The history of pineapple nematology in Hawaii over the past 70 years reflects important developments in the science of nematology during that time. This historical review of Hawaiian pineapple–nematode research and the individual scientists involved in that work encompasses the changes in nematode management strategies employed in Hawaiian pineapple production.

PINEAPPLE IN HAWAII

Hawaii consists of 132 islands, reefs, and shoals and is the southernmost of the United States (46). Pineapple was planted on approximately 14,570 hectares in 1986, and the fresh market and processed commodity value was $242 million (3).

Pineapple was first reported in Hawaii in 1813, but it had probably been present in Hawaii for some time before then (10). The Hawaiian Pineapple Company, later to be Dole Company, was founded in 1901, and the Hawaiian Pineapple Packers’ Association was formed in 1912.

Pineapple research in Hawaii: Research on pineapple production was initiated through an arrangement between the Hawaiian Pineapple Packers’ Association (HPPA) and the Hawaiian Sugar Planters’ Association (HSPA) in 1914. In 1916 it was discovered that iron sulfate sprays significantly improved pineapple growth and organized, scientific research on pineapple production was initiated. In 1924 an experiment station for pineapple research was established, marking the beginning of a scientific approach to growing pineapple—an approach that led to the formation of an agricultural industry based on scientific re-
search. The formal name of the Experiment Station was changed in 1933 to the Experiment Station of the Pineapple Producers' Cooperative Association, and was renamed in 1941 as the Pineapple Research Institute (PRI) of Hawaii.

Nematodes on pineapple in Hawaii: The first disease recognized in Hawaiian pineapple was "wilt." Nematodes were believed to have a role in the wilt disease, but the etiology of the disease was poorly understood and insects, nematodes, and fungi were thought to be involved in the disease (7). The importance of nematodes to pineapple production was recognized in the early 1920s. From about 1920 to 1950 the root-knot nematode, *Meloidogyne javanica* (Treub, 1885) Chitwood, 1949, was the primary nematode problem. Since 1950 the reniform nematode, *Rotylenchulus reniformis* (Linford and Oliveira, 1940), has been the key nematode problem. Crop failures were not uncommon in nematode-infested areas from 1920 to 1945.

Standard cultural practices including 2-year fallow periods with six cultivations during the period, application of fertilizer and the use of Eckart paper mulch, hand planting of crowns or slips through the mulch paper, and fertilization with iron sulfate sprays were used to alleviate plant stresses as early as 1925. Until the advent of soil fumigation with D-D mixture in 1945, management of plant-parasitic nematodes was by fallowing and crop rotation. The use of mulch paper, hand planting, and machine-assisted hand harvesting continues today.

THE NEMATOLOGISTS

Several nematologists have conducted research in Hawaii. A summary of their major contributions is presented with references to their work. In some instances unpublished reports of the director of the PRI are quoted.

Nathan Augustus Cobb: Cobb accepted a position with the Hawaii Sugar Planters' Association in 1905 and remained in Hawaii until 1907 (6). He hired E. M. Grosse and W. E. Chambers as illustrators, and Chambers, with Cobb for approximately 15 years, developed a solid reputation as a scientific illustrator.

During his time in Hawaii, Cobb did not investigate pineapple nematodes, but his research on nematode parasites of sugarcane established the presence of *Meloidogyne javanica* (*Heterodera radicicola* sensu latu) and the general importance of plant-parasitic nematodes in Hawaii. His research established basic information on the life cycle of root-knot nematode, including the observation that it could not survive temperature extremes.

George H. Godfrey: A nematode survey of the pineapple growing regions in 1924 established a correlation between the occurrence of root-knot nematode and pineapple wilt: "the area in which the nematode galls occur on the roots of the plants corresponds with the area in which the pineapples are wilting." Such observations prompted the Experiment Station Director in 1926 to write "it became clear that..."
something decisive should be done about one of our most serious enemies, the root-infesting nematodes." Consequently, a nematologist, G. H. Godfrey (Fig. 1), was hired by the Experiment Station in 1926. Godfrey was hired to serve as head of the Nematology Section of the Experiment Station and to investigate nematode problems. The Nematology Section consisted of Godfrey and Ms. Helene Morita, a technician. At the time Godfrey was hired, the most effective nematode control measure used in Hawaii was extended (2 years) following. Godfrey was aware of nematode-control strategies being investigated in Europe such as the use of trap crops, flooding, desiccation, natural enemies, and application of chemical soil treatments (including ammonia, ammonium sulfate, carbon bisulfide, cyanide, formalin, and others).

