PHYSIOLOGICAL PROBLEMS CONNECTED WITH THE USE OF SODIUM CHLORATE IN WEED CONTROL

A. S. CRAFTS

Introduction

The use of sodium chlorate for controlling weeds has become a general agricultural practice within the past decade. The attendant experimental work has produced a voluminous literature and has brought into prominence many problems of a purely physiological nature. Since progress in the experimental work on chlorate apparently depends upon properly comprehending the mechanics of its distribution and absorption, work on these phases would have an immediate value. This paper presents several problems for consideration by plant physiologists and persons experimenting with weed control and discusses them in the light of our present knowledge.

ÅSLANDER (1) reported in 1926 that chlorates would kill plants by absorption from the soil, and in 1928 (2) he discussed critically the problem of weed control by this method. Meanwhile, however, the use of sodium chlorate solution as a spray (11, 16) claimed the attention of weed workers; and in the popularity of this method, ÅSLANDER’s results were apparently overlooked. Most workers showed by their recommendations that they pictured the toxic action as taking effect through the plant after absorption of the chlorate by the leaves. Stickers, spreaders, various pressures, types of nozzles, and volume-concentration relationships were studied as they affected coverage of the foliage. Control of the hydrogen ion concentration of the spray solution, the inclusion of hygroscopic agents, and spraying methods in general were considered in attempts to improve the technique and avoid the erratic results so often encountered in the field.

Of twenty-nine publications on the use of chlorates that had appeared by the end of 1931, only three (1, 2, 17) emphasized the possibilities of the soil-application method. In 1931, LOOMIS, BISSEY, and SMITH, pointing out the advantages of this method, suggested that the action of sodium chlorate, as used in regions of summer rains, resulted largely from root absorption of chemical leached into the soil. Since then MUENSCHER (20) has pointed out the practical nature of the soil method, while LOOMIS and others (18) have given further experimental evidence of its feasibility.

Meanwhile there had been developed in California a method for treating certain deep-rooted perennials with acid arsenical spray (4, 5, 8, 15). Its success depends upon translocation of the toxicant within the vascular system of the plant. The question naturally arises, will this same mechanism
carry chlorate in the plant and, if so, to what extent does it explain the results obtained in the common use of chlorates?

As the writer has recently reported (6), chlorate may be moved through plants and may kill the roots to considerable depths as a result of leaf absorption and translocation within the xylem. The effects of a given treatment are limited by the same factors that govern penetration and root killing by the acid arsenical. When conditions are right, any application of chlorate solution to the foliage will result in some absorption and downward movement within the plant. The extent of injury will depend upon how nearly the requirements for successful treatment by this method are met.

Besides these two distinct mechanisms available for use in treating deep-rooted weeds, there are several interesting physiological responses by the plant to both lethal and sublethal doses of chlorate. The various effects that chlorates may have on plants will therefore be listed and discussed. Wherever possible, their relation to weed-control practice will be pointed out.

Physiological action of chlorates

There are, apparently, four fundamentally different ways in which chlorates may affect plants:

1. When a chlorate solution is applied to leaves, ions of the salt diffuse through the cuticle and come into contact with the protoplasm of living cells (18, 5). Although the coefficient of permeability of plant cells to chlorate ions is low (23), when they attain a lethal concentration they enter the plant cell, causing injury and eventually death. The exact mechanism by which this result is accomplished is not known. It has been suggested that the high oxidizing potential of sodium chlorate (22), the presence of pentavalent chlorine (22), and the complete oxidation of respiratory chromogens (12) may be involved; but no experimental evidence has been presented to support these ideas. Contrary to popular notion (14, 22, 23, 24, 26), sunlight or ultraviolet light is not essential to this process, which will take place in the dark (17); and open stomata (19) are not necessary, the chemical being fully toxic when applied to the ventral surfaces of hypostomatic leaves (5, 18). The solutions commonly applied as sprays in no way compare in concentration with those generally used in physiological experiments (23). They usually become saturated and therefore strongly plasmolytic soon after application, a steep gradient in concentration developing across the cuticle layers.

