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Phytophthora Root Rot of Avocado — An Integrated Approach to Control in California

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Avocado is a recent arrival on the horticultural scene. In California, the first introductions were made in Santa Barbara in the late 19th century. An extensive industry did not develop until the 1920s, however, with the availability of the first successful cultivar, Fuerte, which proved well adapted to California conditions. By 1969, there were 9,000 ha of avocados planted in the state; and the cultivar Hass, which was more productive than Fuerte, began to dominate the marketplace.

The most dramatic expansion in avocado production took place between 1969 and 1979. During that decade, land planted to avocados in southern California expanded almost fourfold, to 33,000 ha. Of the several reasons for this, two were perhaps paramount in importance. First, hillside plantings became a possibility after the introduction of drip irrigation technology from Israel. This allowed a major expansion, especially in San Diego County, by permitting planting of the native chaparral. Second, the new Hass cultivar was consistently productive, with an average of 8,000 kg of fruit per hectare annually. With the relatively low cost of hill land and the reasonable costs of water prevailing during that period, the average return from Hass of 70¢ per kilogram proved extremely attractive to a new grower.

Currently, the need to find new markets for the increased production of avocados, the escalating costs of water, and the impacts of an expanding human population resulting in the loss of agricultural land are having their negative effects on future expansion. New plantings of avocados are still taking place, however, partly because of losses caused by *Phytophthora* root rot (PRR). In 1986, such plantings included approximately 250 ha with clonal resistant rootstocks and possibly an equal area with traditional seedling rootstocks.

The Diseases of Avocado

The range of disease problems on avocado is quite limited in California, perhaps reflecting the recent history of the crop and the semiarid climate. Verticillium wilt *(V. dahliae* Kleb.) and oak root rot *(Armillaria mellea* (Vahl) Quel.) cause minor problems. Sunblotch, a disease caused by a viroid, can cause severe stunting of trees and in rare instances results in blotching of the fruit. A registration program for sunblotch now operates in the state, and the disease is of minor importance. Blackstreak, a disease of unknown etiology, can cause branch die back and eventual death of some trees. The disease is probably a rootstock problem and is aggravated in severe water-stress situations.

Two *Phytophthora* species account for the majority of disease problems found in avocado groves in California. *P. citricola* Sawada causes a crown or collar rot. The diseased tree declines and in most cases eventually dies. Typically, symptom development takes 5-10 years, and since most of the current avocado plantings were done between 1969 and 1979, the full effects of the disease are only just being felt. Approximately 20% of avocado groves have some trees severely affected by *P. citricola, P. cinnamomi* Rands constitutes by far the most important disease problem (Fig. 1). It causes a feeder root rot and its effects are rapid, resulting in death of the host tissue (10). The infected tree declines, defoliation and branch dieback occur, and death usually follows within 1-2 years. Currently, PRR affects approximately 60-75% of groves in California.

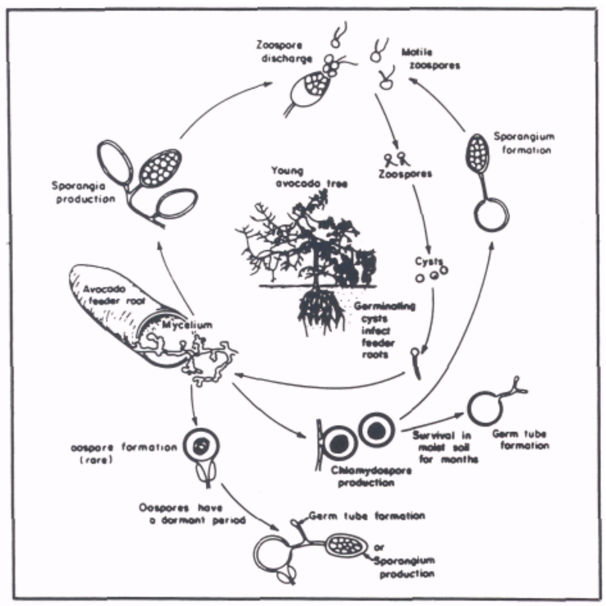

Fig. 1. Disease cycle of avocado root rot caused by Phytophthora cinnamomi.

PRR is present in all avocado-growing regions of California and was originally introduced either on nursery trees or with the planting of various ornamental species. Because *P. cinnamomi* has many hosts, especially among the woody ornamental plants grown in California, it represents a continuing threat to avocado production.

History of PRR

The disease first became important in the 1920s when a severe decline of avocado trees was noticed, especially in regions of San Diego County. The origins are a matter of pure speculation. PRR could have been introduced with avocados, although at that time the disease probably did not occur in the regions of Mexico where the majority of plant introductions originated. More likely, PRR was brought in on one of the many ornamental species introduced into California during the past century.

