EFFECTS ON TREES OF AN ILLUMINATING GAS IN THE SOIL[1]

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Introduction

Problems concerned with trees injured by illuminating gas accidentally leaking into the soil may be said to have commenced in 1807 when the first public street gas lighting system was installed in Pall Mall, London (**10**). Although various phases of the problems presented when illuminating gas is seeping into soil in which the roots of plants are growing have been investigated by botanists, chemists, and others for at least seventy years, no general agreement has been reached upon the exact manner in which vegetation is injured, killed, or otherwise influenced. A brief survey of the literature consulted is given to establish the present status of the general problem.

NEUMAN in 1842, according to GIRARDIN (**12**), described the poisoning of elm trees by gas. By 1864, GIRARDIN, in Lille, France, was studying the soil for the cause of severe injury to Italian poplar trees located near a leaking gas conduit. About this time injuries to street trees were being reported from a number of European cities. The cause of the injury, and death of shade trees on several of the chief thoroughfares in Berlin brought about an extended controversy. This was described by LAISSUS and HEIM (**16**). Some thought that gas in the soil was responsible; others thought that unfavorable conditions of water supply, nutrition, high temperatures, and other factors were chiefly responsible for the conditions of these trees. It was suggested that the soil around the roots of the trees should be inclosed by impervious cylindrical walls to avoid the action of illuminating gas, from leaking conduits, on the trees. In 1900, WEHMER (**25**) described the injury of elm trees in the vicinity of a gas leak in Hanover, Germany, and included an illustration showing the leafless condition of the tops of the trees and the sloughing off of large patches of the basal bark. In 1903 (**18**), at Yonkers, New York, considerable trouble was experienced owing to gas injuries upon shade trees. The writings of STONE (**21, 22, 23, 24**), from 1906 to 1916, gave evidence of the frequent instances of injuries to trees in New England which were attributed to the escape of illuminating gas in the soil. In recent years, in the United States field cases of gas in the soil affecting tree growth unfavorably have rarely been reported in the scientific literature. Accidental occurrences of this type are more frequent than is generally supposed. When they involve a conspicuous shade tree or extensive injury to a number of trees in a small locality the necessity for information upon the factors involved, accurate diagnosis, and possible remedial measures become urgent.

[1] Contribution from the Osborn Botanical Laboratory, Yale University.

Investigative work with trees experimentally subjected to illuminating gas has covered a variety of the aspects of the general problem. LAISSUS and HEIM (**16**) describe one experiment by POSELGER in the 1860's, in Berlin, in which eight young trees planted in a wooden box were subjected to a flow of gas into the soil for three hours a day during forty days. No ill effects to the trees were observed and the conclusion was that gas in the soil was not injurious to trees. The toxic nature of the gas in Berlin was soon afterward established by KNY (**15**), and SPÄTH and MEYER (**20**). Differences in the susceptibility of various species of trees to injury by gas were noted by these investigators, and by WEHMER (**26**), DOUBT (**7**), and others. The toxicity of illuminating gas in the soil was attributed to residues of "brown oily substances" as well as high contents of sulphur and ammonium salts by GIRARDIN (**12**). BOEHM (**1**) associated the injurious action of gas with the "tarry products" left in the soil. BRIZI (**2**), EHRENBERG (**8**), EHRENBERG and SCHULTZ (**9**), SORAUER (**19**), and SCHOLLENBERGER (**17**) considered the displacement of oxygen in the soil atmosphere the chief cause of injury to vegetation. HARVEY and ROSE (**13**) thought ethylene was the most harmful constituent remaining in the soil in a gaseous state. WEHMER (**27**) emphasized hydrocyanic acid as the chief toxic agent. HITCHCOCK, CROCKER, and ZIMMERMAN (**14**) found that while the removal of hydrocyanic acid greatly reduced the toxicity of one illuminating gas it did not eliminate the injurious effects of the gas in the soil. Detailed descriptions of the symptoms and the field conditions associated with shade trees injured in various ways were made by STONE (**21, 22, 23, 24**). The writer (**3, 4, 5, 6**) reported injurious as well as stimulative phenomena which were observed when small trees or tree parts were exposed to illuminating gas.

