rapidly decomposed, so as not to leave a residue affecting the crops which follow.

Because of the inherent advantages of pre-emergence weed control, its use would soon be adopted if a chemical having all of the above-mentioned properties were found. Some day chemicals may be found that are specific enough to kill all the weeds without injuring a crop by nature of the tolerance of the crop itself. In the meantime the chemicals available today are effective, and with more fundamental information on the factors that affect herbicidal efficiency, each one can be used where it is most effective.

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CONTACT HERBICIDES
As Preharvest Defoliants or Desiccants

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Use of contact-type chemical herbicides, defoliants, or desiccants as harvest acids has been rapidly developing, coincident with thetrend toward more complete mechanization in production of important food and fiber crops. Defoliants are used only on crops that have a mechanism of leaf abscission normally activated by senescence or frost. Chemical desiccants are used to hasten drying of stems and leaves of crops with mature seed or tubers, which do not normally abscise leaves or increment of annual growth. Defoliants or desiccants must be contact in action and nontranslocated, and free of residual properties that would be harmful or objectionable to handlers or consumers of seed, tubers, or fibers of treated crop plants. Ease of application, efficiency in action, and economy of use are important. Chemical defoliation has its greatest development in cotton harvesting. Cyanamides and sodium chlorate-borate formulations are most widely used in this practice. Desiccation of legumes is commonly undertaken with dinitro compounds in an oil carrier. Soybeans have been experimentally handled in the same way. Desiccation of rice is promoted by use of herbicidal formulations popular as cotton defoliants. Flax, potatoes, and other major crops have been treated with contact-type herbicides to hasten maturity and permit more efficient harvesting. Formulation and use of contact-type chemical herbicides as harvest aids will undoubtedly be extended to other crops through the teamwork of industrial and public service research groups.

CONTACT-TYPE chemical herbicides have been occasionally used as crop defoliants and desiccants for at least 20 years, but it is only in the past 10 years that this practice has shown marked development, and only in the past 5 years have these herbicides become an important market source for agricultural chemicals.

This new development has followed certain important technological advances in modern agricultural production. The first of these has been the trend and development toward more complete mechanization in growing and harvesting of some of our most important food and fiber crops. During the past 20 years there have been great advances and improvements in the development by plant breeders and geneticists of new varieties of food and fiber crops, which more fully utilize the full growing season and the full productivity of the soil, and which are more precisely adapted to local soil and climate conditions. During the same period research scientists and the agricultural chemical industry have made available fertilizers and soil amendments, insecticides, fungicides, and herbicides, that have made possible the consistent and dependable production of maximum growth and development of these newer and better adapted varieties of crops. This combination of improved varieties and efficient use of plant protection products has in general resulted in later maturation and delayed harvesting.

One of the most striking examples of this development has been observed in the potato production areas in the northern states, where not over 15 years

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ago vines of commercial varieties of potatoes commonly became dead and dry and the potato tubers mature and hard well before the calculated first frost date. Now, some of these very same varieties of potatoes in the same areas, protected from insect and disease damage by modern insecticides and fungicides, maintain vigorous growth over a much longer period of time, and frost or artificial vine killing is necessary in order to mature and ripen the tubers for timely fall harvesting.

The terms "defoliant" and "desiccant," in referring to chemical aids in preharvest conditioning of crops, are not synonymous in meaning, action, or use. Defoliants are used only on dicotyledonous crops where nature has provided a normal mechanism of leaf drop—as with cotton. Desiccants are used for preharvest drying of actively growing plant tissues when seed or tubers are partially mature and in crops where abscission is not a well-defined inherent mechanism—as in potatoes, alfalfa, or rice.

The ideal crop defoliant which nature has provided in most areas is frost. The ideal chemical defoliant would have the physiological and mechanical action of frost. At the base of the leaf petiole in the majority of our important dicotyledonous species of crop plants, there is a short transitional region in which the sclerenchymatous tissues are either reduced or wanting and where the parenchyma cells have very dense protoplasm. This band is usually several cells wide but varies in this respect in different plants. At normal leaf maturation and drop following the first killing frost in the fall, or occasionally following attacks by leaf feeding insects or disease, the middle lamella breaks down or dissolves in this layer of parenchyma cells and the leaf petiole separates from the main stem at this point through the physical agitation of wind or other forces. The ideal chemical defoliant would bring about this same chain of reactions within the plant.

