How Soil Fumigation Benefits the California Strawberry Indust

First-year strawberry production on land fumigated with methyl bromide and chloropicrin (April 1967). Polyethylene film cover on beds shields fruit from the soil. Annual yields of 30 tons per acre are common in this area near Oxnard, California.

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Soil fumigation with mixtures of methyl bromide and chloropicrin has been an integral part of strawberry cultivation in California since about 1960. In addition to achieving high, dependable yields through the control of Verticillium wilt, other soilborne diseases, and weeds, the practice made possible far-reaching changes in crop management and thus has been of immense value to the industry. California has become preeminent in the production of fresh-market strawberries that are in high demand because of their outstanding qualities. To give credit to soil fumigation, however, is not to minimize the value of virus, mite, and insect control, of improvements in soil and water management, or the merits of potentially high-yielding strawberry cultivars.

The impact of soil fumigation in California is reflected in the common reference to distinct eras "before fumigation" and "after fumigation" among growers who remember the difficulties and frustrations of strawberry cultivation before the introduction of the soil treatments. Indeed, the two eras of strawberry growing have little in common. Effective weed control by fumigation, for instance, has led to the practice of covering plant beds with clear polyethylene film to shield the fruit from contact with the soil. By essentially eliminating cultivation for weed control, fumigation has also made possible the use of drip irrigation. Great uniformity of plant growth and high yields in first- and second-year plantings not only have benefited the growers but also have enormously favored the pickers. Nowhere else can a skilled picker harvest in 1 day 50–60 trays of one dozen pint baskets of strawberries, ready for shipment as they leave the field. During the months of highest production, more than 50,000 workers are gainfully employed in California harvesting the berries.

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The Era Before Soil Fumigation

Intensive strawberry cultivation began to develop in parts of California around 1880 (18). Figured from that time, the era during which strawberries were produced without the benefit of soil fumigation with methyl bromide-chloropicrin mixtures spans about 80 yr. According to the yields achieved, this period divides into halves. Until about 1920, annual berry yields of 1 ton per acre (2 metric tons per hectare) or less were typical. Subsequently, after the introduction and wide cultivation of cultivars such as Banner and Nich Ohmer in the central coastal district and Klondike in southern California, yields at times reached and occasionally exceeded 2,500 trays per acre, the equivalent of 15 tons. These yields were the highest in the United States and possibly in the world (10).

Since about 1950, strawberries in California have been produced almost entirely from cultivars developed by the University of California and by Driscoll Strawberry Associates, Inc., Watsonville, California. Although the yields of these occasionally reached 20 or even 30 tons per acre, the state average for the period from 1950 to 1960 did not rise above 5–6 tons per acre. The yield potential of the new cultivars obviously was far from being realized, and we can now say with certainty that soilborne diseases claimed the greater part of the untaken harvest.

The features most distinctive of the period before fumigation were the

Fig. 1. (A) Verticillium wilt of strawberries in July 1973 in a field insufficiently fumigated. (B) Portion of the same field fumigated with 275 lb per acre of a 57:43 mixture of methyl bromide and chloropicrin. Before soil fumigation, Verticillium wilt was a major limiting factor in strawberry production in California.

speculative nature of strawberry cultivation, the uncertainty of achieving economic yields, and a constant search for new land. The crop was considered tenuous and fickle to raise. Not only were root rots common, but fall- or winter-planted fields would often begin to show losses from Verticillium wilt (Fig. 1) when the fruit of the spring crop began to ripen. Frequently, within 2–3 wk after onset of the disease, the plantings would become nearly worthless; yield losses typically were most severe in the best-cared-for and most vigorously growing fields. The disease has been recognized in strawberries in California since 1912 (11) and was identified as Verticillium wilt in 1931 by Thomas (9).

In 1920, the Driscoll-Reiter strawberry organization suffered heavy losses from Verticillium wilt in a large planting on land with a recent tomato crop history. From that time on, growers linked outbreaks of the disease to previous tomato cultivation, and the most important question about land under consideration for strawberry plantings concerned its crop history. Generally, land on which tomatoes had been grown within the previous 10 yr was disqualified for strawberries, although many growers took the chances of planting on infested lands. Subsequently, previous cultivation of potatoes and, in the San Joaquin Valley, of cotton was recognized as having the same effects on strawberries as cultivation of tomatoes. Old orchards in the central coastal strawberry district, especially apple or prune orchards grown without irrigation, held top priority as new planting sites for strawberries, in spite of costs for removing the trees. But even here, Verticillium wilt often appeared and at times was devastating. These infestations were linked to hairy nightshade (*Solanum sarrachoides* Sendt. ex Mart.), a weed host that shows no symptoms except vascular discoloration (20). Thus, land suitable for strawberry cultivation became increasingly difficult to find in the major strawberry-growing districts of California.