Godfrey's research in Hawaii covered many areas of nematology and plant pathology, addressing aspects of nematode biology and ecology that are still poorly understood today. His work established the importance of plant-parasitic nematodes in Hawaiian pineapple.

He conducted research on techniques for studying root-knot nematodes in plants (13,16), the use of indicator plants to assess nematode population densities in soil (14), nematodes other than root-knot that might be problems in pineapple or other plants (12), the use and efficacy of chloropicrin, carbon bisulfide, and hydrocyanic gas as fumigants (15,17,26), the influence of root-knot on pineapple growth (18,21), root-knot nematode development (24), the use and efficacy of trap crops (20,23), and the influence of pH, moisture, and temperature on the root-knot nematode life cycle (19,22,25,29). He was also aware of the value of looking for "escapes" in the field as a means of identifying nematode resistance in pineapple.

Godfrey, a good soil ecologist, noted in a 1927 progress report: "We must not fail to recognize the importance of becoming
thoroughly familiar, by this means (studying soil ecology), with the structure as well as the life and habits of the organisms with which we are concerned. Furthermore, this work must be done to pave the way for what we plan to do ultimately in the way of developing the proposition of biological control.” Godfrey was aware that *Mononchus* might play a role in biological control, and included it in his research plans. The nematode extraction apparatus used by Godfrey featured a set of nested Tyler sieves (Fig. 2).

Godfrey was released by the Experiment Station in 1932, primarily as a result of the depression.

**Harold R. Hagan:** Originally trained in entomology, Hagan was hired into the Nematology Section of the Experiment Station in 1929. His primary responsibility was field nematology. Related appointments during this time were Juliette Oliveira (Fig. 3) as a junior nematologist in 1928, Walter Carter (Fig. 4) in 1930, and Carl Schmidt (Fig. 5) in 1931. Carter and Schmidt were appointed to the Entomology Department.

Hagan worked with Godfrey on several projects, including assessing the effect of root-knot on plant growth (21), influence of pH on root-knot nematode (19), efficacy of trap crops (20), and influence of soil temperatures on root-knot nematode (27). He also worked with J. L. Collins on nematode resistance in pineapples (11,28). They focused on root-knot nematode resistance and identified two varieties (“Wild Brazil”—*Ananas ananassoides*, and Lot 250, a Cayenne × Wild Brazil hybrid) that had tolerance to root-knot nematode damage. They did not assess nematode reproduction on the varieties, limiting their studies to effects of the nematode on plant growth. Attempts to identify and incorporate nematode resistance into commercial cultivars continued through the 1930s and into the early 1940s with little success.

Hagan, like Godfrey, was released from
FIG. 5. Carl Schmidt, entomologist at the PRI, discovered the nematicidal activity of DBCP. Photograph ca. 1938.

FIG. 6. Maurice Linford, plant pathologist at the PRI, pioneered work on biological control of plant-parasitic nematodes by soil fungi. Photograph ca. 1938.

the Experiment Station in 1932 because of the depression. In addition, Walter Carter had suggested that the “wilt” disease was caused by mealy bugs and that nematodes were of minor importance as agents inducing pineapple disease (7). The Experiment Station Director in 1932 was an entomologist, who noted “information is accumulating to show that nematodes have much less effect on the welfare of the plant than had been supposed” and “there is no general systemic effect upon the pineapple plant due to the activity of nematodes on its roots.” In response to these statements, Magistad and Oliveira demonstrated that root-knot nematode infection was deleterious to pineapple growth by decreasing the average total root length, reducing plant growth rate, and decreasing the absorption of nitrogen (45). Nevertheless, the Nematology Section was closed in 1934, and its remaining personnel were moved into the Department of Plant Pathology.

**Maurice Blood Linford:** Hired to head the Pathology Department in 1929, Linford’s initial work focused on plant pathogens, including suspected virus diseases. By 1935 Linford (Fig. 6) had established that fungi parasitic on nematodes were present in pineapple fields. Over the years he continued to study the role of soil fungi in suppressing nematode populations and the possibility of effective and manageable biological control (31,32,34,42,44), work that was continued into the mid-1950s at PRI (30). Linford also worked on methods for observing nematodes and their antagonists within root systems (36,39), demonstrated that root-knot nematodes could infect leaves and shoots of plants (37), and studied nematode feeding behavior (33,35,38).