Monocotyledonous types of crop plants, whether annual or perennial in nature, do not have well-defined structural mechanisms for abscission of annual increment of growth or leaves. Frost or contact chemical herbicides kill the leaves of plants which dry up and deteriorate through mechanical action in annual monocots, such as the common cereal grains—wheat, oats, barley, rice, and corn. Desiccation of the leaves following frost or the action of contact chemical herbicides is followed by rapid drying of the stem and seed. This reaction is essentially different from that of defoliation.

A good herbicidal defoliant or desiccant should be characterized by controlled contact action. A "contact" herbicide is defined as a chemical material whose immediate physical or chemical action on plant tissue is locally phytotoxic and is not translocated through normal channels of sap movement within the plant or by diffusion to remote tissues or organs. In contrast, with materials such as 2,4-D (2,4-dichlorophenoxyacetic acid), the initial contact action is of little normal consequence. The tissues initially contacted by herbicides such as 2,4-D are not immediately killed, and the phytotoxic material may be translocated by various chemical and physical processes to remote tissues and organs within the plant. While there is considerable evidence that all the materials that we now classify as contact herbicides may, in sublethal dosages, be translocated for considerable distances within the plant body, their characteristic herbicidal action is seldom recorded in these instances, whereas, at lethal or above-lethal dosages, the contact and initial action of these materials is phytocidal. and the materials are held within the dead tissues locally. This latter characteristic is essential in using these materials as defoliants or desiccants on most crop plants and on annual weedy growth interspersed with crop plants at preharvest time.

In the use of chemical herbicides as defoliants or desiccants, the established characteristic of nontranslocation is of prime importance due to the fact that the seeds, fibers, or tubers of the treated plants must not become contaminated with the herbicidal chemicals or their breakdown products to the extent of impairing their qualities for food or fiber. Likewise, chemical herbicidal materials that might stain or inhibit certain normal pigment production in fruits, tubers, or fibers would be objectionable in that this would result in reduced market quality and consumer appeal.

Required Characteristics

A satisfactory contact herbicidal defoliant or desiccant must be relatively safe to handle in field application, must have minimum corrosive action on application equipment, and must be formulated and constituted so as to permit relatively low quantities of application to unit areas. Dust formulations requiring in excess of 30 to 35 pounds per acre for defoliation are in general undesirable and unpopular with applicators and growers. Sprayable formulations should be highly soluble in water as a carrier and should be formulated to permit application in volumes of water not to exceed 10 gallons per acre. The preponderance of chemical defoliant applications are, and will be, made by airplane and the utility of the airplane as an applicator drops sharply in operations that require in excess of 30 pounds of dust per acre, or 10 gallons of liquid spray solution per acre.

The ideal contact herbicide will defoliate or desiccate weeds associated with specific crops as well as the crop plants. In certain cases, particularly where fall-seeded legumes, such as vetch, are raised as an inter-rowed winter crop in cotton, the ideal cotton defoliant will have a minimum toxic effect on the vetch ground cover. Above all, a satisfactory chemical defoliant or desiccant must be low in unit area cost in order to represent an economic advantage to the grower. As a general figure, chemical defoliation, including materials and cost of application, which costs the farmer over $4.00 to $5.00 per acre approaches the limit of attractive economic use.

It is doubtful whether any one particular chemical compound or formulation will be developed as an ideal for defoliating or desiccating the variety of crops in which there is considerable interest at this time. Each crop, and the weeds associated with the culture of each crop, have peculiarities in growth, morphological structure, and ultimate utilization which require distinct qualities in a herbicide unique to that particular crop. In a crop such as cotton, the wide range of soil and weather conditions under which this crop is raised have further demonstrated the need for special formulations in each of several well-defined areas of production.