Until the early 1940s, avocado decline was judged to be caused by some soil factor such as poor aeration, waterlogged conditions, or high nitrite levels. No evidence of pathogen involvement had emerged. This changed in 1942 when a South African graduate student, Vincent Wager, isolated *P. cinnamomi* from avocado feeder roots in California. Over the next decade, George Zentmyer established beyond reasonable doubt that *P. cinnamomi* was indeed the primary cause of avocado decline. During the 1950s, he laid the foundations of an avocado rootstock program that has produced such resistant rootstocks as Duke 7, G6, and, most recently, Martin Grande (G755). He also pioneered research on fungicides, searching for chemicals that might eventually permit economical control of the disease. Most important, he introduced the concept of integrated control of PRR to the California industry, by which a combination of a moderately resistant rootstock such as Duke 7 could be used with a fungicide such as metalaxyl (Ridomil®).

Integrated Control Rationale

There are several reasons why PRR is such a devastating problem on avocados. Most seedling rootstocks are extremely susceptible to the disease. In addition, the majority of soils on which avocados are grown in California are not very suitable, being very shallow, typically 0.5 m or less in depth, and often poorly drained. Soil texture is quite variable. Sandy loams predominate; but, unfortunately, many are stratified, with clay pan subsoils that impede drainage. Organic matter is relatively low, ranging from 1 to 3%; pH ranges from 5.5 to 7.5. In summary, the California soils used for avocado culture are generally very conducive to PRR. The lack of any mulching practice in most groves in California may also be an important factor. The choice of cultivar is also influential, since the dominant choice, Hass, is extremely demanding on a rootstock. In a grove with a mixture of Bacon, Fuerte, and Hass cultivars, the last will frequently succumb to PRR several years before the other two do.

There does not appear to be a single solution to the problem of PRR on avocado. Although significant progress has been made in the selection of resistant rootstocks, these still do not allow establishment of trees in root rot areas without the use of a fungicide such as metalaxyl. Neither does use of metalaxyl alone permit establishment of avocados on susceptible seedling rootstocks. The disease pressure from PRR is too great.

Use of metalaxyl has allowed initial establishment of trees on clonal resistant rootstocks. This practice has been used for only 3-4 years, however, and a final judgment is still pending. A disturbing feature is that even with appropriate use of metalaxyl and a clonal resistant rootstock such as Duke 7, approximately one-half of the plantings still do relatively poorly and have not resulted in productive groves.

An analysis of the situation where replanting has succeeded shows that the level of cultural care, especially careful irrigation and fertilization of the trees, is a deciding factor in achieving initial success. Unfortunately, the margin for error in a PRR situation is quite narrow. During the summer months, even a single mistake in irrigation that allows the trees to become severely stressed can cause tree growth to halt. Consequently, the need to develop additional cultural and biological methods of control would appear to be obvious.

There are other good reasons to develop an integrated control philosophy for PRR on avocados. Site-specific fungicides can be vulnerable to loss of efficacy with continued usage because of either enhanced biodegradation (1) or appearance of resistant strains of the pathogen (5). Also, the resistance available in rootstocks has not been analyzed genetically, and the possibility exists that it could be rendered ineffectual should virulent strains *of P. cinnamomi* emerge. Finally, avocado, in the absence of PRR, is a perennial crop with a useful life span of approximately 50 years. Failure to control PRR could mean more than the loss of the existing planting. Typically, at least 5-6 years are needed to reestablish a productive avocado grove, assuming that suitable control measures are still available. The answers to control of PRR must lie in developing a combination of better rootstocks, more economical and efficacious chemical and biological methods, and suitable cultural practices.

Integrated Control Principles

Integrated control practices for PRR should embrace four principles: hygiene and sanitation, cultural and biological controls, resistant rootstocks, and fungicides.

HYGIENE AND SANITATION. Measures have been developed to reduce the possibility of introducing the disease on infected nursery stock.

The key factors are steam sterilization or chemical fumigation of the nursery mix; use of well-aerated, free-draining growing mixes; and hot water treatment (30 minutes at 48-52 C) of the seed used in propagation. Also, nurseries should be located on well-drained sites where the risk of flooding is minimal. Access to the nursery should be severely restricted by fencing, and all footwear should be cleaned and treated with a biocidal material before entry. Typically, a footbath of dry Bordeaux mixture is used for this purpose. A physical barrier between the nursery boundary and other vegetation should also be provided.

Seedling rootstocks are extremely susceptible to *P. cinnamomi,* and clonal propagation of resistant cuttings is becoming an increasingly popular alternative. However, even these more resistant materials are highly vulnerable to *P. cinnamomi* at the nursery stage. The entire clonal propagation process can take from 18 to 24 months, and during this time the cuttings must be maintained free from PRR. After successful grafting with a scion such as Hass, the trees are generally placed in a holding area in blocks of 200-300 on bare ground that may have been treated with a chemical fumigant. This represents the most vulnerable stage for PRR infection. The disease can spread rapidly from tree to tree in a block, and may easily go undetected because of the combination of well-aerated growing mixes and relative resistance of clonal rootstocks. An additional precaution should involve the periodic testing for PRR in the trees in each holding block. A sensitive test involves sampling roots and growing mix, especially from the base of the container, and use of a *Persea indica* (L.) Spreng, trap, in which a young seedling is placed in a mixture of the test material and an approximately 10-fold volume of water. *P. indica* is highly susceptible to PRR, and if infected will succumb within 2-6 days. Root sections of the *P. indica* seedling can then be plated out on a *Phytophthora*-selected agar medium to allow positive identification of *P. cinnamomi.* Fortuitously, the hyphal morphology of *P. cinnamomi* is quite unique, and its characteristic coralloid outgrowths and clusters of hyphal swellings provide a good diagnostic feature. Ideally, nursery trees should be raised on benches rather than on bare ground, but this is currently not a common practice in California.

