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Hawaii's Approach to Control o

Sugarcane smut, caused by *Ustilago scitaminea* Syd., was first detected in the United States in Hawaii in 1971. Smut was then discovered in Florida in 1978 and in Louisiana, Puerto Rico, and Texas in 1981 (13; S. Ferreira and B. Villalón, *personal communications*). Finding smut in the continental United States was expected because the disease had spread rapidly throughout the Caribbean and Central America after being discovered in Guyana in 1974 (12,16) (Fig. 1).

The outbreak and spread of smut in the Caribbean and the United States received national and international media coverage. Rapid spread of the disease was not new, however. Since the first report of sugarcane smut in the Natal region of South Africa in 1877, the disease has had a history of new occurrences and rapid spread (3). Smut was confined to the eastern hemisphere until its detection in Argentina in 1940 (3). The disease spread rapidly to Argentina's sugar-producing neighbors, Bolivia and Paraguay, then subsided until its detection in Guyana.

The sugar industries of several countries have been threatened by sugarcane smut. At present, Australia is the only major sugarcane-producing country that has never reported the disease. We recommend the control practices that have been used successfully in Hawaii and stress the need for regional and international cooperation.

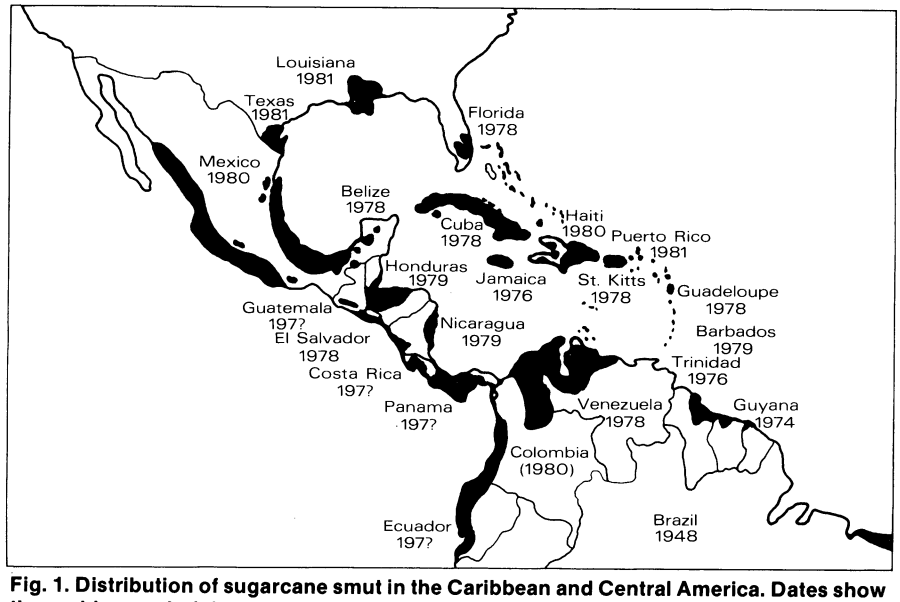

Fig. 1. Distribution of sugarcane smut in the Caribbean and Central America. Dates show the rapid spread of the disease from the first sighting in Guyana in 1974.

Symptoms

Sugarcane smut was one of the first recognized sugarcane diseases because of its obvious whiplike sorus (Figs. 2 and 3). Whips (common term for sori) arise either from the terminal meristem (Fig. 2) or from side shoots of infected stalks (Fig. 3). They vary in length from a few centimeters to 1.5 m, with terminal whips usually longer than those from side shoots. The sorus contains a central core of parenchyma and vascular host tissue around which a thin cylinder of teliospores is produced. A thin silver-white membrane surrounds the teliospore cylinder and eventually ruptures, allowing wind dispersal of teliospores as the whip emerges. Whips grow from 6 to 10 cm per week and continually release teliospores. After weathering and teliospore dispersal, all that remains is the tan central core of the whip (3,8).