Potato Vine Killers

The preharvest killing of potato vines undoubtedly represents the earliest wide-scale use of chemical herbicides as harvest aids. In normal seasons, earlier maturation and hardening off of tubers through the artificial killing of vines and the subsequent earlier harvest represent an economic advantage to growers in certain segments of the industry. Late-developing diseases in potatoes are occasionally halted by destruction of the heavy vine growth without material reduction in potato yield or quality. The most common herbicides used for desiccation of potato vines are dinitro-*o*-*sec*-butylphenol applied in either oil or water; and calcium cyanamide, applied as dust at 125 pounds per acre as a single treatment or, if vines are extremely rank, applied in two treatments of 50 to 60 pounds per treatment with 48 hours between applications. Sodium arsenite and sodium nitrate have also been used as potato vine killers, but their use has never been extensive. Regardless of the type of material used, a week to 10 days is necessary after application for the potato tubers to harden off before they can be harvested and stored or shipped. The materials are generally applied by airplane. One of the reported disadvantages of chemical herbicides as potato vine killers is the fact that under certain conditions of temperature and vine growth, tubers of treated plants develop physiological discoloration that is difficult to differentiate from ringrot symptoms. As a result of this phenomenon, and because after chemical killing vines must still be removed from the field for efficient harvesting operations, mechanical cutting of potato tops has been widely adopted as a substitute for chemical desiccation (*5*). Growers are of the general opinion that mechanical removal of potato tops with a roto-beater results in fewer instances of tuber discoloration than with chemical killing, but these observations are not entirely supported by statistics of carefully conducted research and investigation.

Defoliation of Soybeans

Preharvest defoliation or desiccation of soybeans may offer certain advantages to the producers of this crop and may represent an additional important source of agricultural chemical consumption (*8*). To date, however, this application is almost strictly limited to the experimental stage. There are in excess of 15,000,000 acres of soybeans produced annually in the United States and production is centered in the area where late fall rains often interfere with harvest, which is normally undertaken by straight combining. Weeds of both the dicotyledonous and grass type commonly infest soybeans during the latter part of the season, and even in seasons when the soybean plants mature and lose their leaves before the time of first frost, the presence of succulent weed growth makes harvesting of the crop difficult and raises the average moisture percentage above the minimum requirement for safe shipping and storage. Early harvesting of soybeans, in general, represents an advantage in marketing, and, in areas where winter wheat is commonly seeded following soybeans, there is a distinct advantage in getting the wheat crop planted before the normal time when heavy fall frosts would kill and desiccate both beans and interspersed weeds. Because of the methods employed in harvesting soybeans, defoliation is not necessary when a chemical herbicide is used as a preharvest treatment. If the leaves and weeds are rapidly killed and desiccated, the crop can be harvested with standard combines without difficulty, as the dried leaf material is readily separated from the seed in the process.

J. L. Cartter, U. S. Regional Soybean Laboratories, Urbana, Ill., in cooperation with the Agricultural Experiment Station of the University of Illinois (*7*), has for several years conducted rather extensive trials to determine the relative chemical herbicidal qualities of several materials. Endothal (disodium 3,6-endoxohexahydrophthalate), sodium monochloroacetate, pentachlorophenol in oil, sodium pentachlorophenate applied in water spray, sodium chlorate-borate mixtures, potassium cyanate, sodium cyanamide, and contact dinitro herbicides applied in oil have been tested. The results indicate that all these materials have, under ideal conditions, given satisfactory desiccation of soybeans and weed growth, which has enabled them to advance the normal harvest date from 4 days to 1 week without reduction in soybean yield. No detrimental effect on germination or quality of bean seed was found if the applications were made when at least 25% of the leaves had begun to show yellow color. Application of herbicides before this indicated stage of maturity have, in general, resulted in some reduction in bean yield and have adversely affected the percentage composition of oil and protein in the beans and have reduced the iodine number of the extracted oil.

