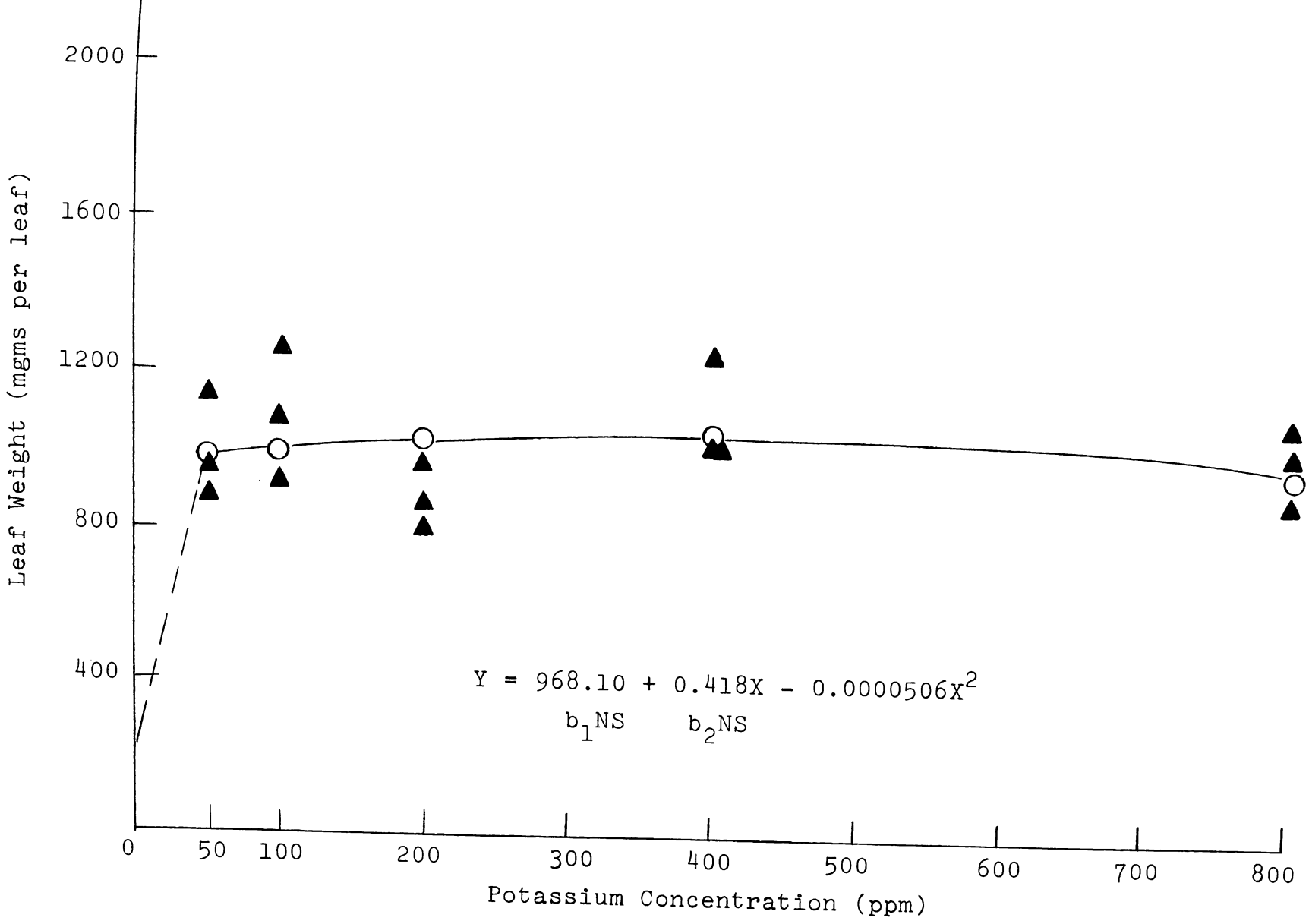

Figure 22.--Yellow-poplar growth experiment. Regression of leaf weight on potassium solution concentration.

Figure 23.--Potassium series. Pots are arranged in order of increasing solution potassium concentration from right to left. Optimum growth at 400 ppm fifth pot from right.

Figure 24.--Calcium series. Pot arrangement same as in Figure 23. Optimum growth at 50 ppm second pot from right.

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TABLE 25.--Calcium series. Yellow-poplar seedling weights (OD) and stem/root ratios.

Seedling Part	Calcium solution concentration (ppm)				
	50	100	200	400	800
	grams				
Stem	10.0	7.7	7.2	5.5	4.0
Root	8.5	6.8	4.8	4.1	2.2
Stem + Root	18.5	14.5	12.0	9.6	6.2
Leaves	1.0	0.9	1.0	0.9	0.8
Petioles	0.12	0.14	0.13	0.13	0.06
Seedling	19.5	15.5	13.1	10.6	7.1
	ratio				
$\frac{\text{Stem wt.}}{\text{Root wt.}}$	1.17	1.13	1.50	1.34	1.82

The fresh weight of stems and roots were, like the dry weights of stems and roots, greatest at 50 ppm solution calcium concentration. However, there was no consistent relationship between the fresh weight of leaves or petioles nor fresh stem weight to fresh root weight ratios and solution calcium concentration (Table 26).

There was a pronounced difference in the moisture percentage of roots, leaves, and stems. Roots had the highest moisture percent, leaves the next highest, and stems the lowest. Moisture percent of stems, roots, and petioles in relation to solution calcium concentration did not follow a consistent trend (Table 27).

TABLE 26.--Calcium series. Yellow-poplar seedling weights (fresh) and stem/root ratios.

Seedling Part	Calcium solution concentration (ppm)				
	50	100	200	400	800
	grams				
Stem	21.0	18.9	15.8	11.4	7.7
Root	43.9	29.9	21.1	19.6	11.2
Stem + Root	64.9	48.8	36.9	31.0	14.0
Leaves	3.6	3.3	3.5	3.2	2.8
Petioles	0.41	0.38	0.41	0.37	0.38
Seedling	68.9	52.5	40.8	34.6	17.2
	ratio				
$\frac{\text{Stem wt.}}{\text{Root wt.}}$	0.48	0.63	0.75	0.58	0.69

TABLE 27.--Calcium series. Moisture percentages of yellow-poplar stems, roots, and leaves.

Seedling Part	Calcium solution concentration (ppm)				
	50	100	200	400	800
	percent (ODW basis)				
Stems	110	145	119	107	92
Roots	416	340	340	378	409
Leaves	242	171	215	185	533

The maximum value of most seedling parts was observed at a calcium concentration of 50 ppm. In addition to stem and root weights, maximum values were obtained for stem diameter, number of branches per stem, number of mature and immature leaves at 50 ppm (Table 28).

The length of stem, root, and petioles reached their greatest values at 50 ppm of calcium (Table 29).

TABLE 29.--Calcium series. Length of yellow-poplar stems, roots, and petioles.

Seedling Part	Calcium solution concentration (ppm)				
	50	100	200	400	800
	inches				
Stem	25.6	24.2	23.1	19.2	17.2
Roots	10.5	11.5	10.8	10.3	8.6
Petioles	4.3	4.0	4.1	4.2	3.9

The percentage of calcium in leaves, stems, roots, and petioles increased as solution calcium concentration increased (Table 30). Calcium concent per leaf increased as the solution calcium concentration increased (Table 31).

The calcium content of stems, roots, and petioles did not change consistently as the solution calcium concentration increased.

Of the total quantity of calcium in the seedling about 68 percent is contained in the mature leaves. Stems have

TABLE 28.--Calcium series. Yellow-poplar stem diameters, size and number of leaves.

Calcium Solution Concentration	Stem Dia. G.L.	Branches Per Stem	Leaves				
			Mature	Immature	Mature + Immature	Mature Leaf Thickness	Size of Mature Leaves
ppm	mm	number	---- number per seedling ---			mm	index*
50	10.8	9.8	25	80	105	0.21	48.9
100	10.0	8.9	14	74	88	0.20	42.1
200	9.9	9.1	12	54	66	0.24	50.0
400	9.1	6.2	11	30	41	0.16	45.3
800	7.6	5.3	5	14	19	0.12	39.6

*Product of widest width and center length of the blade in inches.

TABLE 30.--Calcium series. Calcium percent and content of yellow-poplar leaves, stems, roots, and petioles.

Seedling Part	Calcium solution concentration (ppm)				
	50	100	200	400	800
	Calcium percent (ODW)				
Leaf[1]	0.42	0.65	1.01	1.22	1.84
Stem	0.22	0.30	0.36	0.46	0.64
Root	0.18	0.27	0.32	0.41	0.58
Petiole[1]	0.23	0.26	0.23	0.40	0.48
	Calcium content per seedling part (mgms)				
Leaf[1]	4.2	6.0	9.9	10.6	13.6
Stem	22.0	23.1	25.9	25.3	25.6
Root	15.3	18.4	15.4	16.8	12.8
Petiole[1]	0.3	0.4	0.3	0.5	0.3
	Total calcium content (mgms)				
Leaves[1]	105	84	119	117	68
Stem	22	23	26	25	26
Root	15	18	15	17	13
Petioles[1]	8	6	4	6	2
Seedling	150	131	164	165	109

[1]Only mature leaves were analyzed for calcium. The contribution of the small immature leaves are not included in the above values but their weights were small and their omission does not materially affect the relative numerical values presented.

TABLE 31.--Calcium series. Mineral percent composition and content of yellow-poplar leaves (ODW).

Element	Calcium solution concentration (ppm)				
	50	100	200	400	800
			Percent		
N	2.73	3.16	3.34	3.66	3.68
K	1.62	1.72	1.77	1.91	1.61
P	0.90	0.77	0.64	0.61	0.44
Ca	0.42	0.65	1.01	1.22	1.84
Mg	0.81	0.73	0.55	0.38	0.30
			Parts per million		
Mn	40	38	39	33	42
Fe	168	123	121	99	119
Cu	10	13	12	14	13
B	10	7	7	5	12
Zn	64	35	50	49	40
Mo	2	3	4	5	6
Al	76	65	55	45	48
			Content (mgms per leaf)		
N	27.3	28.4	33.4	32.9	29.4
K	16.2	15.5	17.7	17.2	12.9
P	9.0	6.9	6.4	5.5	3.5
Ca	4.2	5.8	10.1	11.0	14.7
Mg	8.1	6.6	5.5	3.4	2.4
Mn	0.040	0.034	0.039	0.030	0.034
Fe	0.168	0.111	0.121	0.089	0.095
Cu	0.010	0.012	0.012	0.013	0.010
B	0.010	0.006	0.007	0.004	0.010
Zn	0.064	0.032	0.050	0.044	0.032
Mo	0.002	0.003	0.004	0.004	0.005
Al	0.076	0.058	0.055	0.040	0.038

next highest amount, followed by roots and petioles. Only about 11 percent is found in the roots. Stems contain 18 percent and petioles 3 percent of the total calcium.