Besides the characteristic whiplike sorus, tillering increases and stools develop a grassy appearance. Other less common symptoms are leaf and stem galls, bud proliferation (Fig. 4), serpentine-shaped sori (7), and modified stamens and inflorescences (14). Smut infection occasionally causes leaf yellowing and stunting on highly susceptible varieties 3–4 weeks before whip emergence. Seven to 10 days before whip emergence, the leaves become stiff and erect and the upper internodes lengthen. Dissection of the spindle leaves of these plants usually exposes a small whip that positively identifies the disease.

The Pathogen

Classification. The sugarcane smut pathogen was first identified as *Ustilago sacchari* Rabenh. and later renamed *U. scitaminea* Syd. *U. scitaminea* can be identified by its dark brown, minutely punctate teliospores (5.5–9.5 μm diam.) with a thin epispore. *U. scitaminea* is pathogenic to sugarcane and the *Saccharum* spp. (3). Sorghum (*Sorghum vulgare*) and corn (*Zea mays*) have been infected with *U. scitaminea* by injection with teliospores but have not been shown to be natural hosts (12). A complete taxonomic description can be found in Antoine's chapter on smut in *Sugar-Cane Diseases of the World* (3) and in Lee-Lovick's review (12).

Teliospores. *U. scitaminea* is capable of producing large numbers of teliospores, a single whip producing up to 10^{11} teliospores during the life of the whip (12). Assuming a sugarcane field has approximately 75,000 stalks per hectare, a 20% stalk infection would release up to 1.5×10^{15} teliospores. Teliospores are windborne and may be dispersed long distances. Abandoned sugarcane fields in the Kohala region of the smutfree and quarantined island of Hawaii became infected presumably by teliospores blown

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ugarcane Smut

60 miles from the island of Maui, the closest known source of smut. The rapid spread of smut in the Caribbean over longer distances was probably a result of windborne teliospores. This abundant teliospore production with widespread dissemination increases the difficulty of controlling smut locally as well as regionally.

Relative humidity and moisture conditions affect teliospore survival. Teliospores can survive up to several years in the laboratory if kept dry. In the soil, teliospores survive several months under dry conditions but only 2–3 weeks under moist conditions. Byther and Steiner (6) found that teliospores suspended in water at 56 C were killed in 2 minutes. J. C. Comstock (*unpublished*), however, found that 15% teliospores treated with dry heat for over 48 hours at 60 C survived and that germination was slow, taking 24–30 hours instead of the usual 6. The results of these experiments suggest that teliospores become more heat-sensitive as their water content increases.

How teliospores of *U. scitaminea* germinate depends on temperature and nutrition. At 30 C or higher on nutrient-rich media (potato-dextrose and Czapek-Dox agars), teliospore germination of *U. scitaminea* is typical of *Ustilago* spp. A promycelium is produced; it divides transversely, giving rise to three or four cells, each capable of budding sporidia. The oval sporidia measure 2×6 μm. On nutrient-poor medium (water agar) and as temperature decreases, germinating teliospores tend to produce long, septate hyphae (4). Hyphal and/or sporidial fusions take place and, presumably, a dikaryon is produced and becomes the infectious hyphae. Occasionally, a "giant" sporidium with two nuclei is produced at low temperature and sucrose concentrations (R. S. Byther and G. W. Steiner, *unpublished*). White mycelial colonies are evident 48–72 hours after teliospores are placed on either nutrient or water agar plates.

Infection. Infection is initiated when teliospores are deposited on the lateral buds of standing cane. Teliospores germinate to produce infectious, presumably dikaryotic hyphae. The infectious hyphae penetrate the basal portion of young bud scales, invading the meristematic region of the bud (3). When the meristematic region of the bud is dormant, the fungus also remains dormant. When the meristematic region is active, the fungus maintains an association with the meristematic region. Mycelium becomes associated with each bud primordium produced in the developing stalk. Mycelium is not uniformly present in internodal tissue (3), however. If the lateral buds germinate, stalks developing either from a side shoot or from an infected seed piece are infected.