Desiccants in Seed Crops

In the improved and highly technical practices recently developed in legume seed production, especially in the irrigated areas of the Pacific Southwest, the chemical desiccants are playing an important role as a preharvest aid in producing seed crops (*4*). Most widely grown legume crops, other than red clover, sweet clover, and lespedeza, are indeterminate in fruiting habit, and efficient harvesting of seed of these crops is always complicated by the presence of succulent foliage which must be cut and dried before the seed can be mechanically removed. Maturation and harvesting of legume seed are, in general, further handicapped by the depredation of insects which clip the seed pods from the stems. In some areas seasonal rains and high humidity at time of harvest make drying of the windrowed crop difficult and loss of from 20 to 70% of the seed produced in certain crops, such as trefoil and ladino clover, has been common. As with soybeans, succulent weed growth interspersed with any legume seed crop, which does not normally mature coincidental with the legumes, further complicates harvest drying and processing. In preharvest desiccation of legume seed crops, the density of foliage and often weed growth makes it necessary to use highly active and nonselective herbicidal materials, which are applied in relatively large volumes of solution in order to wet the dense foliage thoroughly (*2*). Applications of dust formulations such as calcium cyanamide are not generally so effective as spray solutions applied in large volumes. Dinitro compounds, of the general type, using 1 to 3 pints of the standard formulation in 10 to 15 gallons of Diesel oil per acre have been generally most effective and widely adopted in use. This material is almost universally applied by airplane. The applications are made 1 to 5 days before anticipated harvest, and timing of harvest operations following this treatment is an important consideration. The combining must start as soon as the leaves are dry and before regrowth from the basal crown, or seed drop, has started. Shattering of seed of most legumes following effective application of a preharvest herbicidal material may start in 4 to 5 days after spraying and in general becomes serious in 8 to 10 days after treatment.

In certain cases where very dense growth of a crop such as alfalfa or alsike clover is being treated, a common practice is to make two applications of the herbicide at reduced rates—generally 1 quart of the standard dinitro formulation in oil per acre on successive days. Here, the first application opens up the dense foliage by killing the top growth and the second application can efficiently reach the lower growth.

In harvesting trefoil seed, ordinary methods of mowing and windrowing, as conditioning processes for harvesting, have resulted in excessive losses of from 70 to 90% of the seed because the pods of trefoil normally split and scatter the seed coincident with pod drying. The use of chemical herbicides as conditioners to cause trefoil foliage to wilt and dry has markedly improved the efficiency of seed harvesting of this crop. When temperatures are 90° F. or above and good threshing weather prevails, combining operations are started 5 to 24 hours after application of contact herbicides, such as the general dinitros, to trefoil. Growers carefully time their spray applications with their harvest facilities and seldom treat unit areas greater than can be harvested in a day's normal operation. Preharvest spraying of trefoil does not desiccate the seed and subsequent artificial drying is necessary in order to bring the seed to storage or shipping condition.

Data from California, where more than one fourth of the area producing 24,000,000 pounds of alfalfa seed was treated with preharvest sprays in 1951, record no cases of impaired germination of the harvested seed (*4*). Regrowth of perennial crops such as alfalfa, ladino, alsike, and trefoil, following preharvest herbicidal applications, such as here described, is as rapid and normal as where conventional harvesting operations are practiced and many growers report a distinct advantage in the preharvest conditioning treatments due to the fact that straw can be removed from the field within several days after threshing, whereas under normal conditions of harvest, the longer period required for drying in the windrow commonly interfered with regrowth of subsequent crops.

The use of preharvest contact herbicidal materials in production of flax appears to be practical only under conditions of weather and growth where the presence of heavy weed infestations prolongs the period of windrow drying of the crop for pick-up combine harvesting (*5*). Straight combining of standing flax is practiced only in relatively small areas such as some of the localized areas of southern winter production. In these situations contact herbicides, such as the dinitros, have been employed to desiccate succulent weed growth with marked advantage in harvesting operations and low moisture content of the harvested seed. In the north central states where the majority of flax is now produced, the unit value of the flax crops is relatively low and the economics of preharvest spraying, to accomplish more rapid drying of later windrowed crops, limits its possible future wide use.