The accurate determination of injuries to established trees, directly attributable to gas in the soil, is attended with many difficulties. Three major factors involved in determining the cause of injuries are: the gas, the soil environment, and the tree. Each of these is complex and highly variable, and the diverse combinations that may and actually do result present many confusing field problems. Frequently the symptoms of gas injury in a tree are distinguished with difficulty from those resulting from other unfavorable conditions for growth. Conditions such as a hard packed surface soil, and coverings of impervious paving, which restrict aeration of the soil, make the solution of the problem more difficult. Illuminating gases are of different types depending on the process of manufacture. The composition of one gas may vary widely from time to time. Differences in the chemical composition of manufactured gases may account for the more severe action of gas leaks on vegetation in one community than in another. Gas from a modern manufactory is subjected to purification processes in the recovery of by-products and in the removal of ingredients known to have a corrosive action on metal pipes so that the constituents held chiefly responsible for the toxic action of gas in the soil during the past and from older manufacturing plants may not be those responsible for the effects of all illuminating gases. In an unpublished work the writer tells of three types of currently used manufactured gas. He here indicates that the epinastic response of tomato plant leaves varies with the respective gases when these gases surround the roots. The extent of a gas leak, the rate of flow of the gas, the quantity passing into the soil, and the time over which it acts are additional conditions of importance in determining the influence of illuminating gas on vegetation. It is with the latter features of rate and volume of gas flow that the present study is concerned. An attempt was made to establish for the gas used, and under the conditions imposed, quantitative limits for the amount of gas required to kill small trees when the illuminating gas was passed into the soil about their roots.

Experimentation

During the spring and summer of 1934 the following tests were made for the purpose of recording the influence of various rates of flow and quantities of a typical manufactured gas supplied to the soil in which three-year-old American elm trees were growing. The trees had been grown in clay pots and in April were transplanted to cans holding approximately 1 liter of soil. A layer of sand was placed on the bottom with a glass tube extending from the sand layer to beyond the rim of the cans for the introduction of the gas at the bottom of the soil and the root system. Upon a layer of loam soil the root mass of the potted trees was placed and additional soil sifted and tamped around the sides. Thirty trees were prepared in this manner and given regular greenhouse care.

Gassing of the soil of the trees took place outside a ground level window with rubber and glass tubing reaching from a laboratory gas outlet through a wet meter or a calibrated flow-meter to the bottom of the soil in the cans. The gas was of the coke oven type as supplied by the New Haven Gas Light Company. For the period covered by this study the average composition of this gas, together with the percentage of each component, except for naphthalene which is recorded in grains per 100 cu. ft., is given as follows:[2]

Carbon dioxide	1.70
Illuminants	3.00
Oxygen	0.20
Carbon monoxide	8.70
Hydrogen	51.00
Methane	25.90

[2] The writer is indebted to Mr. W. A. Fitzsimmons, Superintendent of Production of the New Haven Gas Light Company for this analysis.

Nitrogen	10.00
Naphthalene	3.50
Sulphur	trace
Hydrocyanic acid[3]	——

Between May 2 and August 7, 1934, twenty of the elm trees were subjected to a gassing of the soil about their roots. In table I brief descriptions of ten of the trees during and following the gassing treatment are reported. Later, additional data will be reported in regard to trees subjected to gas in the soil when the surface of the soil was covered with paraffin. Ten trees were grown through the summer as controls. Both the control and the gassed trees were placed in shallow trenches in the soil out-of-doors over winter so that the effects of the gas treatment upon the trees during the next season could be observed.