The relationship between solution calcium concentration and the main factors considered in the calcium series are summarized in Table 32 and shown in graphic form in Figures 25 to 30.

The most notable result for the calcium series is the low solution concentration of calcium required for maximum growth. The relationship between foliar calcium percent and content, stem and root weight and stem length was linear. Foliar calcium percent and content increased linearly with increasing calcium concentration but stem and root weight and stem length decreased linearly as calcium concentration decreased. It is evident from the data that the solution concentration of calcium which will produce maximum growth is relatively low and probably lies between 25 to 75 ppm solution calcium concentration. In the Figures 25 to 30, the zero concentration actually is not zero. The solution actually contained about eight parts per million of calcium introduced into the solution in the reagents and distilled water and from other sources of contamination.

Stem weight at 50 parts per million calcium was 10 grams and at 800 parts per million 4 grams, which is a 250 percent decrease. An even larger difference was observed for root weights. Roots weighed 8.5 grams at 50 ppm calcium and 2.2 grams at 800 parts per million, which is a 386 percent decrease.

TABLE 32.--Calcium series. Correlation and regression.

	Foliar Ca	Foliar Ca	Stem Weight	Root Weight	Stem Length
	percent	mgms/leaf	grams	grams	inches
		Correlation coefficients			
Foliar Ca mgms	+.824**				
Stem weight	-.692**	-.497			
Root weight	-.755**	-.589*	+.943**		
Stem length	-.682**	-.556*	+.934**	+.883**	
Leaf weight	-.496	+.0493	+.476	+.443	+.283

Regression equations

$$Y \text{ (Foliar Ca percent)} = 0.3448 + 0.1497X - 0.00357X^{2**}$$

$$Y \text{ (Foliar Ca mgms)} = 3.5924 + 1.3247X - 0.0452X^{2**}$$

$$Y \text{ (Stem weight)} = 10.0627 - 0.8154X + 0.0275X^{2**}$$

$$Y \text{ (Root weight)} = 8.8059 - 0.9382X + 0.0398X^{2**}$$

$$Y \text{ (Stem length)} = 26.3194 - 1.8424X + 0.0682X^{2*}$$

$$Y \text{ (Leaf weight)} = 1016.5857 - 18.3074X + 0.101X^{2}$$

The independent variable (X) is solution calcium concentration in ppm. Regression coefficients are coded in units of 50 ppm.

*Indicates statistical significance at the 5 percent level of probability.

**Indicates statistical significance at the 1 percent level of probability.

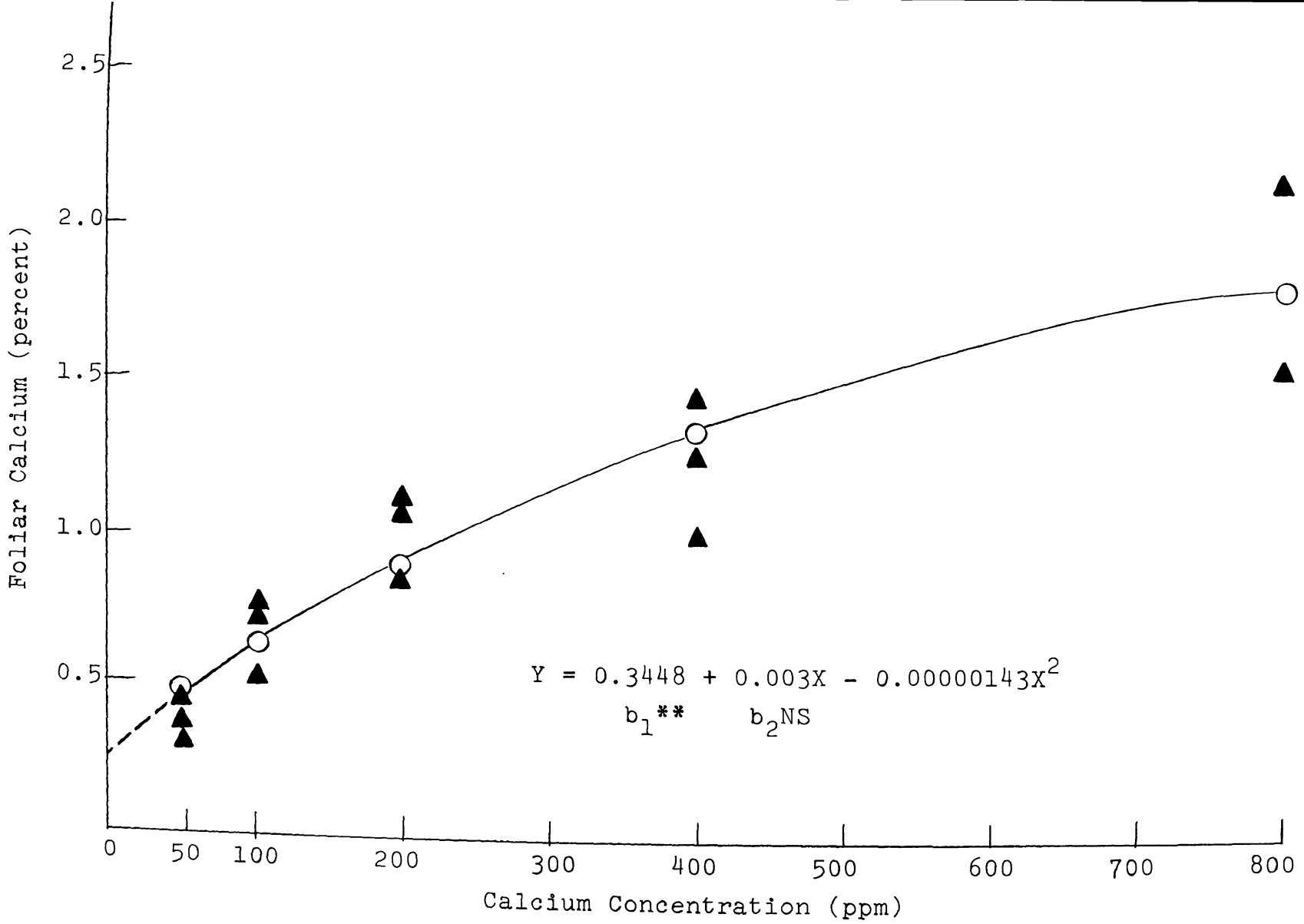

Figure 25.--Yellow-poplar growth experiment. Regression of foliar calcium percent on calcium solution concentration.

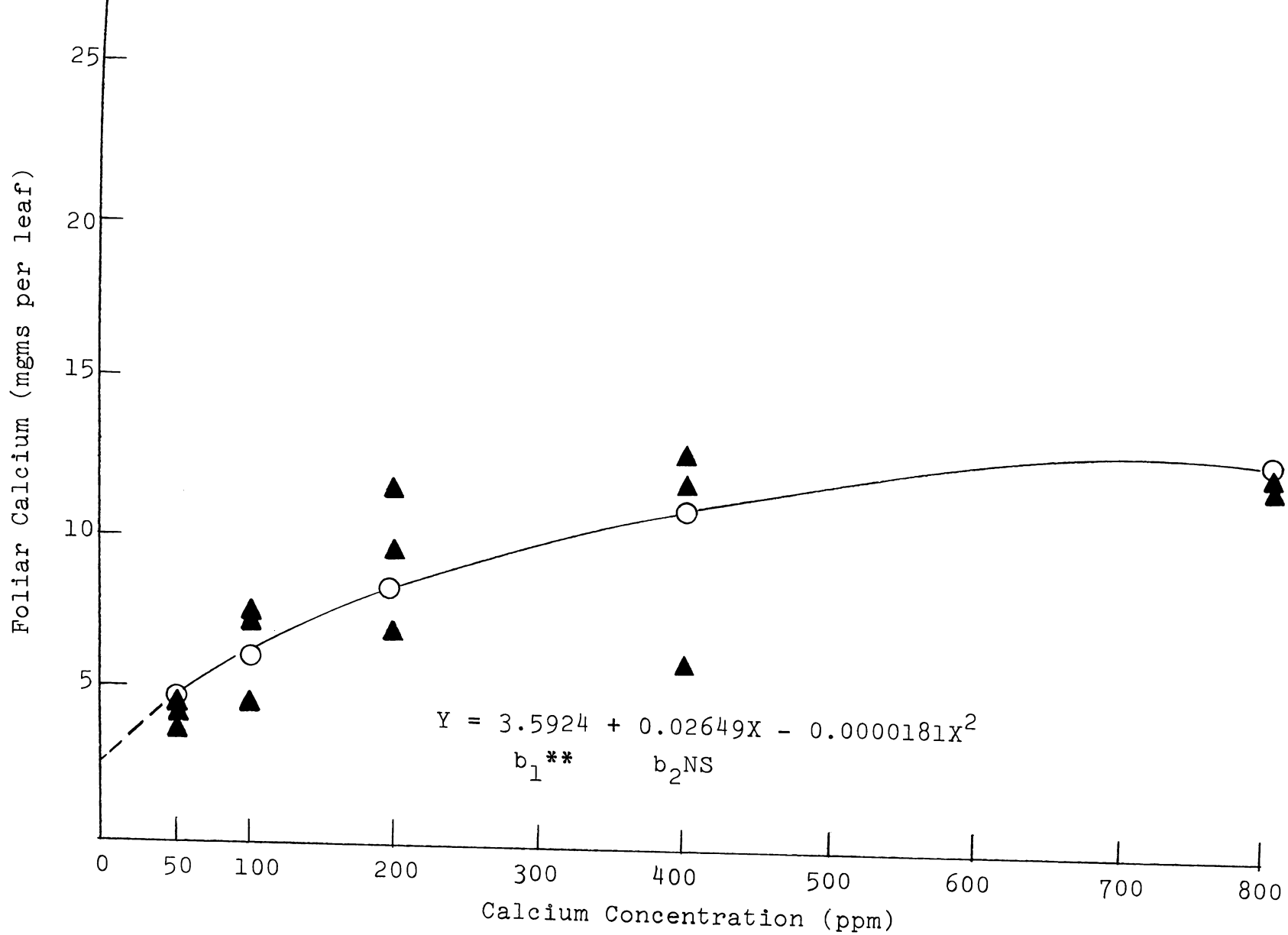

Figure 26.--Yellow-poplar growth experiment. Regression of foliar calcium content on calcium solution concentration.