Fungicides such as metalaxyl and fosetyl-Al (Aliette®) suppress but do not eradicate PRR and should never be used in the nursery. Introduction of PRR into an avocado grove should be avoided in all situations. Even in an existing PRR situation, trees should be introduced in a healthy condition, since a basic aim of good control practices in the field is to minimize the influence of disease for as long as possible.

Perhaps the area where the most effort has been exerted over the decades of dealing with the problem has been with preventing introduction and subsequent spread of the diseases in the field. The majority of established groves are surrounded by secure fences designed to minimize unauthorized access. Some groves also maintain tire dips, usually containing hypochlorite or formaldehyde solutions, for vehicles. Within the grove, infected areas are frequently isolated by fencing to restrict access. Footbaths of Bordeaux mixture are used to protect against movement of infested soil to clean areas. Sometimes trenches are dug around the infested area in an attempt to reduce spread by irrigation and rainfall runoff to clean areas of the grove. Care has to be taken, however, to ensure that the drainage water does not contaminate adjoining groves.

Despite the extraordinary efforts of many growers, PRR has continued to spread. Two main factors have operated. First, some avocado nurseries still produce and sell, knowingly or unknowingly, diseased trees to unsuspecting growers. Second, PRR still spreads from grove to grove on a regular basis, facilitated by the activities of grove management and fruit-picking operations. Because much of the new avocado land is hilly, runoff from irrigation and rainfall can also play a significant role in spread.

Perhaps the most disturbing feature of PRR is that many growers underestimate the extent of its presence. The disease can be widespread in a grove before aboveground symptoms appear. Thus, cultural operations frequently proceed as though no disease problem exists, and further spread occurs rapidly. The safest philosophy with avocado management is to assume the PRR is present and to act accordingly!

CULTURAL AND BIOLOGICAL CONTROLS. There is an increasing emphasis on the development of cultural methods for reducing the severity

of PRR. One of the most effective innovations has been with the planting

of avocados on mounds approximately 1-1.5 m in diameter and 0.5-1 m high

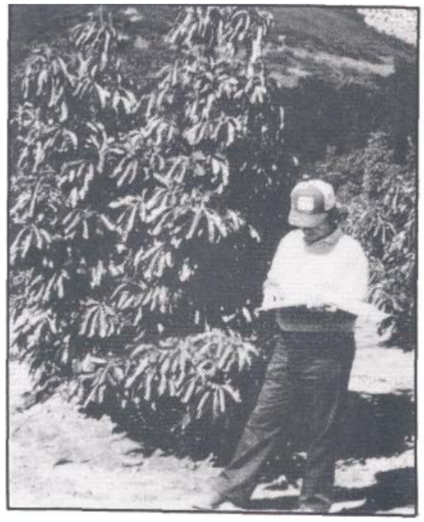

Fig. 2. A 2-year-old Hass avocado tree on a resistant rootstock planted on a mound in a grove infested with Phytophthora *root rot at Embarcadero Ranch in Santa Barbara County, California.*

(Fig. 2). This method was first tried on clay soils in Santa Barbara County, and has permitted establishment of trees growing on clonal resistant rootstocks where previously they had failed routinely in difficult soils. Mounding is being used more and more, even on light sandy soils, generally with good results. One has only to examine the traditional planting method to realize why mounding should prove so successful. Traditionally, a hole slightly larger than the root ball is cut in the compacted ground, the tree is placed in position, and the slight gap is filled with loose earth. The nursery mix is generally much lighter in texture than the surrounding compacted ground, and the roots may have difficulty growing into it. With mounding, in contrast, the planting ground is broken up, and the resulting soil is generally friable in texture and better drained, encouraging root development and reducing the severity of PRR.

Other cultural practices, such as mulching and incorporation of organic material into the soil at the time of planting, have not met with general acceptance. Recently, however, the growing awareness of the problems with excessive use of pesticides and herbicides and the escalating costs of water have revitalized an interest in mulching practices. Experiments with the use of straw mulches into which a material such as composted chicken manure is incorporated form part of a new research program at the University of California at Riverside (UCR).

Irrigation practice has been a hotly debated topic in recent years. Traditionally, the approach with PRR has been to recommend longer intervals between irrigations, which seems logical because *Phytophthora* is a "water-loving" pathogen. Apart from the "logic," this approach also avoided the need for a separate irrigation system for replants. Practical problems arose, however, with replanting of groves using the new clonal resistant rootstocks such as Duke 7. Irrigations were made every 7-10 days, and results in PRR-infested soils were often poor. Subsequent field experience has shown that Duke 7 grows much better if irrigated two or three times a week during the summer. Put in the most simplistic terms, an irrigation regime that optimizes good soil moisture conditions for root growth appears the most desirable for PRR control using clonal rootstocks.