Recent developments in the use of preharvest contact-type herbicides as desiccants to condition maturing rice for straight field combining have shown distinct advantages. Rice grain, when normally harvested by straight combining, will have a moisture content of 18 to 26% and is carried through two or three artificial drying processes to reduce the moisture content to 14%, which is considered safe for storage and shipping. Rice normally matures unevenly over a field, in most areas is subject to lodging when approaching maturity, and green succulent weed growth in rice fields in late fall, when combined with the standing grain, tends to increase moisture content of the combined seed. Work done by D. A. Hinkle of the Arkansas Agricultural Experiment Station in 1951 illustrates the advantages in use of preharvest contact herbicides as desiccants for rice (*3*). Hinkle and his coworkers made both ground and aerial applications of such materials as endothal, sodium monochloroacetate, and the chlorate-borate formulations. They found that, in general, all of the several formulations of herbicides used gave marked reduction in moisture percentage of sampled rice seed. They noted that the sprayed rice was as low in moisture 24 hours after treatment as the check plots were 5 days after treatment. Eight days after application of the several formulations, moisture content of rice in treated plots was in most cases within the range considered safe for storage, whereas the untreated checks still had 19.6% moisture. Data indicate no adverse effect on yield or quality of rice resulting from these practices. Field scale tests are reported by growers as facilitating the straight combining of rice under conditions of lodging or excessive succulent weed growth.

One of the most highly specialized uses of chemical herbicides has been developed for the artificial defoliating and hardening off of ornamental and nursery stock (*7, 10*). A. M. S. Pridham of Cornell University has been the leader in developing these techniques to the point where they are becoming established as a trade practice (*7*). Normally, nursery stock is either hand-stripped of leaves for early fall shipment, or digging, packing, and shipping must be delayed until frost or cold weather defoliates the field grown stock. In the past, growers have been only partially successful in using defoliation methods such as flaming, artificial reduction of water supply, artificial sweating of nursery stock in storage cellars, or the use of apple gas or ethylene chlorohydrin. The latter practices can be undertaken only in a confined area and necessitate removing the plants with foliage to a cellar before the defoliation is undertaken, and all are costly in time and labor. During the course of investigations at Cornell, Pridham found that certain higher alkyl aromatic sulfonates, such as Naconol NR, were useful in defoliating many standard varieties of ornamental nursery stock, but that temperature relations associated with their use often limit the economic advantages obtained. Since 1950, Pridham has been carrying on investigations concerned with the use of endothal formulations as defoliants and recent reports of these investigations indicate that the endothal formulations containing ammonium sulfate appear highly practical in the artificial defoliation of a wide variety of nursery stock common to the trade. This practice can be undertaken through field application at a relatively low cost and without detrimental residual action to later growth and development of the stock plants. While Pridham's investigations and development of this practice are of economic importance to a relatively limited industry, they are reported here as indicative of the diverse and specialized uses that may be made of the contact herbicide defoliants.

Defoliants in Cotton Production

The greatest potential use of herbicidal chemicals as preharvest defoliants is in cotton production (*6, 9*). Ten years ago only a few fields of cotton were defoliated. In 1951 defoliants were applied to about 3,000,000 acres. The marked increase in use of mechanical cotton pickers and snappers is greatly facilitated by natural or artificial defoliation previous to harvest. The additional ease and speed with which hand picking of cotton can be undertaken in defoliated fields, and additional benefits, such as reduction of boll rots, advantages in insect control, and improvement in quality and yield of lint and seed, are factors which are prompting an increasing number of growers to recognize in defoliation an opportunity to lower production costs and improve cotton quality.

Industry has recognized the importance of this development and in the past 5 years an ever-increasing number of formulations of chemical defoliants have been widely tested throughout the cotton-growing area in cooperation with growers and state and federal research workers. The rapid, successful development in use of these new techniques has been facilitated through the energetic and timely cooperation of the Beltwide Cotton Defoliation Conference of the National Cotton Council.