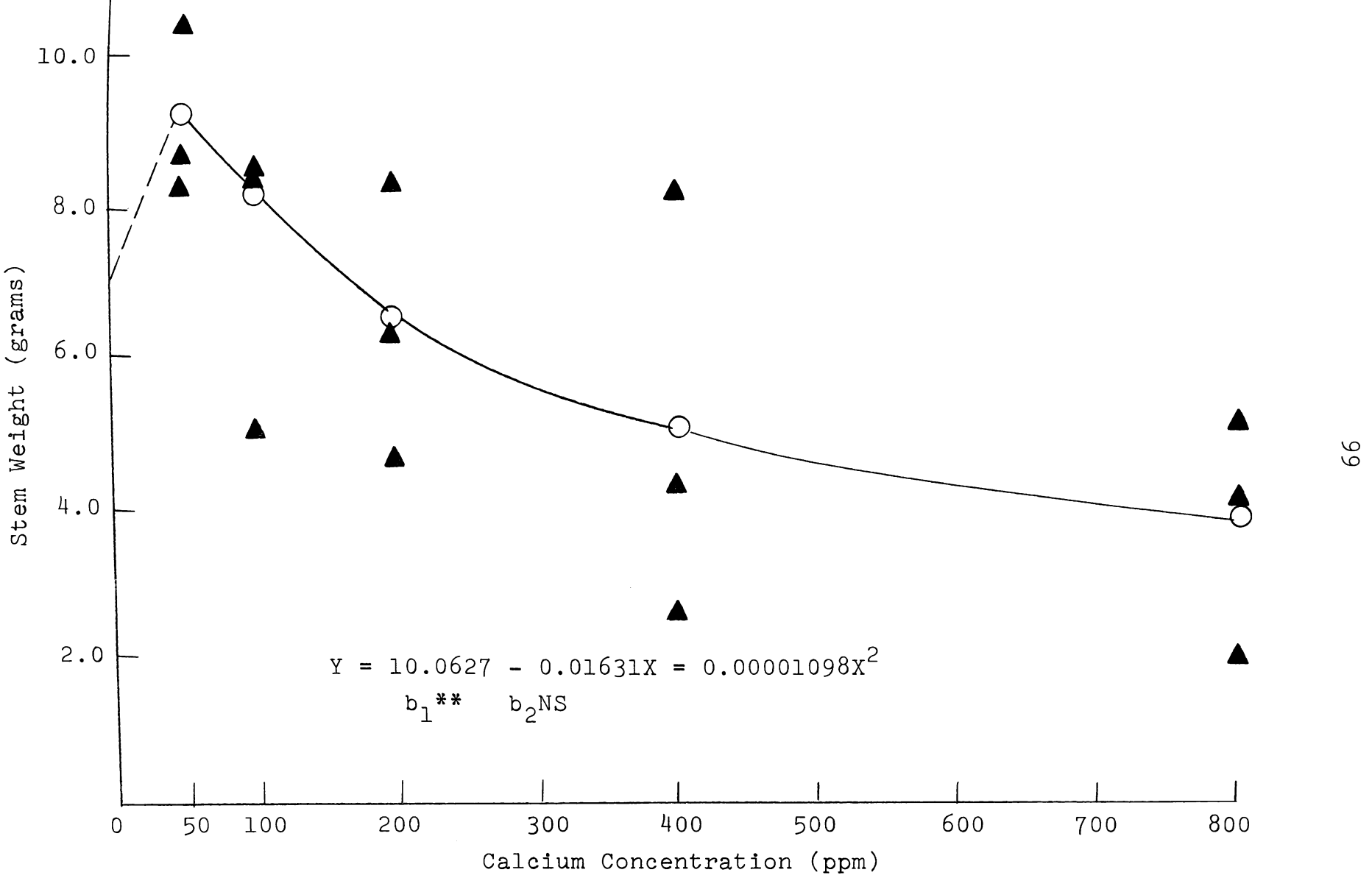

Figure 27.--Yellow-poplar growth experiment. Regression of stem weight (OD) on calcium solution concentration.

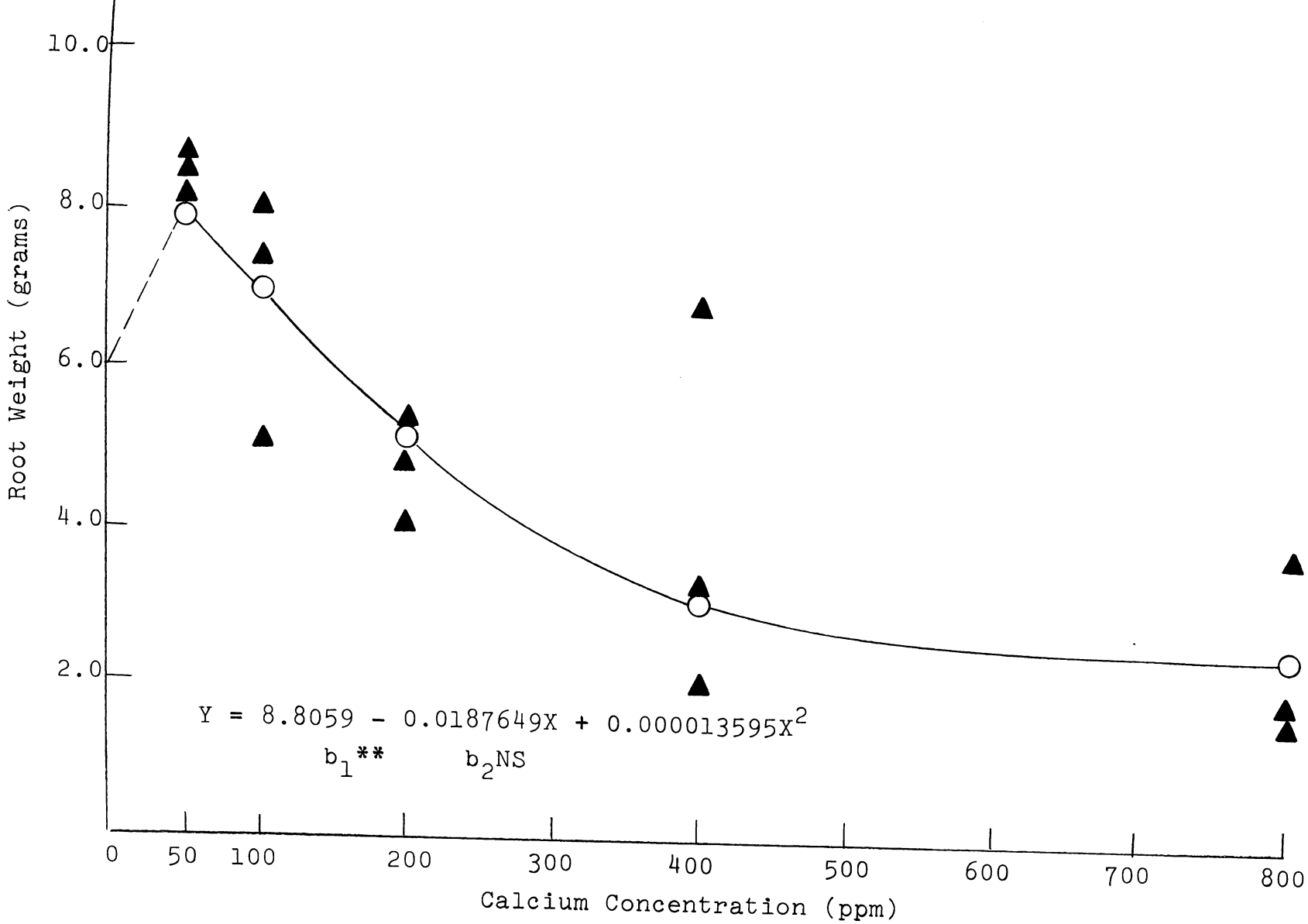

Figure 28.--Yellow-poplar growth experiment. Regression of root weight (OD) on calcium solution concentration.

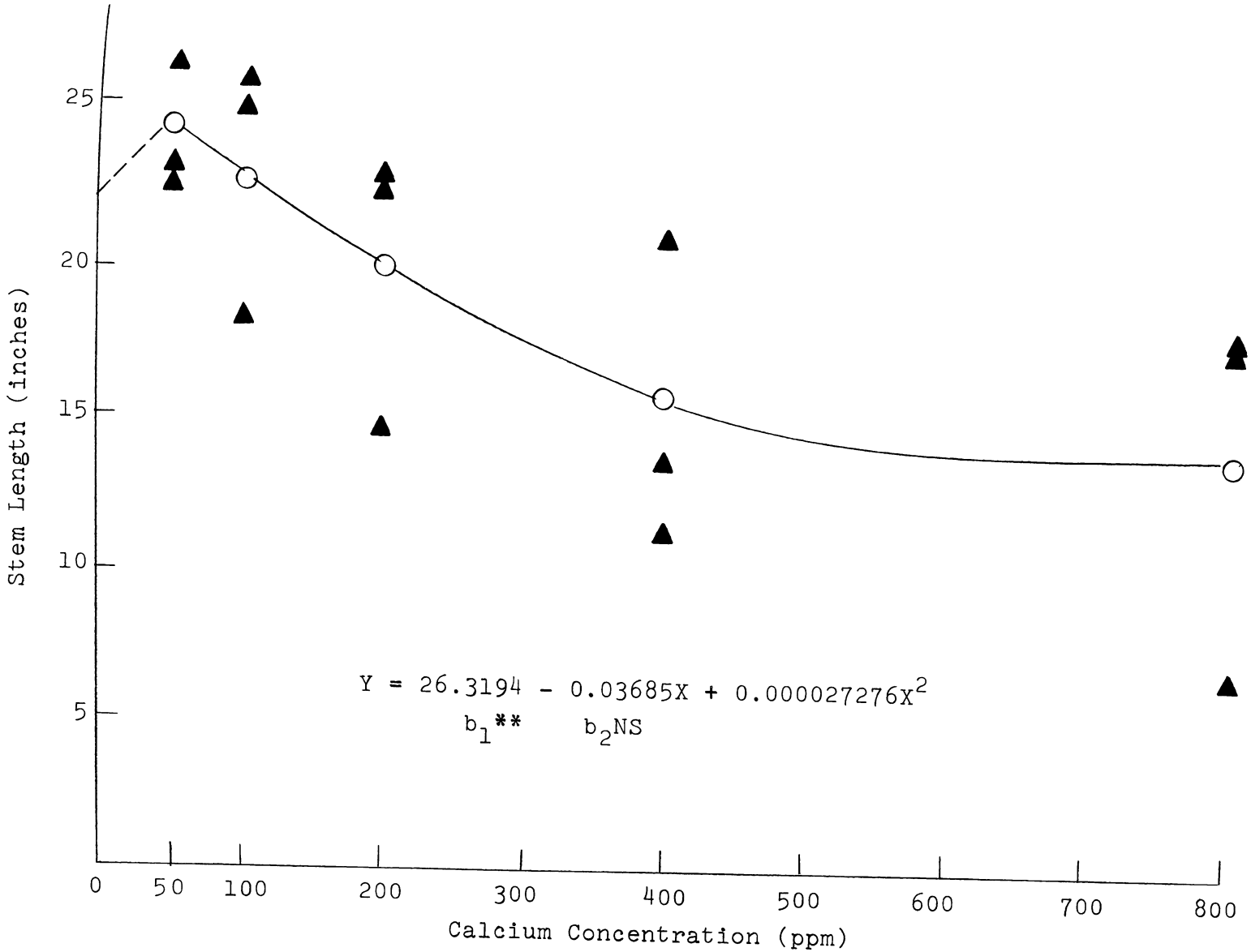

Figure 29.--Yellow-poplar growth experiment. Regression of stem length on calcium solution concentration.