Biological control is still only a good idea, with currently no practical applications in California. In small areas of Australia, especially at Mt. Tamborine in Queensland, biological control is already something of a reality. There, the native soil of the tropical rain forest is naturally suppressive to *P. cinnamomi.* Use of legume-maize cover crops, coupled with mulching, manuring, and adding dolomitic limestone to restore the soil pH, has permitted a high degree of biological antagonism to *P. cinnamomi* to persist after the forest is cleared and planted with avocados (6). The fact that such biological control exists naturally gives impetus to the concept that it can be developed for more general usage with avocados. Initially, many microorganisms will have to be screened for biological control capabilities. At UCR, seedlings of *P. indica* are used in an in vivo screen for potential biological antagonists. Bacteria are added as a suspension, whereas fungi are grown on a suitable organic substrate such as bran and incorporated into the planting mix. After a suitable period of exposure to the agent, the young *P. indica* seedlings are transplanted into U.C. soil mix amended with *P. cinnamomi* inoculum. After four weeks, the infected seedlings are evaluated for their resistance to *P. cinnamomi.* Microorganisms that can suppress *P. cinnamomi* on its host are extremely rare. To date, a screen of nearly 200 microorganisms has revealed one useful fungal antagonist.

Assuming a biological control agent with sufficient efficacy against *P. cinnamomi* could be developed, would it represent a feasible method for control of PRR on avocados? First, avocados are raised in a fumigated growing mix. This should greatly facilitate introduction of the agent, since it initially will have no competition from other soil microorganisms. Second, the avocado is extremely shallow-rooted. Avocado feeder roots are found predominantly in the top 10-15 cm of the soil layer and should be readily accessible to application of a biocontrol agent.

The ideal biocontrol agent should be capable of growing with the feeder roots. It should successfully compete with organisms and be rhizosphere-competent. It should persist for up to six months in native soils of widely different types. After "booster" applications, it should colonize the surface soil layer, increasing its population size very rapidly and providing optimal protection for the developing avocado feeder roots. These conditions may appear overwhelming, but then the development of fungicides such as fosetyl-Al that can move in the phloem was an impossible idea only a very few years ago.

RESISTANT ROOTSTOCKS. There are three horticultural races of avocado: Mexican, Guatemalan, and West Indian. The Mexican race is the most cold-tolerant, followed by the Guatemalan race, with the West Indian race being tropical in character and not well adapted to California conditions. The principal cultivar grown in California is the Guatemalan selection Hass. The fruit of Guatemalan cultivars are generally superior in quality to both Mexican and West Indian selections. Guatemalan cultivars are also usually more productive than Mexican types under California conditions. Both Mexican and Guatemalan rootstocks are available, but the Mexican has been the predominant type used in California. Some 28,000 ha of avocado plantings have been made using susceptible seedling rootstocks, especially the Mexican selection Topa Topa, which is extremely susceptible to *P. cinnamomi.* Since 1975, clonally propagated resistant rootstocks have been available commercially in California. In the decade from 1977 through 1986, the largest avocado nursery in the state, Brokaw Nursery, sold 511,700 clonal rootstocks, most of which were the Duke 7 selection. Currently, approximately 70,000 clonal rootstocks are planted each year. Although seedling rootstocks are still sold, their numbers are dwindling, and many of those are in fact G6 seedlings, a selection with some resistance.

Rootstock research began in the 1940s and 1950s, when George Zentmyer began his search for sources of resistance among seedlings of various commercial cultivars. Among these, he discovered the Duke cultivar, a Mexican variety with appreciable cold tolerance that, when tested, showed some field resistance to *P. cinnamomi.* Further screening of thousands of seedlings of Duke led to the selection of Duke 6 and Duke 7. Both possessed moderate field resistance to PRR and were widely tested in an ungrafted state at various sites throughout California. Duke 7 generally performed better than Duke 6 against PRR, and was also preferred by most nurserymen because of superior horticultural qualities. Almost 20 years later, in 1975, Duke 7 became the first resistant rootstock to meet with commercial success.

The early success with Duke 7 gave impetus to a much wider search for new germ plasm, especially in Central America. The major effort began in 1971 when Eugenio Schieber, a plant pathologist then employed by the government in Guatemala, joined forces with Zentmyer. A rigorous search began of the remote areas of the Guatemalan highlands for new sources of resistance to *P. cinnamomi.* Guatemala is probably the center of origin of the Guatemalan, or *criollo,* race of avocado *(P. americana* Mill.). Also found there are wild relatives, such as *aguacate de mico,* and primitive types of the Mexican race *(P. americana* var. *drymifolia* (Schlecht. & Cham.) Blake), also called *matuloj* or *aguacate de anis,* as well as other closely related edible species, especially *P. schiedeana* Nees, known locally as *cojou* or *chinini* (Fig. 3).