Eventually, whip production is stimulated. The apical meristem assumes an intercalary function and acts as a basal meristem of the smut whip. Tissue developing below continues the growth of the stalk, while tissue developing above the meristem develops into a whip.

Infection by teliospores can also take place in the soil when teliospores come in contact with germinating buds. The frequency of infection in the soil is probably low because of the relatively short survival of teliospores in moist soil.

Cultural types. Variability of the pathogen is indicated by the different culture types that occur. Isolation from infected sugarcane stalks initially yields two distinct types of colonies: primarily slow-growing brown-black colonies and occasionally white mycelial colonies resembling those derived from teliospores. The brown-black colonies are unstable and give rise to three distinct types of growth: cream-colored convoluted, white mycelial, and "yeastlike" sectors (Fig. 5). The conversions between the cultural types are not clearly understood but may be related to levels of ploidy. The slow-growing brown-black colony is pathogenic when inoculated to sugarcane (S. A. Ferreira and J. C. Comstock, *unpublished*). Because the colony is unstable, the significance of this observation is unknown.

Incidence and Severity

Varietal reaction to smut. The incidence and severity of smut are determined by varietal susceptibility in relation to smut race, environment, and cultural practices. Susceptible varieties generally produce whips and other symptoms sooner than resistant varieties and have a higher incidence of stools infected. This effect was illustrated on Maui, where adjacent fields of the

Fig. 2. Sugarcane smut whips (sori) extending above the canopy.

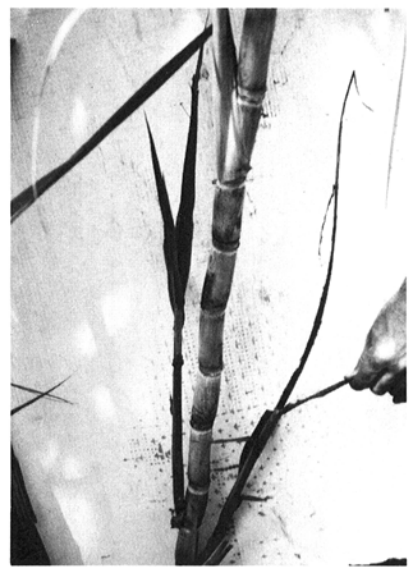

Fig. 3. Side shoots on sugarcane stalk bearing whips.

Table 1. Reactions of sugarcane varieties to *Ustilago scitaminea* in different countries

Country	Variety									Reference
	CB 41-76	Co 331	Co 527	CP 63-588	H50-7209	HJ5741	NCo. 310	POJ 2878	PR 980	
Belize	···[a]	S	···	···	···	S	S	R	···	9
Brazil	R	S	R	S	I	S	S	R	···	1
Guyana	···	R	···	···	···	S	···	···	S	5
Hawaii										
Race A	R	S	R	R	R	···	S	R	···	Exp. Stn., Hawaiian Sugar
Race B	···	···	···	S	S	···	···	···	···	Planters' Assoc.
Jamaica	···	I	···	R	S	S	S	···	S	5; J. Dean (*pers. commun.*)
Kenya	S	R	R	···	S	···	···	···	R	1
Philippines	···	···	R	···	S	···	R	···	R	1
Zimbabwe	···	···	S	I	S	···	S	S	S	1,8

[a]··· = Data not available, S = susceptible, I = intermediate, R = resistant.

susceptible variety H50-7209 and the resistant variety H62-4671 developed 50 and 3% stalk infection, respectively. Likewise, symptoms are more intense on susceptible varieties. Smut reduces the vigor and causes stunting of plants of susceptible varieties, whereas plant growth of resistant varieties generally remains unaffected.

The extent to which a variety is grown contributes to development of epiphytotics. In many countries, a single variety occupies over 25% of the sugarcane acreage. If that variety is smut-susceptible, the disease can be severe. This occurred on Maui, where variety H50-7209 occupied over 70% of the sugarcane acreage. Within a year after a smut race that could attack variety H50-7209 was detected, an epiphytotic was well under way. The inoculum produced in infected fields of H50-7209 caused a moderate infection on even the more resistant varieties H62-4671, H57-5174, and H69-8235.