In addition to Verticillium wilt, more subtle problems, described as unknown in nature and peculiar to the rich, organic valley soils, caused strawberry growers to shun large areas of valuable land. The first plantings of strawberries on such lands often grew profitably, but the second plantings were almost certain to fail. Lipman (4), the first to investigate the soil problems, ruled out nutrient depletion as a cause and, in 1914, concluded that soil compaction and inadequate aeration resulting from frequent irrigations and the foot traffic connected with picking brought about conditions unfavorable for the activity of beneficial soil bacteria. Left with no other choice, strawberry growers often retreated from the valleys to outlying foothill areas that usually had not been cultivated except for

Fig. 2. Prospective strawberry land in California being fumigated with a mixture of methyl bromide and chloropicrin. Simultaneously with injection of fumigant, soil is covered with polyethylene film 0.025 mm (1 mil) thick. One edge of the film is glued to the preceding strip while the other is buried in the soil to provide resistance to wind. Soil remains covered for at least 48 hr. An experienced team can fumigate 25 acres in 1 day.

pasture. There, after wet winters, strawberries often died from a root disease called "brown core," now known as red stele, caused by *Phytophthora fragariae* Hick.

To cope with the tenuity of strawberry cultivation and the problem of diminishing suitable land, California growers developed cultural systems that provided a measure of success. Fields were usually planted in the spring, with plants set several feet apart on the beds. The first year was devoted to establishment of the planting. Flowers were systematically removed, and water and fertilizers were managed to prevent excessive vegetative growth and promote deep rooting (10). Thus, as has been the case with other crops before the causes of soilborne diseases were known, a degree of disease control was achieved through cultural manipulations. With strawberries, however, this control cost the entire fruit production of the first year and at least 50% of the potential yield of subsequent years.

The Era of Soil Fumigation

In 1956, Wilhelm and Koch (15) reported that 480 lb of chloropicrin applied by handgun in the fall of 1953 to one acre of land controlled Verticillium wilt in the strawberry cultivar Shasta and that first- and second-year yields were 9.8 and 16.7 tons per acre, respectively. These were in contrast to normal yields of 4 and 7.6 tons per acre in the same field on land fumigated with ethylene dibromide. A successful trial of machine application of chloropicrin followed in 1955. During 1957 and 1958, the idea of mixing chloropicrin and methyl bromide was conceived and tested. The first experimental results, reported in 1961, indicated that methyl bromide not only augmented the fungicidal properties of chloropicrin but also gave excellent weed control (19). The fumigant mixture required immediate covering of the fumigated soil with polyethylene film