Fig. 3. Large yellow-green fruit typical of the avocado relative Persea schiedeana, *the* cojou *or* chinini, *collected at Tactic in the Guatemalan Highlands in 1986.*

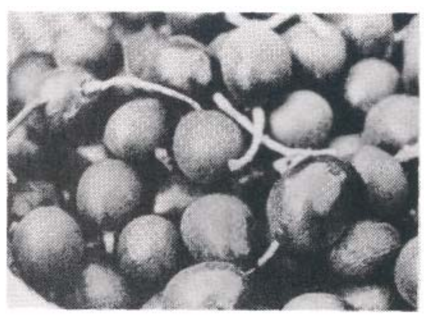

Fig. 4. Small purple fruit of the primitive matuloj *(Mexican) avocado selection G6 collected from a tree on the slopes of the Acatenango volcano in Guatemala in 1971.*

The investment in a search for new germ plasm has paid off handsomely. In 1971, the G6 selection was located on the slopes of the Acatenango volcano in Guatemala (Fig. 4). This primitive *Matul-oj* proved to have field resistance comparable to that of Duke 7. Its subsequent commercial use has been primarily as a source for seedling rootstocks, undoubtedly because it has proved to be a prolific seed producer. However, the heritability of its resistance, although much higher than that of Duke 7, is probably no greater than 10%.

A significant breakthrough came in the fall of 1975 when six seeds were collected in the marketplace at Coban in the Alta Verapaz region of Guatemala. From this small collection, one seedling, G755c, proved to have appreciable resistance to PRR (8). Eventually, G755c was propagated for field testing. Two other seeds, resulting in G755a and G755b, were germinated and raised without testing. By 1983-1984, all three seedling sources had been propagated and tested under field conditions, both ungrafted and grafted with the most popular commercial scion, Hass. All three selections proved to have more resistance to PRR than either Duke 7 or G6 (Table 1). Collectively, they have recently been named Martin Grande in honor of Martin Cumes S., a Mayan who assisted Schieber in collecting G755 in Coban. Botanically, the G755 series has been characterized isozymically as natural hybrids between *P. americana* var. *guatemalensis* and *P. schiedeana.*

Since 1976, a major effort has been made to identify the source of the G755 resistance. Recently, useful resistance has been characterized in a seedling selection of P. *schiedeana* (UCR 2008). Unfortunately, seed of *P. schiedeana* is relatively rare and also is extremely difficult to maintain in viable condition. Consequently, budwood is a preferred source of this potentially useful species. Again, problems arise because budwood is difficult to obtain and to graft.

One feature of the selection program until quite recently was the dearth of useful rootstocks of the common Guatemalan race, *P. americana* var. *guatemalensis.* From 1971 to 1975, efforts were mainly concentrated on collection of *matuloj* types, partly because of the success of G6 and also because the industry in California has traditionally relied on the Mexican type of rootstock. During the 1980s, more emphasis has been placed on collecting and screening for resistance among seedlings of the Guatemalan or *criollo* type. Several *criollo* selections that show early promise are beginning to emerge, notably the G810 (UCR 2010) seedling from Guatemala.

Because 28,000 ha are on Mexican seedling rootstocks and because each hectare has up to 250 trees, there are potentially millions of trees in California from which to select for resistance. As PRR spreads, occasional trees escape its influence. In the few cases in which a rootstock can be successfully recovered by partially girdling the "escape" tree, useful germ plasm has been discovered. Among these selections is Thomas, which has so far performed as well as any other resistant selection in field tests (Table 1).

TABLE 1. Percentage increase in trunk girth and visual ratings of foliage health of 12 rootstock selections (inoculated at time of planting with *Phytophthora cinnamomi*) after 1 year of growth at South Coast Field Station, Irvine, CA.

Rootstock selection (x)	Horticultural character	Percentage growth increase (y)	Visual rating (y, z)
Thomas	Mexican	82 a	0.7e
Martin Grande	Guatemalan,		
G755a	*cojou* hybrids	63 ab	1.7 cde
G755b		57 bc	2.2 cd
G755c		54 bc	1.4 de
Duke 7	Mexican	47 bc	2.2 cd
G1033	Guatemalan	42 bc	2.9 bc
Toro Canyon	Mexican	42 bc	2.6 bcd
Barr Duke	Mexican	36 cd	1.8 cde
D9	Mexican	32 cd	2.8 bc
G6	Mexican	32 cde	3.7 ab
Topa Topa	Mexican	15 de	4.4 a
Borchard	Mexican	10 e	4.4 a

(x) All avocado trees were Hass grafted on the various rootstock selections. No fungicides were used.

(y) Means with the same letter (a, b, c, d, e) are not significantly different according to Duncan's new multiple range test (P=0.05).

(z) Expressed on a scale of 0 to 5, where 0=totally healthy and 5=complete defoliation.

There are several frustrating features concerning available sources of resistance to PRR. Paramount is low heritability, usually less than 1%. Furthermore, the majority of avocado selections cannot be rooted directly. Budwood has to be grafted to a "nurse" seedling, a bud allowed to develop in the dark, and resultant etiolated shoot girdled at its base with a metal ring and finally treated with a rooting hormone preparation. Even with this elaborate, time-consuming procedure, rooting can be quite slow and erratic. Over a 10-year period, avocado propagators have greatly improved the art; but the procedure cannot yet be called routine. Consequently, avocados on clonal rootstocks are expensive—currently, nearly $20 a tree in California.