The type of smut whip development of variety H50-7209 is ideal for teliospore dispersal, as large whips extend above the canopy (Fig. 2). Furthermore, tillering increases and nearly every stalk per stool becomes infected. Spore dispersal from such varieties as H50-7209 contributes to the rapid spread of smut. In contrast, resistant variety H62-4671 produces small whips from side shoots, and most of the whips are near ground level, limiting teliospore dissemination.

Smut races. Unfortunately, changes in pathogenicity of *U. scitaminea* can result in changes in varietal reaction to smut. This happened in Hawaii and dramatically affected the disease picture. From 1971 until 1976, only one pathogenic race of smut was known in Hawaii. Race A, as it was named, did not attack the two varieties, H50-7209 and H59-3775, that occupied over 60% of the acreage in 1976. That year, however, a second smut race, B, was detected that attacked these two varieties, and within 2 years smut severely threatened the Hawaiian sugar industry. These race B-susceptible varieties have been replaced on Hawaiian plantations.

Several pathogenic races of smut have been reported around the world (8,10). The recent rapid spread of smut in the Caribbean stresses the need to know which smut races are present within a geographic region to help develop resistant varieties. Unfortunately, direct comparison of smut races found in different countries has been impossible. All sugarcane-growing countries rightly restrict the importation of foreign races of *U. scitaminea* to protect their own sugar industries. The only way to compare *U. scitaminea* races among countries has been to compare the smut reaction of sugarcane varieties that have been tested worldwide (Table 1). Reaction of a variety to smut depends on the country. Variety NCo. 310 is an almost universal suscept but has been reported to be resistant in the Philippines. Varieties POJ 2878 and Co 527 are susceptible in Zimbabwe but resistant elsewhere. The reactions of variety Co 331 in Belize and Guyana differ, suggesting that at least two smut races occur in the Caribbean; this differential reaction needs reconfirming, however. Although present information is limited, differences in smut races have been clearly indicated among countries.

More knowledge of similarities and differences of smut races would aid in development of resistant varieties. For instance, if smut races in two countries were different, the exchange and utilization of germ plasm would result in an increase of gene frequencies for resistance to the two races in both countries. This would likely result in a broader basis for smut resistance. If smut races in both countries were similar, varieties resistant in one country would have a high probability of being resistant in the other, and exchange and utilization of germ plasm would result in faster development of resistant varieties.

Environment. Smut development is favored by a warm, dry environment such as that of the low, leeward, irrigated cane-growing zones of the Hawaiian islands. By contrast, smut is not a problem in the cooler, windward, unirrigated zones. A susceptible variety, H61-1721, is grown with only traces of smut in a cool, wet environment, whereas 20 km away it becomes heavily infected with smut and cannot be grown.

Cultural practices. The incidence and severity of smut are increased by certain cultural practices. The most important is probably ratooning, ie, harvesting the sugarcane stalks at ground level and allowing the stool to regrow. Generally, a plant crop started with healthy seed pieces will have few whips at maturity. Once the stool is systemically infected and ratooned, however, the regrowth will probably develop whips. In a natural infection test, the incidence of infected stalks in susceptible variety H50-7209 increased from 2% in the plant crop to 26 and 85%, respectively, in successive 6-month first and second ratoons. For resistant variety H62-4671 in the same test, the incidence of infected stalks was 0, 8, and 7% for the plant crop and first and second ratoon crops, respectively.

In Hawaii, because a 2-year crop is produced, varieties tend to lodge and become recumbent, and cane stalks along field edges and irrigation ditches are pushed and bent to provide unobstructed walkways. This practice damages stalks and induces the lateral buds to germinate and produce side shoots. Six to 8 weeks after cane is damaged, lateral shoots usually develop a flush of whips. Field edges, then, tend to have the highest incidence of smut.