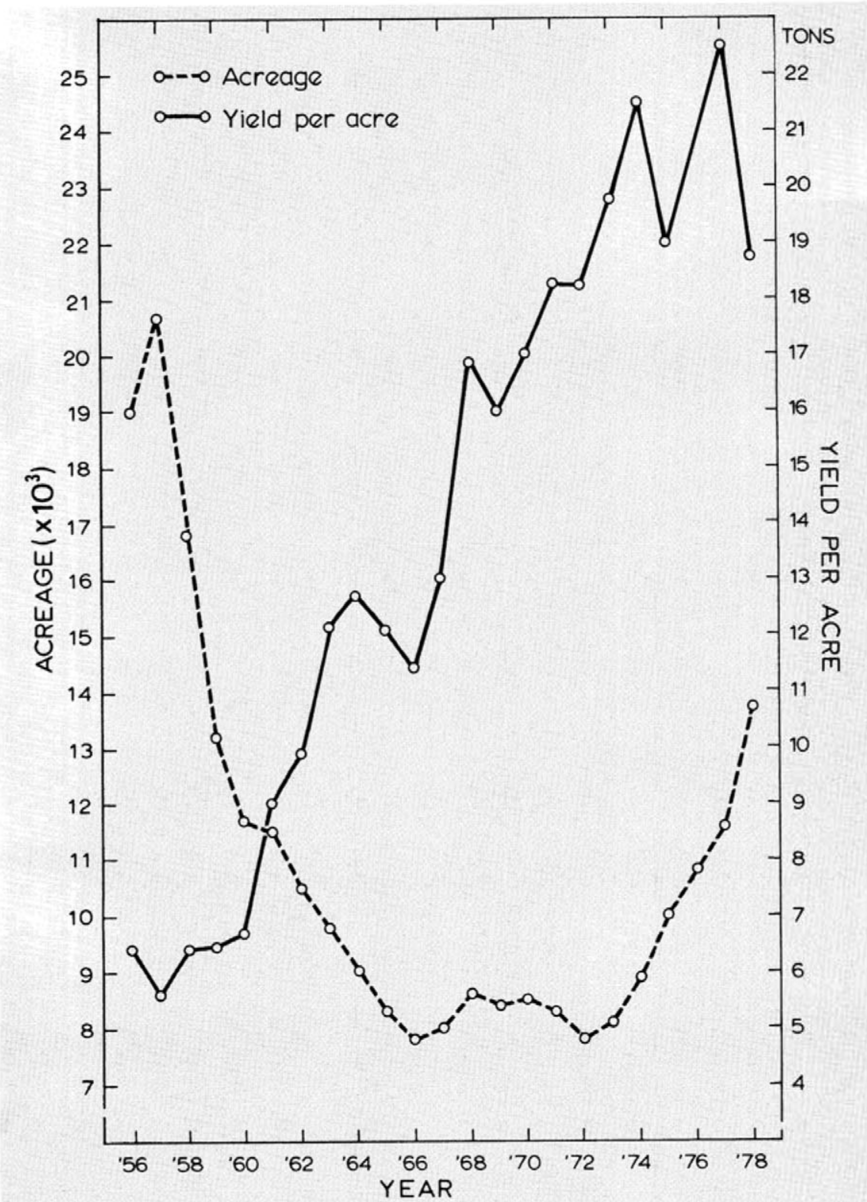

Fig. 3. California strawberry acreages and average per-acre yields from 1956 to 1978. After 1965, essentially 100% of all new plantings were on fumigated land. (California Crop and Livestock Reporting Service)

Fig. 4. Strawberry plant on left was grown in nonfumigated heavy loam field soil; plant on right was grown in same soil fumigated with chloropicrin. Both plants were the same cultivar and planted at the same time.

("tarping"), which was not essential after the application of chloropicrin alone.

The acreage of fumigated strawberry land rose rapidly after equipment was developed to apply the fumigant and polyethylene tarping simultaneously (Fig. 2) and to remove the tarping and after a new manufacturing process made chloropicrin more readily available. Since about 1965, nearly 100% of the strawberry land in California, both for fruiting and for nursery fields, has been fumigated before each crop is planted. Some fields have been fumigated and replanted with strawberries 15 times without buildup of toxic residues or destruction of desirable soil microflora. For the first fumigation of a field, methyl bromide and chloropicrin usually are applied as a mixture approximately 1:1 by weight at a rate adequate to control Verticillium wilt (375–420 lb per acre). Subsequent fumigations, usually with 2:1 mixtures and at lower rates, are aimed mostly at maintaining plant vigor and weed control.

The fumigation era has been characterized by rising per-acre yields of strawberries (Fig. 3). In California, the total statewide (12,000 acres) production for the season (March–December) of 1977 was 520 million lb and that for 1978 was 501 million lb—about 3 lb per plant. These yields are close to the estimated total production in California during the entire 80 yr before fumigation. During the 2 wk of peak bearing in the spring of 1977, California produced 68.5 million lb of berries—approximately 1 lb for every household in the United States.

The Benefits of Soil Fumigation

Increased growth response. Shortly after World War I, Russell (8) in England discovered the exceptional properties of the war gas chloropicrin to restore "worn-out and tired" soils to high productivity quickly and without adding any substantial nutrition to the soil. Chloropicrin negated injurious, crop-nonspecific biologic factors that had built up in the soil during long periods of crop cultivation. The improved crop growth that followed injection of chloropicrin into the soil was far superior to the long-studied effects of manure, crop rotation, and fallow on soil fertility. The full explanation of this growth response still eludes investigators, but research continues to point to elimination of certain *Pythium* spp. that may otherwise act as inducers of crop phytostasis, possibly even without being parasitic (3,5,14). Strawberries respond dramatically to soil fumigation with chloropicrin by developing an extensive fibrous root system (13) (Fig. 4).

Conservation of nitrogen. The soil organisms killed by chloropicrin or methyl bromide-chloropicrin mixtures release ammonium nitrogen derived from their proteins, which accumulates and tends to persist in the soil; it is electrostatically bound to clay soil constituents and does not leach. The killing is not general but, rather, highly selective for the injurious root-infecting fungal parasites. In addition, the bactericidal properties of the fumigants temporarily stop the biologic oxidation of ammonium nitrogen to nitrate nitrogen, which is leachable. The fumigation thus partly converts and conserves this nitrogen and makes it available to plants in a slow-release form.

Before the use of soil fumigation, strawberries commonly responded poorly or not at all to fertilization, and annual applications of nitrogen often amounted to as much as 400 lb per acre. With soil fumigation, fertilizer needs have been reduced to less than half the quantities used previously, a savings to the California strawberry industry of approximately 2.5 million lb of nitrogen per year. A tendency to overfertilize strawberries has continued well into the fumigation era and has been the major cause of the fruit disorder referred to as albino berry.