When injury to a tree occurred from gas passing into the soil the earliest symptoms observed were chlorosis of the leaves and defoliation. The conditions existing in the roots were not determined because it would have required the disturbance of the soil structure, which might have interfered with subsequent effects of the gas or its residues upon the trees. Chlorosis generally involved the leaf margins first and sometimes proceeded no farther. In a few cases, entire leaves quickly turned yellow and shriveled or abscissed without shriveling. Saturation of the soil by rain during the gassing of trees no. 3 and 7 was associated with this rapid type of chlorosis and defoliation. Usually, the lowermost leaves on the main stem or larger branches became chlorotic and abscissed before the younger upper leaves. When complete defoliation of some or all of the branches occurred the buds either remained unaffected or they shriveled and darkened in color as did the distal portions of the branches and twigs which became dry and brittle. Frequently the distal one-third or one-half of a branch and its buds died while the basal portion and its buds remained visibly unaffected. Shortly after complete defoliation trees no. 4 and 6 began producing vigorous new shoots from buds below the injured or dead portions of their branches.

During the summer of 1934 it was possible to class but one tree, no. 2, as killed. By the next spring no. 7 was dead. All the others lived and made some growth during the 1935 season. The older stems of some of the trees had died for a part of their length, but on the uninjured part new shoots developed and made vigorous growth. When the roots of all the trees were examined on October 10, 1935, they showed relatively few abnormalities. It was found that when tree no. 6 was subjected to 864 cu. ft. of gas, in 1934, the distal half of the tap root was blackened and brittle and many of the fibrous roots tore off readily when the soil was removed, but several lateral roots had an abundance of healthy fibers. At this time, the stem of

[3] The laboratory reports showed no hydrocyanic acid present.

TABLE I

SYMPTOMS OBSERVED IN TEN YOUNG ELM TREES GASSED IN CANS OF SOIL

TREE NO.	DATE	RATE OF GAS FLOW	TIME GASSED	TOTAL GAS SUPPLIED	SYMPTOMS
		cu. ft./hr.		*cu. ft.*	
1	May 2	4.2	11 hrs.	46.2	Gradual defoliation of lower leaves except one lower branch. Defoliation complete by August 29 except for the normal lower branch. Buds dried on two branches; others normal
2	May 4	4.2	$7\frac{2}{3}$ hrs.	32.2	Yellowing of margins of lower leaves during the first three months. In August, complete defoliation. Roots injured; buds very small. Dead, 1935
3	May 18	1.5	5 days	180.0	Considerable defoliation of lower leaves on fifth day. Some marginal chlorosis. A number of leaves retained in a functional state until October. Buds well filled
4	June 20	1.5	6 days	216.0	General defoliation on fifth day of gassing, remaining leaves turned yellow and shriveled. In a month, 8 new shoots developed. By end of August, foliage on new twigs about mature and normal. Dead buds at ends of older branches
5	July 13	0.85	15 days	306.0	Slight chlorosis of lower leaves in 3 days; partial defoliation in 62 days. Stem at ground line became swollen; outer bark separating in long plates. Inner bark soft. Buds well filled at end of growing season
6	July 28	7.2	5 days	864.0	Slight defoliation in two days, heavy defoliation next two days. In a month 26 new shoots were developing from buds 2 to 4 inches below bare tips of older branches. New foliage remained normal

TABLE I.—(*Continued*)

TREE NO.	DATE	RATE OF GAS FLOW	TIME GASSED	TOTAL GAS SUPPLIED	SYMPTOMS
		cu. ft./hr.		*cu. ft.*	
7	Aug. 3	0.6	11 days	158.4	Partial defoliation and chlorosis in 4 days. Complete defoliation in 11 days. Buds and twigs dried and became very brittle. Roots severely injured by October. Dead, 1935
8	Aug. 7	5.5	1 hr.	5.5	No visible injurious effects
9	Aug. 7	25.0	12 min.	5.0	In three weeks the foliage appeared a trifle lighter green than that of control trees, otherwise no ill effects observed
10	Aug. 7	20.0	30 min.	10.0	No injury observed.

tree no. 5 had become swollen at the ground line. While a deep crack into the wood had formed it was being covered by the growth of callus tissue and the bark was in unusually thick plates over the base of this stem. Observations of the condition of the stems and buds of the gassed trees at the close of the 1934 season proved to be a reliable guide in determining the severity of the injury sustained. Injury to the trees became evident during and following the actual exposure of the roots to gas in the same growing season. Residual effects of the gas treatment in the soil or in the trees did not appear to accumulate and bring about more severe injury or lethal effects the next year.