2. When chlorate ions exist in the plant in sublethal concentration, there is a typical response, characterized by a chlorotic, stunted condition of any growth that occurs, a reduction of the starch reserves (16), decreased catalase activity (21), and increased susceptibility to frost injury (16). These
symptoms may precede death of the tissues if conditions favor the continued uptake and accumulation of chlorate. Where additional chlorate is not available, the plant may recover and show no permanent effects.

3. Under certain limited conditions, a concentrated chlorate solution applied to the leaves of plants may penetrate the cuticle, plasmolyze and kill the mesophyll tissues, enter the xylem, and be carried down into the roots (7). The conditions essential to this action have been discussed in connection with acid arsenical sprays (4, 5, 8, 15). Experiments to be described indicate that the same response may occur with chlorates and will result in a rapid, deep killing of the root system.

4. Chlorates present in solution in the soil may be absorbed by roots, killing all parts in which they accumulate to a lethal concentration.

Although it has been intimated that chlorates may penetrate the leaves and be translocated through the phloem (11, 22), this possibility seems rather remote in view of the prevailing concepts of phloem tissues (3, 9). Movement of chlorate through a system so dependent upon the functioning of living cells is hard to imagine.

Under different conditions of treatment the four effects listed may occur in almost any combination, singly or together. Rarely in the field are less than two concerned; and often all four may be in evidence during the year. Naturally, therefore, results of plot tests have been difficult to interpret, and recommendations from different localities have been inconsistent and confusing.

Before discussing these four responses of plants to chlorate in greater detail, it would be well to consider briefly the inherent differences in plants with respect to injury in general and also with respect to injury by chlorates.

Many plants are easily killed. When cut off at the ground level, they fail to recover and die with no further treatment. Other plants will resprout from the stump or crown, and still others may regenerate from stem, rhizome, or root tissue and are eradicated only when all vestiges of the root are killed or removed from a suitable environment. In treating a variety of plants with a toxic substance like chlorate, one is sure to find differences in the degree of control; and unless he has previously determined their response to mechanical injury he cannot accurately interpret his results.

Furthermore, plants vary widely in their susceptibility to injury by chlorates. Although this fact has been pointed out many times (6, 10, 13, 28, 29), it will bear repeating because it is a striking phenomenon, vitally involved in the determination of dosages. Until one has determined in an empirical way the susceptibility of a particular species, he cannot well prescribe the dosage necessary for its control in the field.
Killing of plant tissue by chlorate

It has been pointed out that whenever chlorate ions come in contact with plant cells in sufficient concentration, the tissue is killed. Though the mechanics of this killing process form an interesting field for speculation, the critical point, so far as weed control is concerned, is that only the presence of chlorate in lethal concentration is necessary for the death of the cells. Our principal problem is distribution of the toxicant. For the desired results, it must come into contact with the vital tissues.

Obviously, therefore, the technique of application must be related to the plant concerned. If the plant is easily killed, a thorough spraying of the foliage is sufficient. If it resprouts weakly, spraying of the regrowth may effect a kill. On the other hand, if the plant regenerates strongly from the roots, killing of the tops is a small part of the problem, and spraying is effective only as it may lead to leaf absorption and rapid killing by xylem transport as described in (3), page 701, or as it distributes the chemical for leaching and absorption from the soil. Apparently the killing of the cells by chlorate is largely independent of the environment and is a matter only of concentration and cell activity.

Physiological responses of plant cells to chlorate

The effects of chlorate upon plants have considerable interest for workers in plant physiology. Concentrations in the tissues near or below the lethal point cause reactions that are apparently peculiar to chlorate alone. LASHAW and ZAHNLEY (16) pointed out the great reduction in starch reserves of roots after chlorate treatments. The writer has observed the same phenomenon not only in sprayed plants but in those which have absorbed chlorate from the soil. It has been seen in stems of plants containing a sublethal concentration and is undoubtedly present in all tops showing the stunted chlorotic growth that commonly follows dusting with Atlacide, or soil applications. Lowered catalase activity (21) and susceptibility to frost injury (16) accompany this condition; and, taken together, these responses indicate a lowered vitality in the presence of chlorate ions.