At the present time no one formulation or chemical herbicide can be satisfactorily recommended and used over the entire cotton-producing area, but there is considerable field scale evidence to indicate that this new practice may soon be successfully undertaken in almost every locality over the area which covers the wide range of culture, soil, rainfall, and locally adapted commercial varieties of cotton.

The Beltwide Cotton Defoliation Conference has defined certain of the desirable characteristics of herbicidal defoliants (*6*). Dosage tolerance—the range of rates of application which can be safely used under variable field conditions of growth and development without damage to tissues, which may result in leaf kill without leaf drop, or tissue damage to bolls—is an essential characteristic. This must be combined with dependable activation of the abscission mechanism over a wide range of weather conditions and degree of growth activity of the plant and must be operative over a reasonable range of leaf maturity. In producing areas where morning dew or high humidity is characteristic, herbicidal dusts are satisfactory. Where high humidity or dew is infrequent, sprayable formulations are required. Using these characteristics, established through several years of wide field testing, they list the following herbicidal materials for field use in 1952 (*6*).

Dusts

Calcium Cyanamide must be dissolved by dew, mists, or other sources of prolonged moisture supply. Moisture time requirements depend on plant condition. It has a broad dosage tolerance, is not highly sensitive to maturity, causes minimum tissue destruction, and requires fairly active foliage.

Monosodium Cyanamide (partially insoluble) is hygroscopic and remains dry at low humidities. It becomes liquid on the leaf by drawing moisture from leaves or from the air as humidity rises. It requires active foliage, has a broad dosage tolerance, and causes little tissue destruction.

Sprays

None of the following sprays requires dew and none is entirely dependent upon high humidity.

Endothal has average dosage tolerance, causes average tissue destruction, and is not too dependent upon full maturity.

Monosodium Cyanamide (fully soluble) requires active foliage, has an average to broad dosage tolerance, and causes average tissue destruction.

Pentachlorophenol (in oil) has very strong tissue action, usually causing cessation of further boll development at effective rates.

Potassium Cyanate is generally most effective for conditions of low foliage activity and full maturity. It causes average to strong tissue destruction.

Sodium Chlorate with sodium pentaborate is fairly sensitive to maturity and foliage activity. It has average tissue destruction and average dosage tolerance. Sodium chlorate alone is not recommended because it is explosive when dried in the presence of organic matter. This flammable tendency can be retarded if the sodium chlorate is mixed with at least equal parts of sodium pentaborate prior to application.

Sodium Monochloroacetate is sensitive to full maturity. It has average dosage tolerance, with average to strong tissue destruction.

Magnesium Chlorate, Hexahydrate (spray). Experience limited to 1951 indicates average dosage tolerance and tissue destruction with average requirements for foliage activity and maturity.

Many factors concerned with the use of any of the most popular herbicide defoliants, and undoubtedly related to growth conditions and maturity of the cotton, have not been fully established and controlled. Seldom is a field of any size treated under the most ideal predictable conditions with results of 100% defoliation of the cotton plants throughout the field. Artificial defoliation of cotton, however, as well as preharvest desiccation of soybeans, flax, rice, and legumes, has advantages over normal frost or weather drying, which definitely establish it as a growing practice in harvesting of these specialized crops. Artificial defoliation has the distinct advantage of timing which permits the grower to schedule harvesting operation in order to make most efficient use of labor and equipment, to mature crops at highest level of potential production, to evade or control insect and disease infestations, to adjust harvesting operations to most favorable market facilities and prices, and to evade, at least in part, the hazards of adverse harvest weather.

This discussion touches only some of the representative developments where the use of chemical herbicides as desiccants or defoliants is becoming established in field practice. These practices can well serve as typical examples of the expanding use of the new products of chemical research and processing which are being developed by botanists, plant physiologists, agronomists, and agricultural engineers, into efficient and widely accepted means of stabilizing and increasing our agricultural productivity.

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The development of the mechanical cotton picker and the increased use of herbicidal chemicals as preharvest defoliants have taken place side by side