In addition to the foregoing tests, three elm trees in cans, prepared as previously described, were treated by passing 36, 14, and 7 cu. ft. of gas into the soil and immediately sealing the soil surface with a layer of melted paraffin. The surface of the soil of one control tree was similarly sealed and the control trees of the previous tests served as checks of the behavior of the trees in normal soil with a free surface. Within ten days after the treatment of the soil of one tree with 36 cu. ft. of gas the characteristic "ethylene effect" of leaf epinasty appeared. Epinasty was most evident in the lower leaves, and less evident in the upper young leaves. Gradually the leaves of this tree became very dry and hard, the older leaves became brown from the margins to within 1 cm. of the midveins. The tree in soil receiving 14 cu. ft. of gas lost two-thirds of its leaves and exhibited marked chlorosis of the remaining leaves. The tree in soil through which 7 cu. ft. of gas had been passed continued normal in appearance except for a slight chlorosis at the bases of three leaves. The leaves of the control tree with the soil surface sealed became somewhat dry and hard. One month after the gas treatments these trees were removed from the cans for an examination of the roots. The soil was very dry and the small fibrous roots broke readily when the soil was being removed. Secondary roots had some areas of outer bark sloughing off. These features were common to the roots of the control tree with the soil surface sealed as well as of the gassed trees. During 1935 these trees made normal growth of tops and roots.

Discussion

The experimental results in this study in many respects follow the observed conditions and the known facts of a number of field cases of injury to established shade trees by illuminating gases leaking into the soil, which the writer has followed during the past six years. Rapid killing of a shade tree within a few days or a few weeks has been seen occasionally, but the more numerous cases are those in which chlorosis of the foliage on a portion of the tree and partial defoliation is subsequently followed by the drying out and death of uppermost twigs, and the dying of some branches and not of others. This process of gradual injury, although making for an unsightly tree and a hazard on streets because of the brittle branches likely to fall at any time, may continue for three or more years. The latter cases are the most confusing to diagnose, especially when the source of the gas in the soil is no longer evident and the tree is subject to serious insect and fungus attacks as a result of its lowered vitality, exposed branch stubs, loosened bark, and similar features associated with such trees.

With these young elm trees, two of the twenty were completely killed by the spring of the next season after the gassing. While some of the trees, those subjected to 5 and 10 cu. ft. of the coke oven gas, exhibited no signs of injury, those gassed with 32 to 864 cu. ft. of gas showed chlorosis of leaves, partial or complete defoliation, and the death of terminal parts of branches. In two instances, defoliation was soon followed by the development of latent buds on the stems below the injured part. In the following season many instances of partially killed stems were observed but new shoots were also produced and made excellent growth. Complete recovery would be expected with these young trees, based on their behavior the season following the gassing. Complete recovery in a larger tree would not be expected because of its age and the loss of so many branches from its top, regardless of the formation of new shoots.

Flowing 5 to 864 cu. ft., or 141.5 to 24,451 liters, of coke oven gas into one liter of soil for a period of twelve minutes to fifteen days was thought to embrace sufficiently drastic experimental conditions to produce rapid and definite lethal effects in these small elms. The results of the tests made it necessary to abandon the objective to determine even approximately the volume of this gas required to flow into the soil to kill these trees. Neither the conditions of the tests nor the physiological action of the toxic ingredient or ingredients permitted assigning definite values to the amount of this illuminating gas to produce unmistakable lethal effects in a short period of time. A review of the experience of others in experimentally subjecting trees to illuminating gases in the soil will add to the interest in the explanations offered for the results of this investigation.