As has been mentioned, when conditions favor continued absorption of chlorate, this condition of lowered vitality is accentuated, so that the tissues finally die. With lowering chlorate concentration, however, they may recover and show no permanent injury. From the standpoint of weed control this response of plants to chlorates is of minor importance, being useful only as an indicator of the presence of the chemical.

Killing of plants with chlorate following leaf absorption and transport to the roots through the xylem

Having already been described, the action of this mechanism (4, 5, 8, 15) requires no further comment. That it will respond to chlorate sprays has
been demonstrated (6). Its possibilities in weed control, however, are of interest; and its relation to results obtained by present methods warrants comment.

Loomis and others (18) have shown that chlorate ions will enter and move through the xylem of plants. Their results are not surprising, for any solution of molecularly dissolved substance that does not undergo chemical change within the xylem will displace the xylem sap and follow the transpiration stream wherever the gradients in pressure may cause it to flow. The critical point is, will chlorates kill the leaf cells and, rendering them permeable, penetrate the xylem and be carried deep into the roots, causing their death? Recent developments (4) indicate that this method has practical possibilities, after all, and that chlorates might find a logical use in certain cases.

Although some evidence has been presented previously (6) and although this paper does not aim primarily to submit extended experimental results,

### TABLE I

**Effect of time of day, acidity, and concentration upon the root killing of morning-glory plants by sodium chlorate**

<table>
<thead>
<tr>
<th>Plot No.</th>
<th>NaClO₃ per sq. rod</th>
<th>H₂SO₄ per sq. rod</th>
<th>Time of application</th>
<th>Plants resprouting Oct. 8, 1931</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>1</td>
<td></td>
<td>P.M. Aug. 20, 1931</td>
<td>%</td>
</tr>
<tr>
<td>2</td>
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<td>4:00</td>
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<td>2</td>
<td></td>
<td>7:00</td>
<td>90</td>
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<td>4:30</td>
<td>90</td>
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</tr>
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<td>7</td>
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<td></td>
<td>8:00</td>
<td>10</td>
</tr>
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<td>8</td>
<td>1</td>
<td></td>
<td>P.M. Aug. 21, 1931</td>
<td>%</td>
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<td>1</td>
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<td>P.M. Aug. 22, 1931</td>
<td>%</td>
</tr>
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<td>15</td>
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<td>10</td>
</tr>
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<td>16</td>
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<td>1.25</td>
<td>8:00</td>
<td>5</td>
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</tbody>
</table>
the data on a few trials will be given to show the nature, possibilities, and limits of this method.

Table I presents the results of spraying a series of plots with sodium chlorate solutions in August, 1931. These applications were made during a period when the daytime temperatures reached 100° F. Though temperatures were somewhat lower toward evening, the relative humidity was low, and all sprays applied before sundown dried very rapidly on the leaves. The plots were in a young orchard that had been irrigated and disked late in June. A dense growth of morning-glory had matured and had lowered the soil moisture to a point approaching the permanent wilting percentage at the time the sprays were applied. Each plot was approximately 1 square rod in area, and the chemical was applied in 3 gallons of water. The foliage on all plots was killed within 48 hours.

As no rain fell between August 20 and October 8, 1931, the results at the latter date represent the action of chlorate on and through the plants. The plants on the plots showing low percentages of resprouting were killed to a depth of 3 feet or more. Glancing over the data, one observes that the more concentrated sprays were the more effective, that delaying the application until after sundown materially improved the results, and that sulphuric acid markedly increased the efficiency of the method.

Table II presents the results of some plot tests with sodium chlorate applied on September 28, 1931. Plots 4 to 6 and 10 to 12 in this series had been recently irrigated. The temperature at this date was lower and the relative humidity higher, so that penetration during the day was considerably better than in August. These results again show the effects of concentration of the solution and the value of adding acid to increase the rate of penetration. In addition they show the effect of soil moisture upon the action of the mechanism. Even though transpiration was high at this season, the plants in the moist soil did not have the high water deficit of the others, and distribution of the toxicant in the roots was less complete.