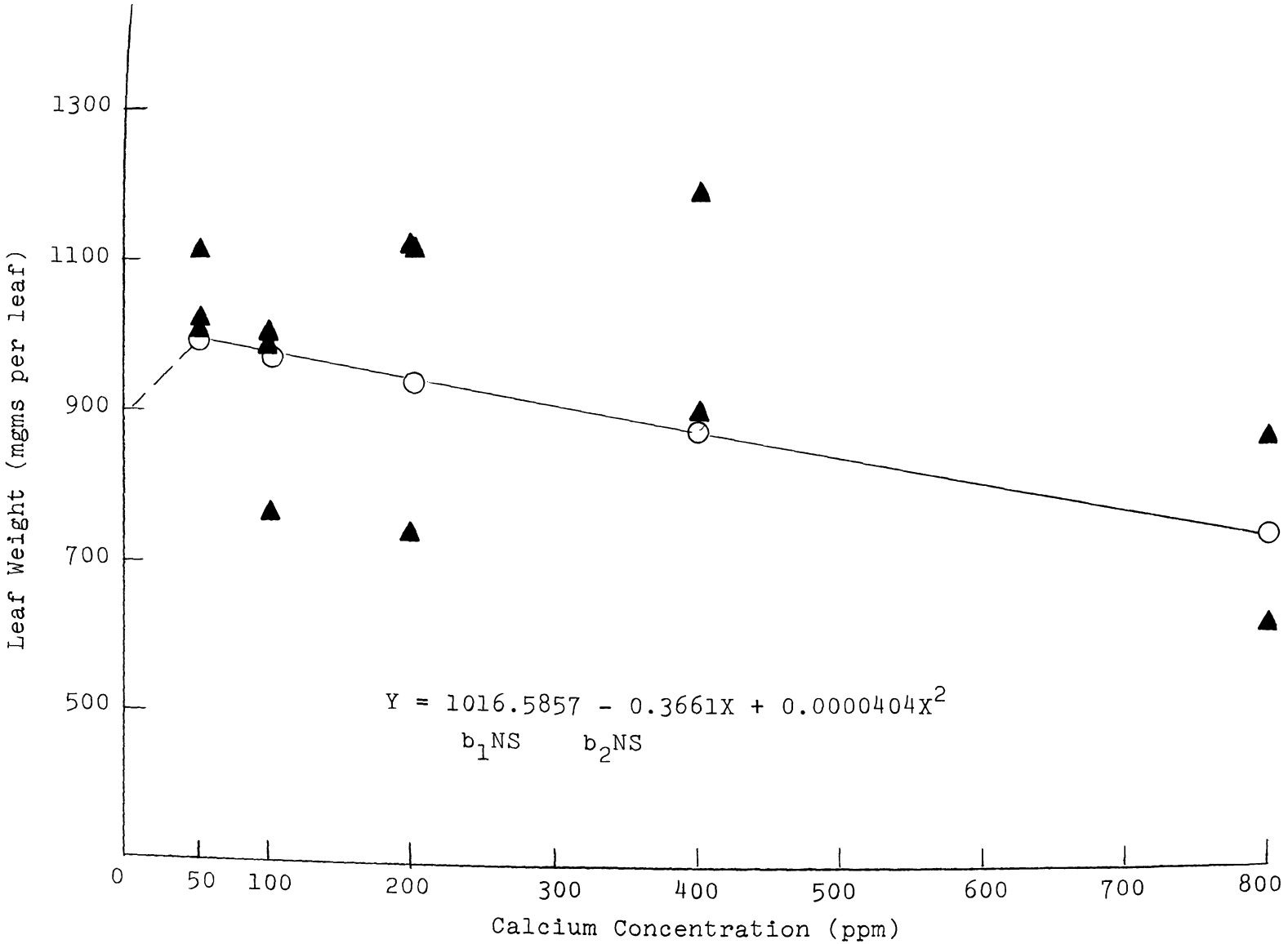

Figure 30.--Yellow-poplar growth experiment. Regression of leaf weight (OD) on calcium solution concentration.

It is clear that under the conditions of this experiment relatively low concentrations of calcium are adequate for maximum growth.

Phosphorus and magnesium uptake were inversely related to increasing solution calcium concentration (Table 31). However, the foliar percentage of phosphorus even at the high calcium levels seems adequate as judged by the percentage of phosphorus found in yellow-poplar growing satisfactorily under natural conditions. In the case of magnesium, no information is available from controlled experiments designed to indicate the growth response of yellow-poplar to different levels of magnesium concentration. However, Schomaker and Rudolph (1964) reported a value of 0.32 percent for the magnesium concentration in yellow-poplar leaves from fast-growing trees in southwestern Michigan. Their value is comparable to the lowest value found in this series, which was 0.30 percent foliar magnesium at 800 ppm solution calcium concentration. Thus, it seems that sufficient magnesium was available at all calcium concentrations.

Deficiency Symptoms Experiment

Deficiency symptoms were induced in seedlings growing in a sand-culture medium from which nitrogen, phosphorus, potassium, and calcium were omitted singly and in all combinations. Seedlings grown in a solution containing a complete complement of required nutrient elements in adequate amounts were used for comparison with the deficiency grown seedlings.

The results of two experiments are reported. In one experiment, six-week-old seedlings were grown for 83 days in 1959; and in the second experiment, two-week-old seedlings were grown for 112 days in 1960. Nutrient composition and concentration were the same for both experiments, except that in the 1960 experiment, third and fourth order combinations of the nutrient elements were not omitted from solutions.

The results of the 1959 experiment are summarized in Tables 33 and 34, and the deficiency symptoms are shown in color photographs in Figures 31 to 45. The 1960 experimental results are given in Tables 35 and 36, and the deficiency symptoms are illustrated by color photographs in Figures 46 to 57.

At least three-fourths of the seedlings which were planted in 1959 survived until harvest. However, growth of seedlings in the complete solution was very slow and the stem + root oven-dry weight was only 2.1 grams; the total length of the seedlings was only 11.6-inches. The omission of calcium from the solution resulted in a greater dry weight, 2.8 grams, as compared to 2.1 for seedlings from the complete solution. However, the omission of any of the other elements from the solution reduced growth by at least fifty percent.

In the 1960 experiment, omission of nitrogen, phosphorus, or potassium resulted in the death of all seedlings growing in solutions from which the three elements had been

TABLE 33.--Survival, weight, and length of six-week-old seedlings grown for 83 days in complete and nutrient deficient sand-culture solutions.

Treatment	Survival	Weight (OD)		Length		
		Stem	Root	Stem	Root	Petiole
	percent	-- grams --		----- inches ------		
Complete	100	0.5	1.6	3.7	7.9	2.4
-N	83	0.2	0.8	2.2	8.6	1.2
-P	92	0.2	0.5	2.9	7.3	1.8
-K	83	0.3	1.2	2.6	8.9	2.3
-Ca	92	0.6	2.2	4.2	9.4	1.9
-NP	92	0.1	0.4	2.5	8.0	1.0
-NK	67	0.2	0.7	2.6	6.1	1.6
-NCa	83	0.1	0.6	2.2	7.6	1.1
-PK	83	0.1	0.3	2.2	6.1	1.6
-PCa	83	0.2	0.4	2.5	6.3	1.3
-KCa	83	0.2	0.7	2.6	7.2	1.8
-NPK	92	0.2	0.8	2.1	8.4	1.1
-PKCa	92	0.2	0.4	2.3	5.9	1.2
-NPKCa	75	0.1	0.6	2.0	8.6	1.2

TABLE 34.--Stem diameter, leaf size, and number of leaves per seedling of six-week-old seedlings grown for 83 days in complete and nutrient deficient sand culture solutions.

Treatment	Stem Diameter One-inch Above G.L.	Maximum Leaf Size	Leaves Per Seedling
	mm	index*	number
Complete	3.4	23.6	28
-N	1.9	7.7	21
-P	1.9	7.4	12
-K	2.6	15.2	30
-Ca	3.5	23.3	37
-NP	1.7	4.7	12
-NK	1.7	7.7	17
-NCa	1.7	3.6	24
-PK	1.6	5.1	6
-PCa	1.8	5.5	17
-KCa	2.4	8.1	32
-NPK	1.7	4.9	16
-PKCa	1.8	5.4	12
-NPKCa	1.6	4.3	20

*Product of widest part of blade by the length of the blade in inches.

Figure 31. -N leaves show typical yellowing as a result of nitrogen deficiency. The upper leaves, from seedlings growing in complete solution, are normal. Photo 10/1959

Figure 32. -K leaves on the left are beginning to show first stage of potassium deficiency along leaf margins. Leaf size much reduced. The upper leaves, from seedlings grown in complete solution, are normal. Photo 10/1959

Figure 33. -P leaves all are beginning to bronze, which begins on the margins. The upper leaves, from seedlings grown in complete solution, are normal. Photo 10/1959

Figure 34. -Ca The effect of omitting calcium from the solution had no apparent adverse effect on either leaf color or size. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 35. -NP The deficiency color symptoms are less pronounced than in either the -N or -K photos. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 36. -NK The color symptoms are intermediate between the color for -N and -K. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959


17 116 140
Cal
124 143


MD
17 120 137


NK
19 115 13

Figure 37. -NCa Little difference in color symptoms between this photo and the -N photo. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 38. -PK Here typical -K deficiency is shown by leaf on right while the leaf is beginning to show some bronzing which is typical of -P deficiency. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 39. -PCa The deficiency color is probably associated with -P rather than with -Ca. Although color looks yellow, it is actually a metallic bronze color. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

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Figure 40. -KCa Color is almost normal only size of leaf is affected. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 41. -NPK The color here is almost normal except for leaf on the left. The upper leaf, from seedlings growing in complete solution, are normal. Photo 10/1959

Figure 42. -NPCa Here too, as more than one of the elements is omitted there is less abnormal color than when nitrogen or phosphorus are omitted singly from the solution. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

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Figure 43. -NKCa Only the leaf on the left shows pronounced color deficiency sumptoms. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 44. -PKCa The dominant color deficiency symptom is due to -K. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

Figure 45. -NPKCa The color of these leaves is almost normal. It is clear that low levels of the four elements do not cause marked color deficiency symptoms. It is only when the balance is greatly altered that the symptoms become pronounced. The upper leaves, from seedlings growing in a complete solution, are normal. Photo 10/1959

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TABLE 35.--Survival, weight, and length of two-week-old seedlings grown for 112 days in complete and nutrient deficient sand-culture solutions.