KNY (**15**) supplied illuminating gas at the rate of 418.5 cu. ft. per day through four burners in the soil at the base of a twenty-year-old maple tree. The gas flowed from early July to January and involved an enormous volume of gas. A neighboring *Evonymus* bush showed withering of leaves and defoliation early in September; a nearby elm tree exhibited signs of injury; while the maple defoliated early in the fall. The following spring the bush and the two trees were dead. Into the soil beneath a linden tree 380 cu. ft. of gas were passed daily. This tree, although severely injured, was able to produce small pale leaves the next spring. SPÄTH and MEYER (**20**) found that 25 cu. ft. of gas per day, in July, killed the roots of established trees in a few days, but in the winter when the roots were dormant the trees were much more resistant to injury by twice this rate of gas flow. SHONNARD (**18**) found that 1.07 cu. ft. of gas per hour added to the soil of a potted lemon tree caused chlorosis of the leaves in five days and defoliation in eight days. EHRENBERG and SCHULTZ (**9**) subjected two-year-old linden trees to rates of gas flow into the soil of 0.2 to 2.7 liters per hour for a month. Partial defoliation was the chief feature noted, and when the trees were transplanted to fresh soil they recovered.

Work at the University of Chicago constituted a major contribution in the United States upon the plant physiological effects of illuminating gas. HARVEY and ROSE (**13**) recorded a variety of experiments with seedlings and potted plants exposed to ethylene-air mixtures, and to illuminating gas. High concentration of illuminating gas brought about rapid killing of the roots, and the chief symptom was death. This same gas flowing slowly through the soil in which woody plants were growing brought about a stimulation of the roots which resulted in the development of new tissue. When "water gas" of the Chicago Gas Light and Coke Company was distributed at the rate of 1.5 liters per hour in the soil beneath an *Ailanthus* tree on the campus from July 3 to September 2, leaves of some of the younger shoots wilted in eleven days. Subsequently, these and a few more leaves shriveled and died but no general effect over the entire tree was observed until early defoliation occurred in September. In October, the tree was dead and was characterized by a general dryness of the tissues. DOUBT (**7**) demonstrated the sensitivity of the tomato plant and other plants to low concentration of ethylene and illuminating gas in the atmosphere, and tested the responses of small potted trees to gas passed into the soil. With eight trees of different species treated forty to ninety days with 60 to 180 liters of gas in the soil, the foliage was little changed by the treatments. Swelling of the basal portion of the stems, cracking of the bark, and the production of proliferation tissue on underground parts were frequent symptoms. The most severe injury was exhibited by an American elm tree subjected to 180 liters of gas during ninety days. This tree lost half of its leaves, the bark at the base of the stem cracked open, and at the conclusion of the treatment the underground parts were dead. The conclusion was reached that the killing of trees by illuminating gas is a very slow process which may take months or years.

Previous studies by the writer (**3, 4, 5**), in which woody plants and their parts were subjected to a "mixed" illuminating gas, and in some instances to ethylene led him to conclude that there were three classes of plant physiological response to this illuminating gas: First, stimulation, such as acceleration of early development of latent buds, epinastic growth of leaf petioles, hypertrophy of lenticels, and proliferation of root parenchyma cells. Second, injury, such as inhibition of bud development (particularly terminal buds), dwarfing of leaves, loss of rigor by leaves, chlorosis, drying of portions or of entire leaves. Third, killing effects, which differ primarily in degree from those of injury. They were made evident in dormant trees by a blackening and drying out of buds without any sign of normal development, drying and wrinkling of the bark, drying out and brittleness of the stem and root wood, and when rapid, no hypertrophy of root lenticels or proliferation of parenchyma cells of the root. The type and the degree of the physiological response of these small trees varied with the time of exposure to the gas, the volume of the gas, the condition of the tree (dormant or growing), and the organ or part of the tree exposed to the gas.

Hitchcock, Crocker, and Zimmerman (**14**) found that when gas of the Westchester Lighting Company was introduced into the soil of small potted willow, maple, cherry, and silver bell trees at volumes of 1 and 4 cu. ft. for a period of thirty minutes, the larger volume caused the greater injury. Four cubic feet of the gas brought about severe injury to the roots with no ill effects on the aerial parts except in willow and maple. All of the woody plants, including privet, recovered in three to four weeks after the gassing with 4 cu. ft. of this gas. Ten cubic feet of this gas killed the five species of woody plants.