These experimental results are typical of a good many obtained during the work with chlorates. They indicate that this method has certain possibilities in areas where the plants deplete soil moisture rather thoroughly. In regions of frequent summer rains it would have no value.

In considering the practical possibilities of this method, one must note several points. First, it would probably never be more effective than the acid arsenical, and the chemicals will necessarily cost from three to five times as much. Second, the acid cannot be applied along with the chlorate, for the combination forms a strong oxidizing mixture that will ruin any machinery; it would have to be applied as a separate spray following the chlorate application. Finally, applications under the proper conditions would involve the fire hazards attending the use of chlorates.
TABLE II

<table>
<thead>
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<th>PLOT NO.</th>
<th>DATE IRRIGATED</th>
<th>SPRAYED SEPT. 28</th>
<th>NaClO₃ PER SQ. ROD</th>
<th>H₂SO₄ PER SQ. ROD</th>
<th>RESPROUTING NOV. 23, 1931</th>
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<td>1</td>
<td>20</td>
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<td>Aug. 15</td>
<td>5: 20</td>
<td>2</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Aug. 15</td>
<td>3: 45</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Aug. 15</td>
<td>4: 10</td>
<td>1</td>
<td>1</td>
<td>45</td>
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<tr>
<td>5</td>
<td>Aug. 15</td>
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<td>35</td>
</tr>
<tr>
<td>6</td>
<td>Sept. 24</td>
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<td>3</td>
<td>1</td>
<td>40</td>
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<tr>
<td>7</td>
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<td>4: 40</td>
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<td>1.25</td>
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<td>2</td>
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</tr>
<tr>
<td>9</td>
<td>Aug. 15</td>
<td>5: 40</td>
<td>3</td>
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<td>1</td>
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<tr>
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<td>Aug. 15</td>
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<td>3</td>
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</table>

On the other hand, with due caution this method might be used in pasture areas where the acid arsenical would present a poison hazard. Also, where conditions are optimum for this type of spray, the experimental results indicate that the chlorate dosage may be materially reduced. Furthermore, the application of sulphuric acid in a dosage providing a weight of the concentrated acid equal to that of the sodium chlorate will liberate chloric acid and reduce the chlorate ions reaching the soil so that little or no residual effect will be found. Sulphuric acid is best applied in a concentration of about 5 per cent. by weight or approximately one normal. Even this is corrosive to machinery and requires special acid-resistant equipment. Such equipment is available for using sulphuric acid as a spray on mustard in cereals.

KILLING OF PLANTS WITH CHLORATES BY ABSORPTION FROM THE SOIL

It is apparent that treatment of deep-rooted weeds through the soil is a logical method. The regenerative organs themselves are directly affected by the chemical; with proper dosage and distribution there is little possibility of failure. The method is not subject to those diverse and difficulty controlled factors to which the foliar organs are exposed.

In the problem of dosage, species susceptibility and the effect of soil type on chlorate concentration are vital factors. The problem of species
susceptibility has been mentioned. Variations are extremely wide. Timson (25) describes a parasitic plant called "witch weed" that requires a maximum of only 80 gallons of spray containing 12 pounds of sodium chlorate per acre for control of a solid infestation. At the other extreme, chlorates have often been applied to hoary cress and other of the less susceptible species at rates of 6 and 8 pounds per square rod with only partial kills. Though these latter results may be due in part to improper methods, more susceptible species treated under identical conditions are often completely eradicated.

At present the only hope for determining the dosage to use on a particular species in the field is an empirical test under local conditions. Though the operator may be guided somewhat by results described in the literature, soil and climatic factors so affect the growth of plants that local experience is usually required.