Control

Varietal resistance. Planting resistant varieties is the primary means of controlling sugarcane smut. Other control methods are only a means to limit the disease until adequate smut-resistant varieties are available.

In Hawaii in 1971, when smut (race A) was first detected, 16 of the 20 widely grown varieties were susceptible, involving 40% of the sugarcane acreage. Fortunately, the two most widely adopted

varieties, H50-7209 and H59-3775, planted on 45% of the acreage, were resistant to race A. Another critical problem was that approximately two-thirds of the varieties in both the breeding and the selection programs were susceptible (11). A complete reorganization of the germ plasm pool was undertaken, and the selection program was expanded to emphasize development of smut-resistant varieties.

Initially, after smut was detected, all clones used in the breeding program were tested for smut reaction. With few exceptions, all smut-susceptible parents were discarded for breeding purposes (11). Only smut-resistant varieties were used in crosses that allowed maximum random pollination, akin to a polycross. These modified polycrosses constitute the majority of the crosses in the Hawaiian Sugar Planters' Association breeding program. Susceptible parents with other highly desirable characteristics were used only in biparental crosses. Thus, we were able to utilize smut-susceptible germ plasm without altering the frequency of resistance genes in our modified polycrosses. The reorganization was successful; the level of smut susceptibility in seedlings produced annually decreased from 64 to 11% in just 5 years.

During the initial period of germ plasm reorganization, several genetic studies were begun. Data from these studies indicated generally that crosses between smut-resistant parents gave rise to more resistant progeny than did other crosses. There were certain exceptions, however, and these parents were either discarded or retained, depending on the type of progeny produced. One inheritance study using variance components and involving an incomplete diallel design gave heritability values of 0.56 and 0.84 on individual and family bases, respectively (K. K. Wu, *unpublished*). A second inheritance study using parent progeny regressions provided a heritability estimate of 0.52 (K. K. Wu, *unpublished*). Both studies suggest that rapid progress toward increased smut resistance can be made in a breeding program.

Before smut was discovered in Hawaii, Hawaiian varieties were known to be generally smut-susceptible. Through cooperative and exchange programs, Hawaiian varieties had been tested in several foreign countries against the major diseases of sugarcane, emphasizing those not present in Hawaii. After 1971, Hawaiian varieties known to be resistant to smut in foreign countries were emphasized in modified polycrosses. After the detection of smut, the exchange program was expanded. Hawaiian varieties are tested for smut resistance with the cooperation of sugar experiment stations in Brazil, Florida, Jamaica, Taiwan, the Philippines, and Zimbabwe and for Fiji disease resistance in Australia and Fiji.

The importation of exotic germ plasm was always an important aspect of the variety development program. After the discovery of smut, the foreign varieties in our collection resistant to smut in their country of origin were screened for smut resistance in Hawaii. Any variety resistant to smut in Hawaii was used in modified polycrosses. In 1972, any additional commercial variety resistant to smut in a foreign country was imported into the United States. In 1975, after quarantining and smut testing, these varieties were used in the Hawaiian breeding program.

The number of seedlings entering the selection program was doubled to increase the number of smut-resistant varieties with high yield potential. This resulted in a 50% increase in the number of seedlings in preliminary yield tests, from 2,545 in 1971 to 3,788 in 1977. By the time the preliminary yield tests were ready for harvest, the varieties had been screened at least two times, and in many cases three times, for smut resistance.