Treatment	Survival	Weight (OD)		Length		
		Stem	Root	Stem	Root	Petiole
	percent	-- grams --		----- inches		--------
Complete	92	3.5	2.3	16.6	8.9	3.9
-N	0	-	-	-	-	-
-P	0	-	-	-	-	-
-K	0	-	-	-	-	-
-Ca	100	3.7	6.6	15.9	10.0	3.9
-NP	67	0.1	0.1	1.6	5.8	0.2
-NK	0	-	-	-	-	-
-NCa	75	0.1	0.4	2.4	8.4	1.7
-PK	25	0.4	0.8	4.3	7.1	0.8
-PCa	25	0.1	0.2	1.3	2.3	0.4
-KCa	17	0.6	0.4	4.7	7.7	2.8

TABLE 36.--Stem diameter, leaf size, and number of leaves and branches per seedling of two week old seedlings grown for 112 days in complete and deficient sand culture solutions.

Treatment	Stem Diameter One-inch Above G.L.	Maximum Leaf Size	Leaves Per Seedling	Branches Per Seedling
	mm	index*	number	number
Complete	5.8	34.2	12.1	4.4
-N	-**	-	-	-
-P	-	-	-	-
-K	-	-	-	-
-Ca	6.8	40.5	15.4	3.5
-NP	0.9	1.1	2.7	0.0
-NK	-	-	-	-
-NCa	1.6	2.9	5.3	0.0
-PK	3.6	2.6	7.7	0.0
-PCa	0.9	0.5	2.0	0.0
-KCa	3.2	17.3	7.5	0.0

*Product of widest part of the blade by the length of the blade in inches.

**Dash indicates that seedlings died before harvest.

Figure 46.--Complete solution (September 9). Seedlings are from 12- to 40-inches tall and leaves have normal color. Photo 1960

Figure 47. -N (July 15) All of these seedlings subsequently died. Photo 1960

Figure 48. -P (August 17) The actual color is bronze for most of the leaf with the margins a delicate pink due to formation of anthocyanin. All seedlings died. Photo 1960

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Figure 49. -K (July 15) Typical potassium deficiency symptom showing disintegration of chlorophyll in interveinal areas. Photo 1960

Figure 50. -K (August 17) The veins remain green but interveinal areas show further breakdown of chlorophyll. All the seedlings died. Photo 1960

Figure 51. -Ca (September 9) These seedlings are as large as those growing in the complete solution and leaf color is normal. Photo 1960

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Figure 52. -NP (September 9) The leaves show a combination of nitrogen and phosphorus deficiency symptoms but principally nitrogen symptoms. Photo 1960

Figure 53. -NK (September 9) Typical nitrogen deficiency. Very little potassium symptoms evident. These seedlings all died. Photo 1960

Figure 54. -NCa (September 9) The deficiency symptoms are becoming evident and these are due to -N since seedlings in the -Ca solution grew as well or better than in complete solution. Photo 1960


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Figure 55. -Pk (September 9) The first leaves have died and the young leaves show a bronzing along the margins. Photo 1960

Figure 56. -PCa (September 9) The bronze color is due to -P since -Ca has little effect on leaf color. Photo 1960

Figure 57. -KCa (September 9) Typical potassium deficiency symptom but no effect from -Ca. Photo 1960


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omitted. Seedlings in the -Ca solution were heavier than the seedlings growing in the complete solution, but the increased growth occurred mainly in the roots. This was also true for the 1959 experiment. The omission of the second order combination of the four elements resulted in death or in greatly reduced growth of many seedlings before harvest. However, the omission of combinations of elements caused less mortality than the omission of nitrogen, phosphorus, or potassium singly.

Discussion

The failure of the 1959 experiment to produce marked color deficiency symptoms can be attributed to slow growth resulting mainly from two causes. One, the seedlings were in leaf when lifted for planting from the nursery and probably suffered severe shock, which slowed growth. The second cause can be attributed to the high temperatures prevailing in the greenhouse during the summer of 1959. This, too, slowed growth. No cooling devices were available for reducing the temperature. The 1960 seedlings were very small when planted, and suffered little planting shock and also the greenhouse temperatures could be held at or below 90° F. by a water cooling device. This permitted faster growth and induced early and more severe deficiency symptoms since the limited supply of the omitted nutrient was quickly exhausted.

The omission of N, P, and K in combinations of two elements at a time rather than singly, in the 1960 experiment, did not cause seedling mortality but did greatly reduce growth. This can be attributed perhaps to the fact that the omission of N, P, or K singly prevents a main metabolic pathway from operating while permitting other pathways to operate at near full capacity. The net result being that products and by-products of the operating pathways pile up until the whole system is unbalanced and death of the seedling ensues. When two or more elements required in relatively large quantities for the seedling to grow satisfactorily are present in very short supply, several metabolic pathways may be slowed and the products from the pathways will be greatly reduced. The seedlings will survive and grow but at a much reduced rate because essential compounds can be produced even though in relatively small quantities.

The -Ca solutions actually contained about seven ppm of calcium. The sources of this calcium were the reagent grade chemicals used to prepare the culture solutions and the distilled water used in the experiment. This low concentration of calcium seems adequate under the conditions of the experiment to supply sufficient calcium to the seedlings for satisfactory growth.

Fertilizer Experiment

Nitrogen fertilizer depressed growth of seedlings on the sand soil (Spinks) as compared to growth of control seedlings. It slightly increased growth of seedlings on sandy-loam soil (Conover) receiving the complete fertilizer, and substantially increased growth of seedlings on the clay-loam soil (Belfontaine) receiving the 1000 pounds per acre of nitrogen fertilizer and the complete fertilizer. The increase in seedling weight was 47 and 22 percent for the 1000 pound and complete fertilizer treatments respectively. The results of all fertilizer treatments are shown in Table 37.

All seedlings receiving phosphorus fertilizer treatments on the sand and sandy-loam soil were heavier than the control seedlings. The complete fertilizer on the clay-loam soil was the only effective treatment in increasing growth.

Maximum increases in weight of seedlings resulting from phosphorus fertilizer treatments were 32 percent and 20 percent for the sand, and sandy-loam soils respectively, and 25 percent for the clay-loam soil.

Potassium fertilizer had little effect on weights of seedlings growing on the sand or on the sandy-loam soil. However, seedlings were 42 percent heavier on the clay-loam soil receiving 450 pounds of potassium or complete fertilizer.

TABLE 37.--Fertilizer experiment. Weight of stems and roots in grams and stem diameters in millimeters.

Soil	Plant Part	Nitrogen Fertilizer[1]					Mean
		None	500	1000	1500	Complete[2]	
Sand	Stem	0.5	0.4	0.4	-[3]	-	
	Root	2.7	1.3	1.9	-	-	
	S + R	3.2	1.7	2.3	-	-	2.4
	Stem dia.	3.1	3.1	3.4	-	-	3.2
Sandy loam	Stem	1.4	1.2	1.6	2.3	1.6	
	Root	6.2	4.7	5.1	4.8	6.4	
	S + R	7.6	5.9	6.7	7.1	8.0	7.1
	Stem dia.	4.7	4.4	4.6	6.1	5.5	5.1
Clay loam	Stem	0.5	0.6	1.3	-	0.9	
	Root	2.1	1.4	3.2	-	2.5	
	S + R	2.6	2.0	4.5	-	3.4	3.1
	Stem dia.	3.2	3.5	4.7	-	3.9	3.8

Soil	Plant Part	Phosphorus Fertilizer[1]					Mean
		None	250	500	750	Complete[2]	
Sand	Stem	0.5	0.8	0.7	0.8	-[3]	
	Root	2.7	3.3	3.0	3.5	-	
	S + R	3.2	4.1	3.7	4.3	-	3.8
	Stem dia.	3.1	4.1	3.5	3.5	-	3.6
Sandy loam	Stem	1.4	1.6	1.8	1.5	1.6	
	Root	6.2	7.1	7.3	7.0	6.4	
	S + R	7.6	8.7	9.1	8.5	8.0	8.4
	Stem dia.	4.7	4.6	4.9	4.5	5.5	4.8
Clay loam	Stem	0.5	0.4	0.5	0.5	0.9	
	Root	2.1	1.6	1.7	1.9	2.5	
	S + R	2.6	2.0	2.2	2.4	3.4	2.5
	Stem dia.	3.2	3.3	3.2	3.2	3.9	3.4

TABLE 37.--Continued

Soil	Plant Part	Potassium Fertilizer[1]					Mean
		None	150	300	450	Complete[2]	
Sand	Stem	0.5	0.6	0.6	0.5	-[3]	
	Root	2.7	2.4	2.4	1.8	-	
	S + R	3.2	3.0	3.0	2.3	-	2.9
	Stem dia.	3.1	3.4	3.5	3.5	-	3.4
Sandy loam	Stem	1.4	1.5	1.1	1.2	1.6	
	Root	6.2	6.9	4.7	5.3	6.4	
	S + R	7.6	8.4	5.8	6.5	8.0	7.3
	Stem dia.	4.7	4.7	3.9	4.3	5.5	4.6
Clay loam	Stem	0.5	0.5	0.5	1.1	0.9	
	Root	2.1	1.6	1.6	2.6	2.5	
	S + R	2.6	2.1	2.1	3.7	3.7	2.8
	Stem dia.	3.2	3.1	3.2	3.7	3.9	3.4

Soil	Plant Part	Calcium Fertilizer[1]					Mean
		None	500	1000	1500	Complete[2]	
Sand	Stem	0.5	0.5	2.2	0.5	-[3]	
	Root	2.7	2.1	1.5	2.0	-	
	S + R	3.2	2.6	3.7	2.5	-	3.0
	Stem dia.	3.1	2.9	3.3	3.2	-	3.1
Sandy loam	Stem	1.4	1.4	1.0	1.4	1.6	
	Root	6.2	5.3	4.8	4.1	6.4	
	S + R	7.6	6.7	5.8	5.5	8.0	6.7
	Stem dia.	4.7	4.5	4.3	4.3	5.5	4.7
Clay loam	Stem	0.5	0.6	0.6	0.5	0.9	
	Root	2.1	1.8	1.8	1.4	2.5	
	S + R	2.6	2.4	2.4	1.9	3.4	2.5
	Stem dia.	3.2	3.2	3.2	3.1	3.9	3.3

[1]Composition of complete fertilizer is: 1000 lbs. $NaNO_3$ + 500 lbs. H_3PO_4 + 300 lbs. KCl + 1000 lbs. $CaCl_2 \cdot 6H_2O$ per acre.