FUNGICIDES. Fungicides with the potential to control PRR have appeared in the last decade. Successful evaluation in the field of metalaxyl, especially in combination with the Duke 7 rootstock, led to an early registration (September 1981) for nonbearing and later (January 1983) for bearing avocado trees. Recommended annual rates in California are 7.5 g a.i./m2, applied in three equal doses of 2.5 g a.i. at 8- to 12-week intervals. The first application is made around April with existing crops and at the time of planting, usually in May or early June, with new crops. To date, the level of PRR control achieved with metalaxyl and clonal rootstocks, such as Duke 7 or G755, in some replant situations has been outstanding (Fig. 5). No proved failure of fungicidal efficacy has been observed so far. The recommended rates and application timings appear optimal for a wide range of soils and cultural conditions. The material has also proved to be economical for young trees.

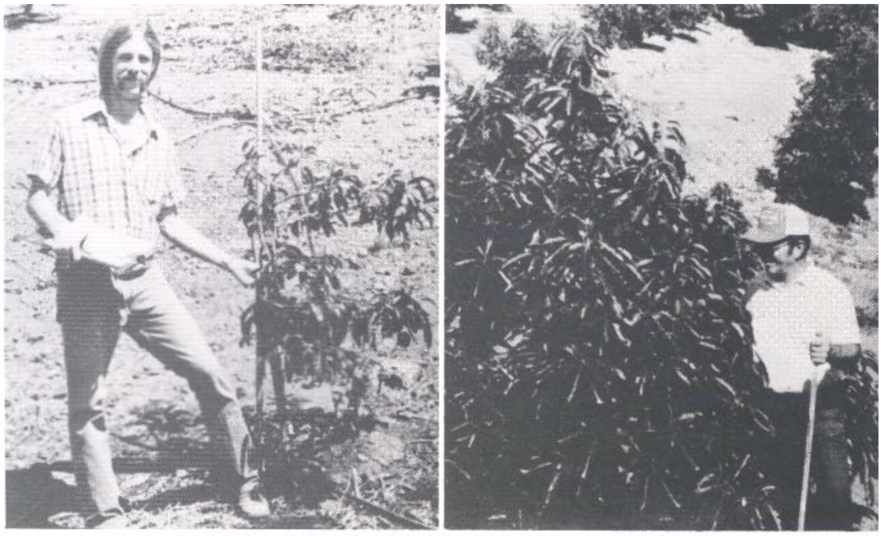

Fig. 5. Two-year-old Hass avocado trees on Duke 7 rootstocks inoculated with Phytophthora cinnamomi *at the time of planting: (Left) No fungicides were used. (Right) Metalaxyl (Ridomil), 2.5 ga.i., was applied three times a year; annual dosage, 7.5 ga.i. per tree.*

Metalaxyl is available either as a 25% EC formulation, which facilitates application via the irrigation system, or as a 5% granular product, which is convenient for application to a few individual trees. High water solubility (7.1 mg/ml) and low adsorption in a wide range of soil types allow metalaxyl to penetrate rapidly through a soil profile. Good soil mobility properties and high biological activity (3) against *P. cinnamomi* (EC50 = ~0. l µg/ml) have made the fungicide an indispensable product in the integrated control of PRR. Over a period of five years, metalaxyl has largely replaced methyl bromide fumigation as an alternative chemical method for suppressing *P. cinnamomi* in replant operations. Fumigation was never very successful under California conditions because of the predominantly hilly terrain and difficult soil profiles typical of many recent avocado plantings. Additionally, methyl bromide fumigation was both expensive and hazardous.

While metalaxyl has been a resounding success with replant situations involving clonal resistant rootstocks, the same cannot be said of PPR control on mature, bearing trees on susceptible seedling rootstocks. Efficacy has been at best relative, in that if the fungicide was applied early enough, decline of the tree might be halted for 3-4 years. Moreover, the cost of treatment usually is not justified. Assuming industry-average production of 8,000 kg of fruit per hectare for Hass, a grower can expect a net profit of just over $5,000. An avocado tree producing such a crop typically has between 10 and 15 m2 of soil surface requiring fungicide treatment. In a PRR situation, metalaxyl would have to be applied at the recommended annual rate of 7.5 g a.i./m2, at a cost of $2,500 to $3,750/ha for materials alone. When labor costs are added, the profit margin dwindles still further. All this assumes that the grower is still achieving a reasonable level of production, which is seldom the case when PRR is present.

In a small survey, over 50% of avocado soils in mature groves were shown to have an enhanced ability for metalaxyl biodegradation after only two years of use (1). In some instances, trees failed to respond to further fungicide applications and PRR became more severe. Thus, even if metalaxyl was much more economical to use, it is unlikely that it could provide a long-term answer to PRR.

Fosetyl-Al, which became available for testing at about the same time as metalaxyl, had a much lower efficacy in greenhouse tests with avocado seedlings, generally requiring between 0.5 and 1.0 mg/ml to achieve adequate control of PRR when used as a soil drench. However, fosetyl-Al had one new and important property—good control of PRR when applied as a 0.3% a.i. solution to the foliage, especially with two back-to-back spray applications. In field tests, three to five foliar applications made to runoff of a 0.3% a.i. solution at 60-day intervals gave excellent control of PRR on mature, bearing avocado trees grafted on susceptible rootstocks (4). Approximate annual costs of such a treatment, excluding labor, would be around $750/ha.