Because new smut races can develop, commercial fields were monitored closely for smut. In 1976, smut was found on H50-7209, and this proved to be a new pathogenic race (race B). Unlike the discovery of race A in 1971, when two-thirds of the seedlings were susceptible, the initial screening for race B smut resistance showed only 35% of the seedlings to be susceptible. Race B-resistant varieties were quickly found in all stages of the breeding program. A

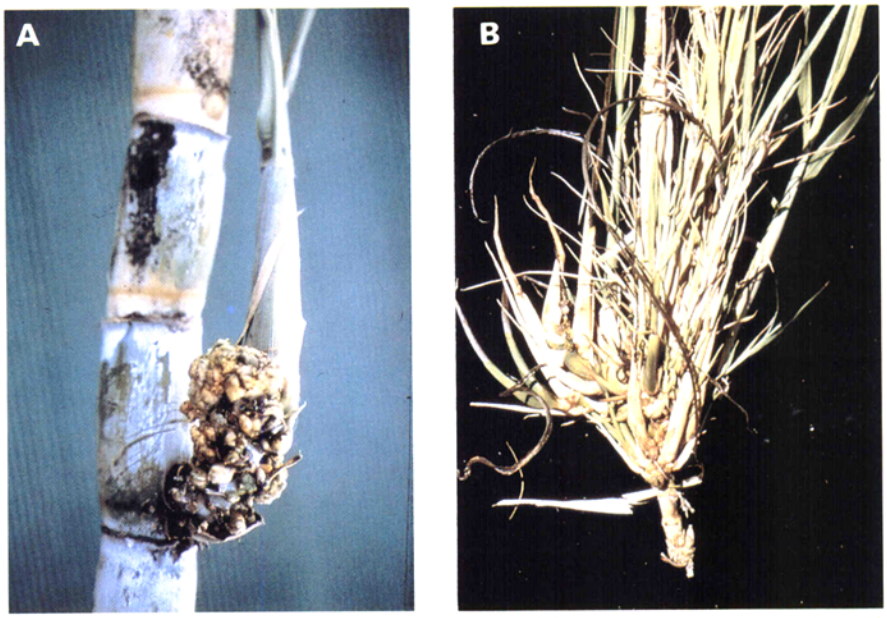

Fig. 4. Rare smut symptoms: (A) Abnormal bud and (B) shoot proliferation with several whips present.

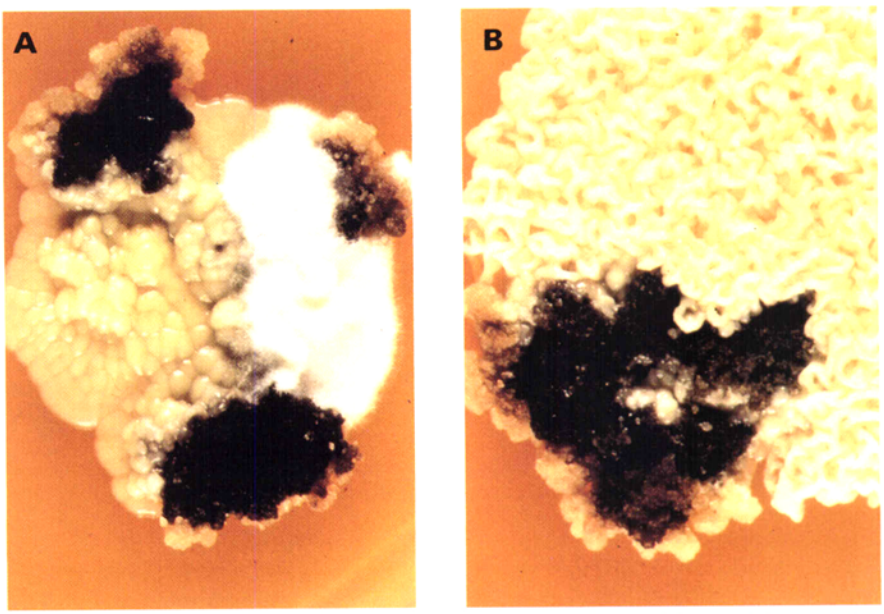

Fig. 5. Types of *Ustilago scitaminea* growth in culture: (A) Brown-black, white mycelial, and yeastlike sectors and (B) brown-black and cream-colored convoluted sectors.

smut nursery and testing station was established for race B and isolated both from race A resistance testing facilities and from commercial sugarcane plantings. After 2 years of testing varieties separately for smut resistance to the two races, the races were combined for inoculation. Separate smut nurseries were maintained to provide inoculum. Currently, equal emphasis is placed on developing resistance to both races, not just the most prevalent one.