While the literature regarding the experience of other workers, who subjected trees to illuminating gases in the soil, does not permit concise generalization, it is evident that in most of these studies rapid lethal effects were not reported. Relatively large volumes of gas were required to seep into the soil for a considerable period of time before the death of entire trees occurred. Leaf, stem, bud, and root injuries frequently occurred, and, if the gas flow was of sufficient magnitude and continued long enough, death of the entire tree resulted. Injury to tops and roots in a number of cases was followed by recovery. A possible exception may be seen in the work of HITCHCOCK *et al.* (**14**) in which lethal effects on woody plants were observed when 10 cu. ft. of the Westchester Lighting Company gas was passed into the soil of small potted trees. The highly toxic nature of this gas was ascribed to the presence of hydrocyanic acid. When this acid was removed from the illuminating gas, twenty to twenty-four times more gas was required to produce the same type and degree of injury induced by the unscrubbed gas. Removing hydrocyanic acid, however, did not make this gas non-toxic.

Since the coke oven gas used in the present study was freed of hydrocyanic acid by an efficient scrubbing process at the manufactory it is logical to seek the explanation for the effects produced in the elm trees in the action of other constituents.

Experiments performed at this laboratory in which a "mixed" illuminating gas as well as ethylene and air mixtures were used, led the writer to conclude that it is possible to ascribe the responses of the elm trees gassed in the soil with coke oven gas to ethylene, or compounds with a similar physiological action on woody plants. In the complex composition of a commercial illuminating gas there may be a number of ingredients which will affect woody plants as ethylene does. The earliest symptoms of controlled soil-gassing in the elm trees were chlorosis and defoliation. Unpublished work done at this laboratory with ethylene in concentrations of 1 to 50 per cent. in air held about the bases of rooted cuttings of privet or the washed roots of small oak trees caused chlorosis, defoliation, and the drying out of the tops of woody plants. It is concluded therefore that ethylene, or gaseous ingredients of similar physiological action on plants, can explain the symptoms observed when relatively large volumes of the coke oven gas employed in this investigation are passed into the soil in which small elm trees are growing.

Summary

1. This investigation is concerned with a description of the symptoms observed when relatively large volumes of a coke oven type of illuminating gas were flowed into the soil in which young elm trees were growing, and with the probable explanation of these symptoms.

2. Five or ten cubic feet of this coke oven gas applied to the roots of elm trees produced no visible signs of injury.

3. When 32 to 864 cu. ft. of gas were used, a variety of injurious symptoms were observed in the trees. Chlorosis and defoliation were the chief early symptoms, followed, in some cases, by the drying out of the apical portions of the stems. Roots sustained injury but the sequence of this injury and its extent were not determined with these trees in undisturbed soil. Epinasty of leaves was observed following gassing when the soil sur-

face was sealed with paraffin. The stimulation of lower buds into active development was observed on stems defoliated by gas passed into the soil about the roots.

4. Two of the twenty trees that were gassed died before the beginning of the next growing season.

5. The trees in which the roots were exposed to 5 or 10 cu. ft. of gas in the soil exhibited no injurious effects the second season. Trees in soil gassed with 46.2 to 864.0 cu. ft. of gas exhibited signs of injury the second season. The injury consisted primarily of dried distal portions of some stems or branches. Below, the killed distal portions of stems or branches new, healthy, foliaged shoots developed. Very little definite injury to the roots of these gassed trees was observed in the second season.

6. It was not possible to assign limits for the volume of gas nor the period over which it must flow into the soil to produce definite degrees of injury or death.

7. From the similarity of these results to those obtained by using a "mixed" illuminating gas, and also ethylene and air mixtures enclosed about the roots of woody plants, it is suggested that ethylene or constituents of the coke oven gas with a physiological action similar to ethylene would explain the injuries, lethal, and stimulative effects upon these elm trees when roots were exposed to this coke oven gas in the soil.

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