With clonal resistant rootstocks, a single soil application of 3 g a.i. of fosetyl-Al in a liter of water to each container 2-3 days before planting has provided up to 40 weeks of PRR control hi a severe disease situation. Monthly applications of a 0.3% foliar spray over the growing season (April-October) gave maximal efficacy. In June 1987, a label for fosetyl-Al for nonbearing avocados was approved in California; a preplant drench followed by up to four foliar sprays at 60-day intervals during the growing season is recommended.

Undoubtedly the most significant breakthroughs in fungicide research came in 1983. In our laboratory, we determined that phosphorous acid, a breakdown product of fosetyl-Al, was extremely active against *P. cinnamomi* (2, 5, 9). Fosetyl-Al is metabolized to phosphorous acid in a few hours in most soils and within 24 hours in plant tissues (5). In South Africa, Darvas et al. (7) discovered that up to 20 ml of a concentrated (7-10%) solution of fosetyl-Al can be injected into the trunk of an avocado tree with a simple 60-ml plastic syringe with an eccentric tip (Fig. 6). The efficacy achieved was equivalent to, and sometimes greater than, that obtained with foliar sprays. Moreover, only two injections per year were necessary. The quantities of chemical required are extremely small, of the order of 20 g per application for a large tree.

In California, formulations of fosetyl-Al (Aliette-Ca) or potassium phosphite (phosphorous acid buffered to pH 6.2 with KOH) are providing equivalent efficacy when used at comparable rates. Recovery of Hass on susceptible seedling rootstocks first becomes observable after 1.5-3 years (Fig. 7). In Australia and South Africa, recovery from PRR has been even more dramatic with the cultivar Fuerte, with control observed after only one year. Cultivar, soil type, cultural conditions, and climate may all influence efficacy.

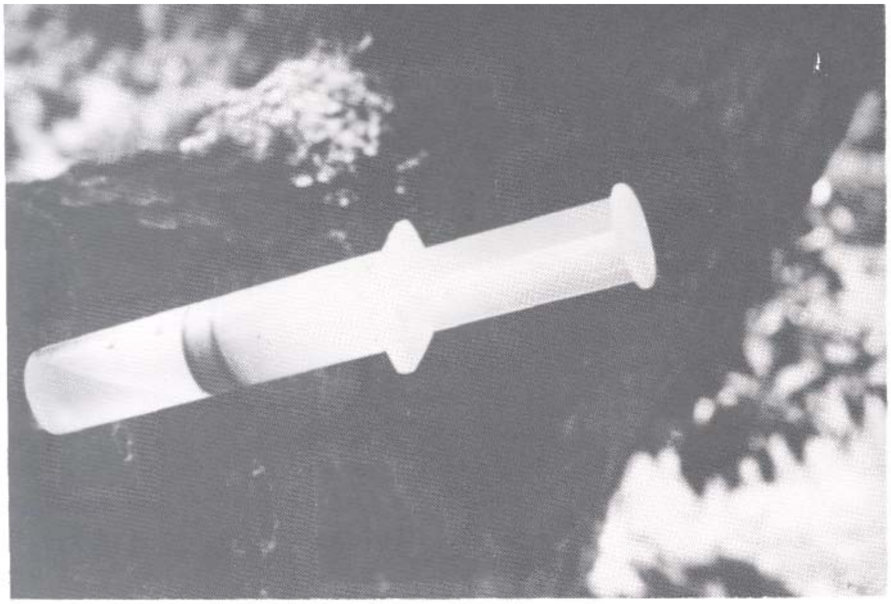

Fig. 6. A plastic syringe containing a 10 percent aqueous solution of fosetyl-Al inserted into a hole drilled in the trunk of an avocado tree.

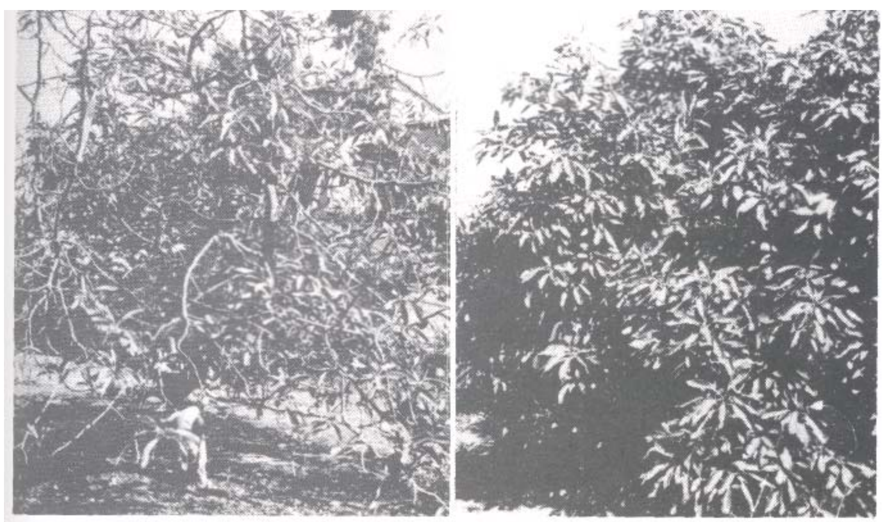

Fig. 7. Ten-year-old Hass avocados on susceptible seedling rootstocks 2 years after initiation of fungicide injection treatments: (Left) Tree without fungicide treatment showing typical symptoms of Phytophthora *root rot. (Right) Tree injected twice a year with a 5 percent fosetyl-Al formulation (Aliette-Ca); annual dosage, 3.2 g per tree.*