In 1936 Francis Yap (Fig. 7), a technician at the Experiment Station, observed a nematode on the roots of cowpea. The nematode did not cause galling, but it could be detected by small masses of soil clinging to the gelatinous matrix of females embedded in roots (Fig. 8). This nematode was
FIG. 7. Francis Yap, technician at the PRI, was the first to observe the presence of *Rotylenchulus reniformis* on the roots of cowpeas. Photograph ca. 1938.

subsequently described by Linford and Oliveira as *Rotylenchulus reniformis* (40), a nematode with a rather wide host range (43). During the early 1940s the potential damage by reniform nematode was studied, along with its ability to withstand desiccation. The nematode was pathogenic on certain host plants, and could tolerate desiccation much better than could root-knot nematodes. Linford et al. also described *Paratylenchus minutus*, a parasite of pineapple, in 1949 (41). During this time the Plant Pathology Department investigated the possible occurrence of races of the root-knot nematode on Oahu. Linford resigned in September of 1949 and moved to the University of Illinois.

Publication of research was opposed by some pineapple industry personnel in the 1930s. The station director vigorously defended the need to publish results of research done at the Experiment Station, and Linford continued to publish his work. By the late 1950s publication of PRI research in the literature was discouraged and any publication required permission of the director.

*Walter Carter:* In 1930 Carter (Fig. 4), an entomologist, was hired by the Experiment Station. As Head of the Entomology Department at the Experiment Station and the PRI from 1932 to 1961, he had a strong influence on Hawaiian nematology. When economic conditions became difficult for the Experiment Station in the early 1930s, the Nematology Department was disbanded, and Carter’s arguments concerning the etiology of wilt disease (7) influenced the perceived importance of nematode diseases. He renamed the wilt disease “mealy-bug wilt” as mealy-bugs were associated with wilted plants and seemed able to transmit the disease. Carter wrote: “Evidence is accumulating, however, from a large series of control experiments, as well as from commercial fields that have been consistently treated for mealy-bug control, that mealy-bug wilt is the major factor in failure of pineapples in Hawaii and that other factors only operate in extremely localized areas and sometimes then only under abnormal weather conditions” (7). Carter emphasized that mealy-bugs were the most important, if not only, pest problem in pineapple. This information was influential because wilt had been the pineapple industry’s major problem since the early 1920s.

Ironically, Carter eventually established the importance of nematodes as limiting factors in plant growth with his discovery of the nematicidal activity of 1,2-dichloropropane, 1,3-dichloropropene (D-D) mixture in 1941 (8,9). He was examining the influence of soil fumigants on mealy-bug wilt and in early 1940 was informed that Shell Company had liquid compounds available that were byproducts of the production of allyl chloride. One compound was not pure and would present a disposal problem when manufacture of other compounds was increased. That compound was D-D. Field trials including D-D were conducted in several pineapple fields in 1940,
and an increased growth response was seen (8). The reason for the growth response was not clear, but increased root growth was observed in treated plots.

The influence of D-D on nematodes was clearly demonstrated in another set of plots about which Carter wrote: "The use of D-D which definitely demonstrated its nematicidal value against root-knot nematode came about in another matter. Prior to Dec. 7, 1941, elaborate plans had been made to provide food in the event of a siege of the Islands and the writer was assigned the duty of organizing this among pineapple plantations. Mr. Colin Lennox was my opposite number in the Sugar Experiment Station and he operated small variety trials on the Station Grounds. With his cooperation, tests were set up in tomato and other vegetable plots to ascertain the growth stimulation effects then showing up in the pineapple field plots. It so happened that the ground was heavily infested with root-knot nematode and the effect of D-D in producing nematode gall-free tomato plants as well as carrots was demonstrated conclusively."

In 1943 the acting director of PRI noted: "D-D mixture is most likely to fulfill its promise of being an answer to the need for a cheap soil fumigant which can be applied as an insurance measure in any field where failure due to soil organisms is likely to be a factor." By 1944 the toxicity of D-D to root-knot nematode eggs, even if the eggs were within roots, was recognized. In addition, Linford's work suggested that D-D was not overly toxic to nematode-destroying fungi.

In 1943 Carter applied for a patent on D-D mixture for use as a soil fumigant to rid agricultural soils of deleterious organisms. The patent was awarded in 1950. The efficacy of D-D as a soil fumigant in promoting plant growth (Fig. 9) revolutionized nematology. Shell Oil Company increased production of D-D mixture in response to the demand for the fumigant.
by the Hawaiian pineapple industry. Soil fumigation assisted in the eventual differentiation of wilt symptoms resulting from nematode induced moisture stress and wilt associated with mealy-bugs.

Carter summarized the ramifications of the discovery of D-D, noting: "It will be generally agreed that the advent of D-D ushered in a new phase of practical plant protection, initially with a profound effect on the maintenance of the pineapple industry in Hawaii; it contributed to a long overdue support for the expansion of Nematology as a specialized branch of zoology; it intensified the research programs of primary chemical producers leading to the development of practical alternatives as well as to many basic contributions to soil microbiology; and last but not least, it is contributing to the alleviation of the problem of a hungry world." D-D remained an effective soil fumigant, widely used in the Hawaiian pineapple industry, until its U.S. registration was revoked in March of 1984.