[2]Pounds/acre of $NaNO_3$, H_3PO_4, KCl, and $CaCl_2 \cdot 6H_2O$ respectively.

[3]Dash indicates that all seedlings died before harvest.

Generally, calcium fertilizer either depressed growth or where a stimulating effect was observed it was small.

The weight of roots exceeded the weight of stems by two to five times. This was true for all fertilizer treatments on all soils with one lone exception. The heaviest seedlings were always found on the sandy-loam soil either in the presence or absence of fertilizers. Roots in the sand soil were very finely fibrous, less so in the sandy-loam soil, and quite coarse in the clay-loam soil (Figures 58 to 60).

Foliar nitrogen, potassium, and calcium percentages generally increased as the rate of fertilizer application increased. The growth response to phosphorus fertilizer was more consistent and greater than for the other fertilizers. The relationship between foliar phosphorus percent and amount of applied fertilizer was erratic and differences in foliar percentages were small (Table 38).

Some characteristics of the three soils are shown in Appendix B.

The fertilizers applied to the three soils were available to the seedlings; and this is shown by foliar analyses, which indicated increased uptake as the rate of fertilizer application increased. Foliar percent of nitrogen, potassium, and calcium increased more with increasing rate of fertilizer application on the sand soil than on either the sandy-loam or clay-loam soils.

Figure 58.--Root development of seedlings after one growing season in a clay-loam soil (Belfontaine B).

Figure 59.--Root development of seedlings after one growing season in a sandy-loam soil (Conover A).

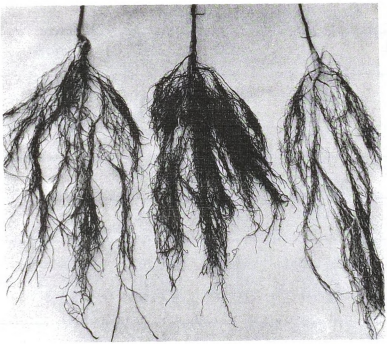

Figure 60. Root development of seedlings after one growing season in a sandy soil (Spinks B).

TABLE 38.--Fertilizer experiment. Nutrient percent of leaves (ODW) in relation to fertilizer rate of application (lbs/A).

Soil	Nitrogen Fertilizer[1]				
	None	500	1000	1500	Complete[2]
Sand	2.82	3.41	3.90	-[3]	2.78
Sandy loam	2.34	2.98	3.92	3.46	3.43
Clay loam	2.54	3.30	3.28	-	3.52

Soil	Phosphorus Fertilizer[1]				
	None	250	500	750	Complete[2]
Sand	0.16	0.18	0.16	0.16	-[3]
Sandy loam	0.14	0.16	0.15	0.17	0.20
Clay loam	0.16	0.18	0.22	0.24	0.20

Soil	Potassium Fertilizer[1]				
	None	150	300	450	Complete[2]
Sand	0.49	0.78	1.01	1.36	-[3]
Sandy loam	0.64	0.70	0.86	0.90	1.20
Clay loam	0.68	0.72	0.72	0.94	0.96

Soil	Calcium Fertilizer[1]				
	None	500	1000	1500	Complete[2]
Sand	1.46	1.68	2.07	2.47	-[3]
Sandy loam	1.72	1.73	1.78	2.01	2.05
Clay loam	1.43	1.52	1.78	2.05	1.58

[1]Pounds per acre of $NaNO_3$, H_3PO_4, KCl, and $CaCl_2 \cdot 6H_2O$ respectively.

[2]Composition of complete fertilizer is: 1000 lbs. $NaNO_3$ + 500 lbs. H_3PO_4 + 300 lbs. KCl + 1000 lbs. $CaCl_2 \cdot 6H_2O$ per acre.

[3]All seedlings died before harvest.

This greater increase probably results from less of these elements being involved in cation exchange. The cation exchange capacity of the sand soil is 75 percent or less than the cation exchange capacity of the other two soils. There was no correlation between total soil nitrogen and foliar nitrogen percent. The sandy-loam soil total nitrogen percent was 0.179. This is two to three times as great as for the other two soils. The foliar nitrogen percent for the sandy-loam soil was, in most cases, less than for either the sand or clay-loam soil. The lack of correlation between total soil nitrogen and foliar nitrogen could be expected, since a large part of the total soil nitrogen is in organic form and not available to the seedlings.

The effect of the phosphorus fertilizer on the foliar phosphorus percent was small. Even on the clay-loam soil, where the relationship was strongest, the relationship between foliar percent phosphorus and growth were not meaningful.

Comparing the foliar analyses for the soil experiment to those obtained in the calcium series of the sand nutrient growth experiment, where growth was greatest, foliar percent nitrogen is satisfactory. However, foliar phosphorus percent is about one-fourth optimum, potassium about one-half optimum, and calcium is two to three times too great. It is unlikely that calcium per se is restricting growth, but rather that it is causing an imbalance between other elements. This view is somewhat supported when the effect of

single element application on growth is compared to the complete fertilizer effect on growth. Generally, growth associated with the complete fertilizer is greater than growth associated with single element fertilizer.

It seems evident from the data for this experiment that texture is the principal factor correlated with the observed differences in growth along with other associated soil factors. Under the conditions of this experiment, of the four fertilizers applied, only phosphorus significantly increased the dry weight of the seedlings.

Mycorrhizae Experiment

There were no significant differences in weights or length of seedlings due to treatments. The results of this experiment are summarized in Table 39.

The seedlings were grown for 56 days and then were harvested. This apparently was too short a period in which the mycorrhizal relationship could be established between the seedlings and the fungus. However, Clark (1964) grew yellow-poplar seedlings for 84 days in soil and the seedlings developed endotrophic mycorrhizae during this time. His mycorrhizal seedlings were about five times heavier than non-mycorrhizal seedlings.

It is also possible that the inoculum used did not contain fungi capable of forming the mycorrhizal relationship with seedlings, although this is not very probable.

TABLE 39.--Mycorrhizae experiment. Weight and length of stems and roots.

Soil	Soil Treatment	Not inoculated		Innoculated		Sterilized innoculum		Mean S + R
		Stems	Roots	Stems	Roots	Stems	Roots	
				Weight (grams)				
Spinks (sand)	Sterilized	0.4	1.4	0.2	0.7	0.3	0.2	0.5
	Not sterilized	0.4	1.1	0.3	0.8	0.3	0.6	0.6
Conover (sandy loam)	Sterilized	0.1	0.4	0.3	0.9	0.3	0.9	0.5
	Not sterilized	0.3	0.7	0.2	0.2	0.2	0.6	0.4
Mean		0.3	0.9	0.2	0.6	0.3	0.6	
				Length (inches)				
Spinks (sand)	Sterilized	4.6	8.3	2.6	6.6	1.7	4.3	4.7
	Not sterilized	0.4	1.1	0.3	0.8	0.3	0.6	5.1
Conover (sandy loam)	Sterilized	2.1	5.5	2.7	6.4	2.7	5.8	0.4
	Not sterilized	2.6	7.9	2.5	5.5	1.6	5.9	0.4
Mean		2.4	5.7	2.0	4.8	1.6	4.1	

The seedlings were planted August 3, 1960, and harested October 28. The seedlings were not planted until ate in the growing season, and this may have been a factor n the non-formation of mycorrhizae. The fungi may well ave completed most of their growth by the time the seedings were planted; and, hence, would not be aggressive in enetrating the seedling roots. Phares (1964) failed to ind mycorrhizae on red oak seedlings at the end of the first rowing season, but did find them at the end of the second rowing season.

The roots were scanned for the presence of mycorrhizae nd mycelia, but none were seen. However, the roots were ot sectioned. Even if mycorrhizae were present, they did ot significantly affect growth.

Based on Clark's work, success probably could be ttained by planting the seedlings early in the growing eason, using inoculum also collected early in the growing eason, and harvesting the seedlings after a full growing eason.

CHAPTER VI

GENERAL SUMMARY AND CONCLUSIONS

Growth Experiment

The sand-nutrient growth study indicated that maximum wth of yellow-poplar seedlings occurred at a solution centration of 300 ppm for nitrogen, 400 ppm for potassium, 50 ppm for phosphorus and calcium.

The oven-dry weight of stems exceeded the oven-dry ght of roots; but the fresh weight of roots exceeded the sh weight of stems, indicating that the roots are much re succulent than the stems.

Generally, size and number of leaves, length of stems d roots, stem diameter, and number of branches per stem re maximum at the optimum solution concentration of the ur elements.

The percentage of the four elements in leaves, stems, ots, and petioles generally increased as the solution con- ntration of the four elements increased.

The percentage distribution of total nitrogen in the edling parts for a solution nitrogen concentration of 0 ppm (optimum) was: leaves 60, stems 14, roots 25, and tioles 1 percent. Hence, the major portion of total

ıing nitrogen is in the leaves with the roots account-
for about one-fourth of the total.

The percentage distribution of total phosphorus in
lings parts for a solution phosphorus concentration of
ppm (optimum) was as follows: leaves 15, stems 38,
ts 44, and petioles 3 percent. Stems and roots have
ut equal amounts of phosphorus and between them account
more than 80 percent of the total.

The distribution of potassium in the seedling parts
400 ppm potassium (optimum) was: leaves 52, stems 26,
ts 17, and petioles 5 percent. As in the case of nit-
gen, the major share of the total potassium is contained
the leaves.

Calcium distribution in the seedling parts at the
timum of 50 ppm calcium solution concentration was:
aves 70, stems 15, roots 10, and petioles 5 percent.

Increasing the concentration of one element often af-
cted the uptake of some elements which were at a fixed
lution concentration. Thus, as nitrogen solution concen-
ation increased, the foliar percent and content of
tassium generally decreased. Also, as potassium solution
ncentration increased magnesium foliar percent and content
nerally decreased. Another example of the interaction
fect of ions is taken from the calcium series. In this
ries, as solution calcium concentration increased foliar
rcent magnesium decreased. This was not a dilution effect

e foliar content of magnesium also decreased as solution
ium concentration increased.