The Hawaiian variety development program involving intensive smut screening has proved effective in providing high-yielding smut-resistant varieties. At present, the industry has a choice of nine resistant varieties yielding as well as or better than the smut-susceptible varieties they replaced. Of the nine, eight have achieved commercial status (> 1% of total acreage) in the last 4 years, and all are being increased. Even with high-yielding smut-resistant varieties available, plantations are obliged to live with existing varieties in most situations for at least 4–6 years because of physical limitations, such as the capacity to plow and replant fields scheduled for ratooning, and because of inadequate amounts of seed of the new smut-resistant varieties. During the time required to change from susceptible to resistant varieties after the occurrence of race B, some plantations experienced yield losses.

Smut inoculation methods. The methods of inoculating and screening sugarcane varieties for smut resistance vary among countries. The three basic methods used are 1) immersion, 2) wound-paste, and 3) natural infection (8).

The immersion technique, in which three-bud seed pieces are immersed in a teliospore suspension, is used routinely in Brazil, Florida, Guyana, Hawaii, India, Jamaica, and the Philippines. The method varies considerably among countries. Teliospore concentrations range from 2.5×10^6 to 5×10^8 spores per milliliter, with variable immersion times. In Hawaii, 5×10^6 spores per milliliter with a 10-minute immersion is used. The number of seed pieces tested and replications used also varies. In Hawaii, tests are not replicated, but varieties are tested during each of the three stages of visual selection before the initial yield tests, using 2, 3, and 16 seed pieces, respectively. Varieties entering advanced yield trials are tested at least one additional time, using 16 seed pieces. Results are obtained in the plant crop 4–6 months after inoculation and planting. In Hawaii, data are also taken at 4 months in the first ratoon (8).

The wound-paste technique is used in Brazil and Taiwan. Two to six puncture wounds are made on the edge of the bud, then a teliospore paste is spread on the bud. This method bypasses the morphological barrier of the overlapping bud scales. Generally, varieties give a more severe reaction to smut with this procedure.

The natural infection test is conducted by exposing test varieties to high natural levels of smut inoculum. Generally, the test varieties are planted adjacent to an inoculated susceptible variety serving as an inoculum source. Few smut whips develop in the plant crop, so the test is taken through two or more ratoons. In Zimbabwe, the natural infection test is used routinely. In Hawaii, it is used to reevaluate varieties with intermediate or susceptible reactions to the immersion test. A correlation of $r = 0.72$ between the natural infection and the immersion tests has been obtained in Hawaii (8).

In Hawaii, as in most areas, varietal smut reactions are evaluated on the basis of percent infected stools. Both actual counts and visual estimates of infection are made. A rating scale of 1–9 is used by sugarcane pathologists throughout the world to express varietal reactions, 1 being highly resistant and 9 being highly susceptible. There is, however, a lack of uniformity in transforming the percent infection to a number grade on the 1–9 scale. Most pathologists use 10% infection and lower as the cutoff point for being resistant; pathologists in Hawaii use 25%. Variation also occurs in indicating intermediate and susceptible reactions. The cutoff point for susceptibility ranges from 16 to 40% (8). Because of the variations in smut reaction evaluation and in inoculation methods, caution must be used when comparing percentages of smut between countries and between locations within countries.

Cultural practices. In conjunction with screening for and planting resistant varieties, several cultural practices are used to reduce inoculum levels. All susceptible varieties, infected or not, should be removed from seed nurseries. Roguing is done manually or with a 10% solution of the herbicide Roundup. All planting material should be cut from smutfree nurseries or from nurseries with the lowest amounts of smut. Seed pieces should be treated with hot (52 C) water for 30 minutes. Byther and Steiner (6) showed that 20-, 30-, and 45-minute treatments in water at 52 C reduce smut incidence by 90, 98, and over 99.5%, respectively, in systemically infected seed pieces (6). The 52 C temperature gave the best control with the highest viability of lateral buds. Each of these hot-water treatments serves a unique purpose in Hawaii. In areas not prone to smut, the 20-minute 52 C treatment is used commercially to stimulate germination of the lateral buds. The 30-minute treatment is used commercially on the hot, dry plantations where the environment favors smut development. The 45-minute treatment is used for seed pieces destined for smutfree plantations and isolation nurseries. Unfortunately, the 45-minute treatment significantly reduces bud germination and cannot be used commercially.