While there appears every intent to proceed with registration of fosetyl-Al in California both as a foliar spray and as a trunk injection for use on bearing avocados, the same cannot be said for potassium phosphite. On most crops, fosetyl-Al is undoubtedly a much safer product than potassium phosphite when used as a foliar spray. The argument is not applicable to its use as a trunk injection, however. From a grower's perspective, potassium phosphite used as a trunk injection is an extremely inexpensive and efficacious product for PRR control. As far as can be determined, potassium phosphite is essentially nontoxic to both plants and animals, and thus would appear to be ideal for PRR control. A major investment in lexicological research would be required to allow registration in California, however; and currently no commercial sponsor is interested in pursuing the idea. Ironically, .a net profit of only $125/ha for the 33,000 ha of avocados threatened by PRR in California could bring back several million dollars in annual profit to the manufacturer of such a product.

Prospects for Cost-Effective Integrated Control

In 10 years, the avocado industry has been transformed from one trying to outrun PRR by a dramatic expansion of new plantings on virgin land to one squaring up to the problem. The possibility that a durable solution will be found through appropriate integrated control methods is become more realistic. Several factors are responsible for this turnaround. The economic climate is presently not very favorable for further expansion of plantings, since current production has at least temporarily outstripped demand. Meanwhile, new resistant rootstocks such as Martin Grande (G755) and efficacious fungicides such as metalaxyl and fosetyl-Al are now available to help combat the problem.

Yet, rootstock research is essentially still in its infancy. The next 20 years will doubtless see the selection and perhaps the breeding of a range of rootstocks suitable for different soils, cultural conditions, and climates. Seedling lines might also eventually become available, thus cutting drastically the costs to the nurseryman of producing resistant rootstocks. Resistant rootstocks are unlikely ever to provide a complete answer, however. They may prove to be susceptible to other diseases, or may have other horticultural weaknesses. Further, the genetic basis of resistance to PRR has yet to be analyzed. Conceivably, breakdown of resistance owing to emergence of new pathogenic races of *P. cinnamomi* could become a problem with some selections.

Fungicides should also be used judiciously to avoid causing major problems with fungicide resistance (5) or accelerated biodegradation by soil microorganisms (1). Strategies should be evolved that achieve good efficacy with a minimal application of each useful product.

The increased research emphasis on improving cultural conditions and screening for useful biological antagonists is obviously to be encouraged and eventually should add a further dimension to integrated control strategies. At present, planting on mounds, sensible irrigation practices, and mulching are cultural components that may have a significant impact on PRR. In the future, biological control may also have a useful role in PRR suppression. The method of raising the trees in a fumigated growing mix should be readily adaptable to biological control.

Finally, what of the impact of genetic engineering on PRR control? Potential biological control agents; i.e., fungi and bacteria, are now becoming increasingly amenable to genetic transformation; and strain improvement of useful biocontrol agents may be possible. But first, we will have to find those suitable rhizosphere-competent organisms that can be used with avocado.

More distant is the possibility that the high resistance found in populations of some distantly related *Persea* species of the subgenus *Eriodaphne,* such as *P. borbonia* (L.) Spreng., can be transferred to avocado. These species are not graft-transmissible with avocado, but conceivably a means can be found through genetic engineering to bridge this incompatibility barrier and transfer the resistance.

An Economic Survey

The future of the avocado industry in California is currently in the balance. Rapid expansion in hectarage has saturated the traditional market in the United States, and prices are generally depressed. The impact of higher water prices is also being felt, and PRR is becoming an increasing threat to the economic survival of many growers. Balanced against this, however, is the fact that approximately 80% of the domestic market for avocados is still centered in the western states. The potential for expansion of the domestic market is enormous. Also, the exploitation of the production potential of avocado is in its infancy. A new cultivar, Gwen, can produce two to four times more fruit than Hass on a per-hectare basis.

But the threat of PRR will have to be dealt with. What is the estimate of its current economic damage? Based on the known rate of replanting with clonal rootstocks, a minimum estimate of loss attributable to PRR would be 200 ha per year. Since about five years are needed to get back into full production, the loss, based on an expected return of $5,000/ha, would be $5 million. Because over 60% of groves (20,000 ha) are also affected to some degree by PRR, the real losses are in fact much greater, perhaps closer to $30 million. The value of the entire avocado crop in California in 1986 was $115 million. Obviously, the economic impact of PRR is considerable. Currently, integrated control strategies represent the most hopeful approach to eventually reducing those losses, thus permitting the grower to learn to live with *P. cinnamomi.*

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