The influence of soil type upon chlorate toxicity, having been introduced in another place (7), will be only touched upon here. Though toxicities may vary as widely as five times between soils of different types (7), no generalization can be offered now that will aid in their determination. Again empirical testing is indicated as the most promising method for studying this effect. It seems at present that, within a soil series, toxicity will run higher in the coarser grades. Among series, recent alluvial soils exhibit the lowest toxicity; old weathered soils the highest. Much more work is required, however, before these statements can be proved. The results of such testing at this station will appear as the work is continued.

The fixing of chlorate in a form available to plants is another soil property to be considered. As experiments have shown (7), certain soils are able to hold chlorates so that they do not move freely in the soil solution. In general the soils showing the lowest toxicity have the strongest fixing power, and in these the proper vertical distribution of chlorate within the soil is a problem. Under the conditions at Davis, morning-glory must be killed to a depth of at least 4 feet or it will resprout and survive. A lethal concentration of chlorate, therefore, must be provided throughout the top 4 feet of soil if the treatment is to be a success. In a Yolo silt loam, leaching experiments showed (6) that about 6 inches of water were required when the chlorate was applied to moist plots, and from 8 to 12 inches when dry plots were treated. In a heavier soil these requirements might well be doubled. Where the moisture came as rainfall with opportunity for evaporation between storms, even more water would be needed. This one factor probably explains many of the failures attending the use of chlorates in the arid regions of the west.

Soil moisture enters the problem again in the matter of chlorate decomposition. Where rains keep the soil wet during the hot summer season,
residual effects from chlorate treatments are of little importance. Where the top soil dries out during the summer, chlorate remains intact and may persist for three years (6) or more. Under these conditions leaching with irrigation water is the easiest method for ridding the land of chlorate (6, 7). Where irrigation is not available, chlorates should be used with considerable discretion on heavy soils.

The proper season for chlorate application has been much debated. Many publications recommend the blossoming stage of the plants, which usually occurs in early summer. Sometimes the same recommendation will state that the plants should be mature or fully mature for successful treatment. In central California morning-glory comes into blossom in April and May. On unirrigated land it reaches maturity, as denoted by ripening of seed and cessation of terminal growth, in June and July. On irrigated land it may not mature until October. Obviously, therefore, these recommendations cannot be followed in any one treatment.

Hulbert, Bristol, and Benjamin found in Idaho (13) that treatments from May to August were equally effective by the following summer. Willard (27), and Sampson and Parker (24) treated successfully during the spring; Åslander (1, 2), Muenscher (20), and the writer (6) have had excellent results from winter treatments. Stage of growth therefore would appear to have little effect in this response. Careful analysis, however, indicates that this is not altogether true. Loomis and others state: "...sodium chlorate dissolved in the soil water readily penetrates and kills the roots and rhizomes of either active or dormant plants" (18). Although this is undoubtedly true, absorption of chlorate by dormant roots is apparently slower than by active ones. The writer has noted many cases where plants have survived fall and winter applications only to weaken and die in the early summer. Spring and early summer treatments through the soil have been generally more successful than summer and fall applications except as the latter have provided a lethal concentration in the soil for absorption during the following spring. Midsummer applications have given the greatest success only in regions of summer rainfall where the chlorate is very soon made available for absorption through the roots.