Uptake of basic nutrients. Plants in soils fumigated with chloropicrin and methyl bromide-chloropicrin mixtures may take up more chloride, phosphate, potassium, and probably other nutrients than plants in soils not fumigated (7). This increased capacity for nutrient uptake undoubtedly reflects greater development of the root system in fumigated soils, as the rootlet apices in strawberries are believed to be the primary sites of nutrient absorption (16). This view is supported by the fact that extensively developed plants growing in fumigated soil commonly lack the mycorrhizal fungus *Glomus fasciculatus* (Thaxter) Gerd. & Trappe; they also lack root hairs. Extensive field observations in California by the senior author indicate that strawberry roots in nonfumigated soils are highly mycorrhizal because of infection by *Glomus* spp. Thus, any dependency on mycorrhizae that may exist in strawberries appears to be negated in fumigated soils.

Low levels of bromide. The breakdown of chloropicrin and methyl bromide shortly after application of fumigants results in release of inorganic chloride and bromide into the soil. The breakdown occurs readily both in the soil and in the air, especially in the presence of sunlight. Chloride is a plant nutrient required in trace amounts, and bromide, although perhaps not a nutrient, is commonly absorbed and concentrated by various plants (2). Despite several years of repeated fumigation of a variety of soils with methyl bromide and chloropicrin, however, bromide contents in strawberries are generally well below the EPA tolerance level of 30 ppm. One reason bromide levels are low may be that chloride derived from the chloropicrin component of the fumigant mixture interferes with absorption of bromide by the plant (12).

Weed control. Weed control has been an important beneficial effect of fumigating strawberry fields with methyl bromide-chloropicrin mixtures in California. Increasing labor costs over the years and legislation banning the short-handled hoe have mandated the use of integrated pest management techniques.

Weeds commonly controlled with 320 lb per acre of a 2:1 mixture of methyl bromide and chloropicrin include *Amaranthus* spp. (pigweed), *Chenopodium album* (lambsquarters), *Capsella bursa-pastoris* (shepherds-purse), *Oxalis corniculata* (yellow oxalis), *Portulaca oleracea* (purslane), *Senecio vulgaris* (common groundsel), *Solanum sarrachoides* (hairy nightshade), *Stellaria media* (common chickweed), and *Euphorbia* spp. (spurge). Weeds difficult to control with fumigation include species of *Erodium, Malva, Medicago,* and *Convolvulus.* Tests with a 2:1 mixture of chloropicrin and methyl bromide at 320 lb per acre suggest that chloropicrin in amounts above 200 lb per acre supplements methyl bromide's destruction of weed seed.

When gel mixtures with slow release of methyl bromide and chloropicrin (Agel-67) were developed in the early 1970s, polyethylene tarps were considered unnecessary for efficient weed control. When tarps were not used, however, only half the weed control was obtained and plant growth response and yields were considerably less than when tarps were used.

Boon to other crops. In 1948, Allen (1) reported that chloropicrin applied at the rate of 500 lb per acre controlled big-vein disease of lettuce. Rich (6) confirmed the finding in 1950 by field tests in Connecticut. Big-vein control in lettuce growing on old fumigated strawberry land has often been observed and has endeared such land to lettuce growers. Harvests of potatoes, string beans, and other vegetables have also been significantly greater on such lands.

Realization of Yield Potential

In strawberries, sustained high yields go hand in hand with healthy roots. Most tangible benefits of soil fumigation with methyl bromide and chloropricrin are the healthy strawberry plants growing in soils temporarily free from fungal root pathogens. Their main structural roots penetrate the soil to a depth of several feet, develop extensive fascicles of transient feeder rootlets, and maintain a favorable balance between the rates of death and replacement of individual rootlets. This balance is promoted by soil fumigation, primarily through control of fungi pathogenic to the rootlets, such as species of *Ceratobasidium* (17).

The numerous and widespread soilborne diseases that plagued the crop before soil fumigation prevented the genetic yield potential of the strawberry from being realized. In fact, the magnitude of the production losses became apparent only after the success of fumigation. Improved cultivars undoubtedly have played an important part in the yield increases of the past 20 yr, but without the control of major soilborne diseases, the yields today, despite genetic advances, would be no better—or possibly even worse—than those of the middle 1950s.

In breeding strawberries for cultivar improvement, the requirement of resistance to diseases overrides all other considerations. This need slows progress, may even cause setbacks, and limits choices among breeding materials. In California, two simple fumigant chemicals have greatly reduced the need for genetic resistance to Verticillium wilt and root-deterioration diseases, thus allowing breeding efforts to concentrate on factors of fruit production and quality. We suggest that if the requirements of resistance to Verticillium wilt and root-deterioration diseases were imposed on the requirement for high yields, a breeding effort 10 times greater than the present one would still be inadequate.

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