The quadratic polynomial model seems to fit the data
his experiment very well. In only one case was lack of
of the model significant. Some relationships were linear
ner than quadratic, but this resulted partly from not in-
asing solution concentration to the levels where growth
drastically reduced. Perhaps the major cause of non-
nificance for the quadratic relationship was due to the
ge variance and small number of observations per treatment.

The relationship between solution concentration of the
ied element and foliar percent of the four elements was
ghly significant (**). The relationship was linear for
trogen and calcium but quadratic for phosphorus and po-
ssium, although the coefficient for the X^2 variable in the
osphorus and potassium series was only significant (*)
ile the X variable (linear) was highly significant (**).
em, and root weights were highly significant, linear, and
versely related to solution phosphorus and calcium concen-
ations. Stem and root weight in the nitrogen and potassium
ries were not significantly related to solution nitrogen
potassium concentration. However, other evidence clearly
dicates that stem and root weights increase as nitrogen
creased to 300 ppm and potassium increased to 400 ppm
lution concentration. This evidence consists of leaf
ights, size, numbers, stem diameters, number of branches
r stem and similar data the values of which are maximum

0 ppm and 400 ppm respectively for nitrogen and po-
.um. Also, stem and root weights in the nitrogen series
correlated with foliar nitrogen content. In the phospho-
series stem and root weights were correlated with foliar
ent phosphorus. Stem and root weights were not corre-
d with either foliar percent or content in the potassium
.es. Root weights in the calcium series were correlated
ı both foliar percent and content while stem weights
ɛ correlated with foliar percent calcium.

It is evident from all the data that yield is related
nutrient solution concentration and that foliar percent
content are related to both solution concentration and
ld. Additional replication would undoubtedly improve the
imates of mean treatments and hence would strengthen the
ationships between solution concentrations and the de-
ndent variables.

The gain in yield in the nitrogen series from 100 ppm
the optimum (300 ppm) solution nitrogen concentration was
ly 21 percent for stems and 19 percent for roots, as com-
red to the increase in yield from zero to 100 ppm of nit-
gen. Similarly, the gain for stems in the potassium
ries was 37 percent and 20 percent for roots. This com-
rison cannot be made for the phosphorus and calcium series
nce yields were highest at the lowest phosphorus and
lcium solution concentration (50 ppm). The data from this
periment indicate that near optimum yields could be ob-
ined with an external level of available nitrogen of about

) ppm, which corresponds to a foliar nitrogen percentage
3.25. Similarly, for phosphorus, an external level of
ppm corresponding to a foliar percentage of 0.34; for
tassium, 50 ppm corresponding to a foliar percentage of
59; and for calcium, 50 ppm corresponding to a foliar
rcentage of 0.42.

The evidence from this experiment raises a question
s to whether or not the yields obtained by varying the con-
entration of a single element are meaningful. The follow-
ng table will illustrate the point (Table 40). It will
e seen that yields, nutrient concentration, and foliar per-
ent or content do not bear a constant relationship to each
ther. The logical design to use to test the interaction
ffects of combinations of nutrients at several levels of
olution concentration on yield would be some kind of a
actorial. This design requires a very large amount of
aterial, time, and money, if more than a few elements and
oncentration levels are tested.

For example, if five elements in combination are
ested at four solution concentrations and are replicated
hree times the number of pots required would be $4^5 \times 3$,
which equals 3062, clearly an impractical number. However,
Cochran and Cox (1960) in their textbook on experimental
design describe some rotatable designs. With modifications
the rotable design could be adapted to the problem of find-
ing a range of nutrient concentrations of the nutrient combi-
nations that result in essentially equal yields. This can

concentrations of N, P, K, and Ca and to foliar nutrients.

Stem + root weights - optimum solution concentration

Series	Weight (OD)	Solution concentration				
		N	P	K	Ca	Mg
	grams			ppm		
N	11.29					
P	16.12	300	253	319	364	176
K	16.37	300	50	319	244	176
Ca	19.50	300	253	400	244	176
		300	253	319	50	176

Foliar concentration and content

Series	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium	
	Percent	Mgms/ Leaf	Percent	Mgms/ Leaf	Percent	Mgms/ Leaf	Percent	Mgms/ Leaf	Percent	Mgms/ Leaf
N	4.28	30.8	0.52	3.7	1.41	10.2	1.55	11.2	0.56	4.0
P	3.88	38.8	0.34	3.4	2.00	20.0	0.88	8.8	0.54	5.4
K	3.54	40.4	0.46	5.2	2.09	23.8	0.95	10.8	0.48	5.7
Ca	2.73	27.3	0.90	9.0	1.62	16.2	0.42	4.2	0.81	8.1

TABLE 40.--Continued

Base content per leaf (K + Ca + Mg)

Series	Mgms	Chemical Equivalence
N	25.8	40.6
P	34.2	48.4
K	40.3	46.8
Ca	28.5	40.8

achieved with but little sacrifice in statistical in-
rmation, but with an immense gain in efficiency. By this
stem, five element combinations at five levels and five
plications would require only 135 pots. In this system,
ird and higher order interactions could not be tested;
t main effects and second order interactions could be
sted very sensitively.[1]

Deficiency Symptom Experiment

It was found in this experiment that slow-growing
eedlings do not develop foliar deficiency symptoms as
apidly nor as severe as do fast-growth seedlings.

Nitrogen, phosphorus, potassium, and calcium omitted
rom a nutrient solution either single or in combination
roduce deficiency symptoms of different degress. Thus,
f N, P, or K are omitted singly from the nutrient solution,
oung, fast-growing seedlings soon die. However, older,
lower-growing seedlings survive. If some elements are
mitted in combinations of two, the results are less drastic.
or example, omitting NCa and NP resulted in about 30 percent
ortality; but omitting PK, PCa and KCa resulted in about 80
ercent mortality. Thus, seedling mortality is high when
olution nitrogen concentration is high and P or K is low.
pparently, the omission of Ca has little effect, since

[1]Personal communication from Dr. Robert E. Phares,
orth Central Forest Experiment Station, Ames, Iowa.

lings receiving about 7 ppm Ca grew better than seed-
s growing in a supposedly balanced solution. Obviously,
omission of the elements greatly reduced growth.

Foliar color deficiency symptoms were developed in
es from slow and fast-growing seedlings, and these are
ıstrated by color photographs. It is believed that the
ographs will be useful as aides in identifying severe
eral N, P, K, or Ca deficiencies.

Fertilizer Experiment

Nitrogen fertilizer increased the growth of young
dlings on a clay-loam soil, but depressed growth of
dlings on a sand soil; and had little effect on growth
seedlings on the sandy-loam soil.

Phosphorus fertilizer increased growth of seedlings
ewhat on a sand and sandy-loam soil, but not on the clay-
m soil. Potassium fertilizer had little effect on growth
seedlings on the sand or clay-loam soil. The 1500 pounds/A
lication slightly stimulated the growth of seedlings on the
y-loam soil.

Calcium fertilizer either depressed growth or only
mulated it to a small degree.

Generally, the complete fertilizer was more effective
n the application of the elements singly.

However, growth was not stimulated to a great degree
any of the three soils. From the results of foliar

yses and growth data, it appears that the four nutrients present in the soil in adequate available amounts for sfactory growth.

Soil texture and associated soil properties exerted ry much greater effect on growth than did fertilization. rth of seedlings on the sandy-loam soil generally was e as great as on the other two soils. This was true ardless of rate or kind of fertilizer applied.

Mycorrhizae Experiment

No significant differences in growth of seedlings on culated or on uninoculated soil was observed. Reasons the failure to obtain positive results in this experi- t probably can be ascribed to the fact that the seedlings e not planted in the pots until late in the growing son (August 3) and grew for a relatively short period 5 days). It is probable the fungi had already completed ir rapid growth; and hence, mycelia failed to reach the dling roots. The roots were scanned for the presence of corrhizae or mycelia, but none was found. Since the roots e not sectioned, it is not known whether or not mycor- zae formed. The mycorrhizae which have been found on low-poplar are the endotrophic type, and this type is easily identified on the root surface.

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APPENDIX

APPENDIX A

PLANT TISSUE ANALYSES PROCEDURES

Microkjeldahl Method

Total nitrogen of leaves, petioles, stems, and roots was determined by a modified microkjelkahl procedure. Fifty to 80 milligrams (weighed to nearest tenth of a milligram) of finely ground oven-dried (70°C) plant material were introduced into a 10 ml microkjeldahl flask. A microspatula of dry mixture consisting of one part of K_2SO_4 plus three parts of $HgSO_4$ is added to the flask followed by one cc of concentrated H_2SO_4 solution (1 gram of salicyclic acid to 30 cc of H_2SO_4). The flask contents are digested until the solution is water clear (2-3 hrs). All flask contents are brought into solution using a small quantity of distilled water.

The flask contents are transferred to the distilling apparatus and 5 cc of concentrated NaOH is added. The ammonia is distilled into a receiver Erlenmeyer flask containing 10 cc of 1.5 percent boric acid and a few drops of brom cresol green-methyl red indicator. The distillate is titrated with standardized 0.01 normal HCl and the quantity of total nitrogen is calculated.

In this procedure organic matter (fats and carbohydrates) is oxidized to CO_2 and H_2O and the protein nitrogen is hydrolyzed to amino acids. The nitrogen is liberated as ammonia and converted to ammonium sulphate by H_2SO_4 solution.

The NaOH solution releases the nitrogen as ammonia from the $(NH_4)_2SO_4$.

Flame Photometer Procedure

Potassium was determined on a model B Beckman flame photometer. Approximately two-tenths of a gram (weighed to nearest tenth of a milligram) of oven-dried (70°C) finely ground plant material was placed in an Erlenmeyer flask and shaken at intervals for thirty minutes with fifty ml. of 1.0 normal ammonium acetate and then filtered. The filtrate is oxidized in the acetylene-oxygen flame of the flame photometer, and the galvanometer reading is recorded. Potassium as ppm is read from a previously calibrated curve relating galvanometer readings to solution potassium concentrations expressed as ppm potassium.

Photoelectric Spectrometer Procedure

Analyses for phosphorus, calcium, magnesium, iron, manganese, copper, boron, zinc, molybdenum, and aluminum in leaves, petioles, stems, and roots were carried out on Michigan State University's "Quantograph" photoelectric spectrometer operated under the direction of Dr. A. Kenworthy of the Horticultural Department.

A one-half gram of finely ground and oven-dried plant material is ashed for 12 hours at 500°C. The ash is dissolved in 5.0 ml. of HCl acid-cobalt-lithium-potassium

solution and a portion of this solution is burned in the spectrometer. Using prepared tables, chart readings are converted into percent or into ppm of the elements.