During 1943–46, the potential of ethylene dibromide (EDB) as a general soil fumigant was also studied by Carter and Schmidt, with good success. By 1950 EDB was established as an effective soil fumigant; it was used until it was removed from U.S. markets in September of 1983.

The focus of nematology research at PRI and the culture of pineapple in Hawaii were changed dramatically by Carter’s discovery. The age of nematicides had arrived, and many potential fumigants were soon being screened at the PRI. By the late 1940s preplant soil fumigation for nematode control was standard industry practice.

Carter retired from the PRI in 1962.

Carl T. Schmidt: Hired by the Experiment Station as an entomologist in 1931, Schmidt (Fig. 5) worked at PRI until he was released in 1963. He was responsible for the discovery of the soil fumigant 1,2-dibromo-3-chloropropane (DBCP). He claimed a patent with the U.S. Patent Office in 1954 for the use of DBCP as a method of treating soil to improve its plant-
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growing properties. The patent was awarded in 1960. DBCP was unique as a soil fumigant, providing effective nematode control at relatively low application rates with the capacity for use as a postplant fumigant.

DBCP became a widely used, effective nematicide until it was removed from U.S. markets in 1977. A testament to the importance of DBCP to Hawaiian pineapple is that Maui Pineapple Co. obtained a special-use permit allowing use of DBCP on the island of Maui until 1984.

E. J. Anderson: Hired as a plant pathologist by the PRI in 1945, Anderson was named Department Head when Linford left in 1949, and he remained there until the PRI eliminated the Department in 1966. During his tenure at the PRI he was responsible for work on the development of fumigant usage patterns, specifically placement depth and application rates for D-D, EDB, and DBCP and the efficacy of mulches in promoting fumigant action (1). His work clearly demonstrated the toxicity of D-D to nematodes. He investigated the effect of soil moisture on the efficacy of fumigation and showed that D-D and EDB were more effective in moist than in dry soils.

During the mid-1950s the importance of reniform nematode was increasing. Fields with problem-level populations of reniform increased in frequency on all the islands, and Anderson was responsible for the sampling program to assess infestation levels. He developed rapid methods for determining the numbers of nematodes in a sample (2). During the same time period soil acidity was becoming a problem in many fields; some fields recorded a pH as low as 3.8. The increasing importance of the reniform nematode during the 1950s has been attributed, in part, to increasing soil acidity (47).

John D. Radewald: Appointed nematologist at PRI in 1960, Radewald initiated work on the efficacy of fumigants and the ability of reniform nematode to withstand moisture stress. He remained in Hawaii for 3 years.

Walter J. Apt: During 1958 and 1959 Apt served as a consultant nematologist with the Hawaii Sugar Planters Association in Honolulu. In 1963 he returned to Hawaii and the PRI where his research program included the evaluation and development of effective nematode management strategies using volatile and nonvolatile nematicides. He is credited with being the first individual to design a nematode management program based upon the systemic properties of foliar-applied fenamiphos (50). He also has continued work initiated by Linford on the ability of reniform and root-knot nematodes to withstand desiccation (4,48,49).

In 1973, the PRI was closed and Apt was appointed Professor of Plant Pathology at the University of Hawaii. He has pursued techniques for applying nematicides through drip systems (5) and has continued to investigate desiccation tolerance in root-knot and reniform nematodes.

The Present

Current pineapple plantation practices include 6–12-month fallow periods with all fields receiving preplant fumigation with dichloropropene. Oxamyl and fenamiphos are labeled for use through drip irrigation and for foliar applications. These may be applied to supplement preplant soil fumigation or used alone (47).

The current pineapple nematology research program in Hawaii is focusing on development of integrated nematode management strategies through balanced use of biological, cultural, and nematicide-based management practices. This approach was prompted by the loss of the soil fumigants DBCP, EDB, and D-D mixture, as well as increasing concern with environmental contamination and the industry's reliance on preplant soil fumigation using 1,3-dichloropropene for nematode management.

The Future

The future of pineapple and pineapple-nematode management in Hawaii is uncertain. Integrated management ap-
approaches, if successful, will allow judicious use of nematicides in combination with cultural practices and biological control agents. Such an approach would depend on developing a firm understanding of the biology and ecology of root-knot and reniform nematodes in Hawaiian pineapple production, a goal stated by Godfrey more than 50 years ago.

**Literature Cited**


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