The plant root goes through three definite stages during the year. In the spring and early summer it is in a vegetative state characterized by rapidity of growth, absorption of water and mineral nutrients, and depletion of organic food reserves. During the summer and fall it replenishes its food reserves; growth and absorption become slower. During the winter, growth and absorption are at a minimum, and organic foods are only slowly changed. From the standpoint of its physiology, the root should be most susceptible to chlorate injury during its vegetative stage in the spring. The discussion just presented indicates that this is probably true.
At least two important factors are involved in this increased susceptibility during the spring. Rapid absorption of water and mineral nutrients by the roots should favor absorption and accumulation of chlorate within the plant, and the low level of food reserves should make the roots vulnerable. On the other hand, the gradual killing of plants in the spring following fall and winter applications takes place generally where a given dosage has been leached to a considerable depth and the actual chlorate concentration at any point is low. With the depletion of soil moisture, the chlorate concentration increases generally throughout the soil mass. In addition, because of the water moving into the plant roots and the selective rejection of chlorate resulting from the low coefficient of permeability of protoplasm for these ions, the chemical must concentrate at the surface of the root. As the ions concentrate to the lethal point the roots become injured, increasing in permeability, and then chlorate enters the plant in much greater amounts than before. The result is the complete breakdown and death so often noted as the soil moisture runs low. The effective concentration at the absorbing surfaces must be much higher than if the soil moisture were maintained by irrigation or rainfall. That this factor of concentration within the soil is important is indicated by the number of recommendations that warn against irrigating after chlorate applications. The writer has used irrigation water (6) for attaining a vertical distribution of chlorate in the soil with considerable success. Apparently it is harmful only where it maintains a high moisture content that effectively dilutes the chlorate, or where it leaches the chlorate beyond the region of absorbing roots.

Discussion and summary

Chlorate, as a plant poison, seems to have unique properties. It acts slowly (18) compared with the heavy metals, seeming to enter the plant in low concentration, and gradually accumulates if the source of supply is maintained. Though arsenic, when present in the soil, affects principally the absorbing organs and has little primary effect upon the tops, chlorate apparently affects the whole plant at the same time and in essentially the same way. Seedlings that have germinated in soils containing large amounts of arsenic are often found to have their roots so injured that water is absorbed through dead tissues as through a wick. Plants in soils containing chlorates in just as injurious quantities have strong root systems. Here the plants may exhibit considerable growth and then dry up and die completely. Very high concentrations of chlorate in the soil will kill roots just as does arsenic.

The writer is reminded of some early experiments with arsenic and chlorates on morning-glory shoots. Excised shoots placed in dilute solutions of these two chemicals react characteristically. The young tender tips of the shoots in arsenic solutions turn black and droop within 16 hours, and
the older leaves die later. With the chlorate-treated shoots, the older leaves die first; the tips turn chlorotic but do not die, and many actually grow for several days, elongating to the extent of 10 to 20 centimeters. Apparently, arsenic is primarily a protoplasm poison and kills as it goes, entering young and old tissues alike. Though chlorate will also kill by contact when present in high concentrations, it seems to enter the plant more slowly when absorbed from the soil or when applied in solutions of low concentration and allowed to act by accumulation in the tissues. The plant dies under these circumstances, not because the protoplasm has been killed by direct reaction with the toxicant, but rather because this material so disturbs the metabolic processes that the plant can no longer function normally. The symptoms are systemic in nature, and apparently assimilation and utilization of foods as well as other vital functions are affected.

The discussion presented shows that there can be no universally successful method for using chlorates. With the extreme variations in susceptibility of species and the number of factors affecting toxicity and absorption, methods must be adapted to the conditions of the treatment, the operator taking every possible advantage of the situation at hand. Though summer rains provide an ideal means for distributing the chemical in the soil, insuring the success of spring and summer applications in the humid regions, other methods must be used in the more arid parts of the west. Directions provided by chemical companies and experiment stations for the use of chlorates should be adapted to the locality in which the chemical is to be used.

The successful use of chlorate is obviously more difficult in arid regions. In California, three methods have been proposed (6): (1) fall spraying where rapid absorption and root killing are followed by leaching and absorption from the soil; (2) a straight soil treatment during the winter; (3) spring soil treatment followed by proper irrigation. All three methods, however, are subject to differences in growth conditions and soil type, and the first two depend upon rainfall. They must be used, therefore, with utmost care.

All soil applications should aim to provide a toxic concentration of chlorate throughout a proper depth of soil for absorption during the spring vegetative season. Plants left undisturbed in such soils accumulate chlorate as the moisture decreases and grow weaker with the advancing season. Hoeing or weed cutting will eliminate the few plants that struggle along and sometimes survive this treatment (6). This should not be done, however, until the plants are severely affected. At least one complete season must be allowed for success by the chlorate method, and provision must be made for destroying such seedlings as appear in succeeding years.

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