APPENDIX B

Fertilizer experiment. Soil texture and soil nutrients before applying fertilizers.

Soil	Mechanical analyses			Available nutrients				Total Nitrogen
	Sand	Silt	Clay	P	K	Ca	Mg	
	percent			pounds per acre				percent
Spinks B_1 horizon Sand	87.2	7.1	5.7	150	64	1152	576	0.088
Conover A_1 horizon Sandy loam	62.4	24.8	12.8	31	136	3360	1376	0.179
Belfontaine B horizon Clay loam	48.1	30.8	21.1	22	280	2352	1264	0.061

Fertilizer experiment. Soil pH, C.E.C.[1], and base saturation before applying fertilizers.

Soil	pH	C.E.C.[1]	Base saturation			
			K	Ca	Mg	Total
			percent			
Spinks	5.0	11.9	0.7	24.2	20.2	45.1
Conover	6.2	18.4	0.9	45.4	31.3	77.6
Belfontaine	5.3	16.0	2.2	36.5	32.9	71.6

[1]Milliequivalents per 100 grams soil.

APPENDIX C

Growth experiment. Nitrogen series. Composition and concentration of nutrient solutions.

Source	Milligrams of Source Per Liter	Concentration of nutrient elements (ppm)						
		N	P	K	Ca	Mg	S	Fe
KH_2PO_4	1112	--	253	319	--	--	--	--
$CaCl_2 \cdot 6H_2O$	1335	--	--	--	364	--	--	--
$MgSO_4 \cdot 7H_2O$	1780	--	--	--	--	176	232	--
Iron Citrate	80	--	--	--	--	--	--	4

	Solution nitrogen concentration (ppm)					
	0	100	200	300	400	800
	Source - NH_4NO_3					
Source per liter mgms	0	285.7	571.4	857.2	1142.9	2285.8

Growth experiment. Phosphorus series. Composition[1] and concentration of nutrient solutions.

Solution Phosphorus Concentration	Source	Milligrams of Source Per Liter	P	N	K	Ca
ppm						
0	KCl	609	--	--	319	--
	NH_4NO_3	857	--	300	--	--
	$CaCl_2 \cdot 6H_2O$	1335	--	--	--	244
		Total	--	300	319	244
50	KCl	489	--	--	256	--
	NH_4NO_3	857	--	300	--	--
	$CaCl_2 \cdot 6H_2O$	1335	--	--	--	244
	KH_2PO_4	219	50	--	63	--
		Total	50	300	319	244
100	KCl	369	--	--	193	--
	NH_4NO_3	857	--	300	--	--
	$CaCl_2 \cdot 6H_2O$	1335	--	--	--	244
	KH_2PO_4	439	100	--	126	--
		Total	100	300	319	244
200	KCl	128	--	--	67	--
	NH_4NO_3	857	--	300	--	--
	$CaCl_2 \cdot 6H_2O$	1335	--	--	--	244
	KH_2PO_4	878	200	--	252	--
		Total	200	300	319	244
400	NH_4NO_3	478	--	167	--	--
	$CaCl_2 \cdot 6H_2O$	817	--	--	--	214
	KH_2PO_4	1112	253	--	319	--
	$NH_4H_2PO_4$	544	147	66	--	--
	$Ca(NO_3)_2 \cdot 4H_2O$	558	--	67	--	30
		Total	400	300	319	244
700	$CaCl_2 \cdot 6H_2O$	110	--	--	--	20
	KH_2PO_4	1112	253	--	319	--
	$NH_4H_2PO_4$	1287	347	157	--	--
	H_3PO_4	316	100	--	--	--
	$Ca(NO_3)_2 \cdot 4H_2O$	1320	--	157	--	244
		Total	700	314	319	244

[1]To all solutions of this series 1780 mgms per liter of $MgSO_4 \cdot 7H_2O$ were added resulting in 232 and 176 ppm of magnesium and sulfur respectively. Also 80 mgms of iron citrate per liter were added resulting in an iron concentration of 4 ppm.

Growth experiment. Potassium series. Composition[1] and concentration of nutrient solutions.

Solution Potassium Concentration	Source	Milligrams of Source Per Liter	K	N	P	Ca
ppm						
0	$NH_4H_2PO_4$	940.5	--	114.5	253.4	--
	$Ca(NO_3)_2 \cdot 4H_2O$	964.9	--	114.5	--	163.8
	NH_4NO_3	202.8	--	71.0	--	--
	$CaCl_2 \cdot 6H_2O$	439.7	--	--	--	80.4
	Total		--	300.0	253.4	244.2
50	$NH_4H_2PO_4$	940.5	--	114.5	253.4	--
	$Ca(NO_3)_2 \cdot 4H_2O$	964.9	--	114.5	--	163.8
	NH_4NO_3	202.8	--	71.0	--	--
	$CaCl_2 \cdot 6H_2O$	439.7	--	--	--	80.4
	KCl	95.4	50	--	--	--
	Total		50	300.0	253.4	244.2
100	$NH_4H_2PO_4$	940.5	--	114.5	253.4	--
	$Ca(NO_3)_2 \cdot 4H_2O$	964.9	--	114.5	--	163.8
	NH_4NO_3	208.8	--	71.0	--	--
	$CaCl_2 \cdot 6H_2O$	439.7	--	--	--	80.4
	KCl	190.7	100	--	--	--
	Total		100	300.0	253.4	244.2
200	$NH_4H_2PO_4$	940.5	--	114.5	253.4	--
	$Ca(NO_3)_2 \cdot 4H_2O$	964.9	--	114.5	--	163.8
	NH_4NO_3	208.8	--	71.0	--	--
	$CaCl_2 \cdot 6H_2O$	439.7	--	--	--	80.4
	KCl	381.4	200	300.0	253.4	244.2
400	NH_4NO_3	857.2	--	300.0	--	--
	$CaCl_2 \cdot 6H_2O$	1334.9	--	--	--	244.2
	KH_2PO_4	1111.9	319.4	--	253.4	--
	KCl	153.8	80.6	--	--	--
	Total		400.0	300.0	253.4	244.2
800	NH_4NO_3	857.2	--	300.0	--	--
	$CaCl_2 \cdot 6H_2O$	1334.9	--	--	--	244.2
	KH_2PO_4	1111.9	319.4	--	253.4	--
	KCl	916.5	480.6	--	--	--
	Total		800.0	300.0	253.4	244.2

[1]To all solutions of this series 1780 mgms per liter of $MgSO_4 \cdot 7H_2O$ were added resulting in 232 and 176 ppm of magnesium and sulfur respectively. Also, 80 mgms of iron citrate per liter were added resulting in an iron concontration of 4 ppm.

Growth experiment. Calcium series. Composition and concentration of nutrient solutions.

Source	Milligrams of Source Per Liter	Concentration of nutrient elements (ppm)						
		Ca	N	P	K	S	Fe	Mg
KH_2PO_4	1111.98	--	--	253	319	--	--	--
NH_4NO_3	857.16	--	300	--	--	--	--	--
$MgSO_4 \cdot 7H_2O$	1780.00	--	--	--	--	232	--	176
Ferric Citrate	20.00	--	--	--	--	--	4	--
	Totals	--	300	253	319	232	4	176

	Solution calcium concentration (ppm)					
	0	50	100	200	400	800
	Source - $CaCl_2 \cdot 6H_2O$					
Source Per Liter mgms	0	273.3	546.6	1093.2	2186.5	4375.4

Hydrogen-ion concentration of growth study nutrient solutions.

Nutrient Concentration (ppm)	Hydrogen-ion concentration (pH)					
	July 13[1]	Sept. 15[2]	Oct. 13[3]	July 13[1]	Sept. 15[2]	Oct. 13[3]
		Nitrogen Series			Phosphorus Series	
0	5.02	5.44	5.43	4.72	4.25	4.11
50	--	--	--	4.31	4.52	4.25
100	4.87	4.85	4.54	5.23	4.72	4.41
200	5.49	4.77	3.87	4.53	4.85	4.00
300	4.97	4.55	3.98	--	--	--
400	4.72	5.31	4.26	4.72	4.78	4.33
700	--	--	--	3.76	4.80	4.14
800	4.80	5.39	4.70	--	--	--
		Potassium Series			Calcium Series	
0	5.14	4.20	3.82	5.00	4.70	5.11
50	4.91	5.14	4.58	4.91	4.78	5.16
100	5.15	4.65	3.87	4.72	3.87	4.87
200	4.92	4.68	4.68	4.95	4.50	5.06
400	5.39	4.45	4.45	4.87	4.17	4.89
800	5.33	4.68	3.81	4.71	4.25	4.97

[1]7 or 8 days from date of adding solutions to pots.

[2]35 days from date of adding solutions to pots.

[3]28 days from date of adding solutions to pots.

pH of distilled water supply 6.80 on July 14 and 6.97 on Sept. 15.

Nutrient deficiency experiment. Composition and concentration of the nutrient solution used in the 1959 and 1960 study.

Source	Milligrams of Source Per Liter	Concentration of nutrient elements (ppm)			
		N	P	K	Ca
		Complete solution			
NH_4NO_3	857	300	--	--	--
KH_2PO_4	658	--	150	189	--
H_3PO_4	474	--	150	--	--
K_2CO_3	19	--	--	11	--
$CaCl_2 \cdot 2H_2O$	737	--	--	--	200
	Total	300	300	200	200
		-N solution			
		Same as complete -NH_4NO_3			
		-P solution			
NH_4NO_3	857	300	--	--	--
K_2CO_3	354	--	--	200	--
$CaCl_2 \cdot 2H_2O$	737	--	--	--	200
		-K solution			
NH_4NO_3	857	300	--	--	--
H_3PO_4	948	--	300	--	--
$CaCl_2 \cdot 2H_2O$	737	--	--	--	200
		-Ca solution			
		Same as complete -$CaCl_2 \cdot 2H_2O$			
		-NP solution			
K_2CO_3	354	--	--	200	--
$CaCl_2 \cdot 2H_2O$	737	--	--	--	200
		-NK solution			
H_3PO_4	948	--	300	--	--
$CaCl_2 \cdot 2H_2O$	737	--	--	--	200

Source	Milligrams of Source Per Liter	Concentration of nutrient elements (ppm)			
		N	P	K	Ca
		-NCa solution			
KH_2PO_4	658	--	150	189	--
H_3PO_4	474	--	150	--	--
K_2CO_3	19	--	--	11	--
		-NPCa solution			
K_2CO_3	354	--	--	200	--
		-PKCa solution			
NH_4NO_3	354	300	--	--	--
		-NPKCa solution			
--	--	--	--	--	--

In all pots Mg ppm = 176 and S = 232 derived from magnesium sulfate. Iron = 4 ppm from ferric citrate.