Eliminating the cultural practice of crop ratooning reduces sugarcane smut buildup. Normally, two or three ratoon crops are grown to reduce the production costs of plowing and replanting. Since *U. scitaminea* is systemic, ratooning increases the incidence and severity of smut with most varieties. The same applies for pushing cane to clear roads and irrigation ditches. In Hawaii, the practices of ratooning and pushing have been drastically curtailed in fields in the leeward smut-prone areas. This, along with hot-water treatment for seed pieces, is allowing susceptible varieties to be grown without yield losses until they can be replaced by resistant varieties.

Fungicides. Originally there was no effective chemical means of controlling smut. Now, however, two fungicides have shown activity against sugarcane smut: triadimefon (Bayleton) and CGA-64251 (Vangard). Preplant treatment of seed pieces with Bayleton protected and reduced smut in developing plants in tests conducted in South Africa, Hawaii, and India (2,15). In Hawaii, Vangard treatment of healthy seed pieces of susceptible varieties reduced smut development through one 5-month ratoon crop when the plants were exposed to high inoculum levels. A 6% stalk infection occurred in the first ratoon crop in plants developing from Vangard-treated seed pieces, compared with 18% in untreated controls. Vangard treatment also eradicated or inhibited smut development from systemically infected seed pieces.

Quarantine. Quarantine procedures and regulations prevent movement of the smut pathogen when germ plasm is routinely exchanged between and within countries for breeding purposes. Since sugarcane is vegetatively propagated, variety exchange requires the exchange of seed pieces. Seed pieces are treated with hot (52 C) water for 30–45 minutes either before leaving or on entering a country. During the United States quarantine, varieties are repropagated from seed pieces that have received a 2-hour 50 C water treatment for control of ratoon stunting disease. This treatment also eradicates the smut pathogen from systemically infected seed pieces. Hawaii's unique geographic isolation has for years helped prevent the introduction of new diseases. Most sugarcane-growing areas are not as fortunate.

The true seed of sugarcane is also exchanged between countries as a way to introduce germ plasm. Because smut could possibly be transported in fuzz contaminated with teliospores of *U. scitaminea*, precautions are required. Immersion in 0.525% sodium hypochlorite solution for 30 minutes will destroy surface-contaminated smut teliospores. This treatment of fuzz followed by air

drying is recommended before shipment. Smut infection of the inflorescence has been reported (14) but is extremely rare.

Outlook and Need

Sugarcane smut will probably continue to threaten sugarcane industries around the world. All countries having the disease should maintain integrated pest management programs that develop smut-resistant varieties and should continue cultural practices that reduce smut inoculum levels. Barring the introduction or development of new races, sugarcane smut can be genetically controlled through resistant varieties with no crop losses.

The recent smut epiphytotic in the Caribbean and Central America stresses the need for regional cooperation. Smut races not present in a region must be excluded not only from one's own country but also from geographic neighbors. The nature of the windborne teliospore makes single-nation quarantines ineffective. Quarantines involving the cooperation of all countries within a region should be established.

Since resistance is the primary means of controlling sugarcane smut, a knowledge of the disease reaction of varieties that have been tested around the world would be helpful. A centralized data bank would aid all breeders in selecting varieties for incorporation into their own breeding programs. Centralization of information would help clarify the distribution of smut races and indicate when new races have developed. The world's sugarcane industries have a long history of cooperation, and the threat of losses from sugarcane smut makes it essential that such cooperation continue.

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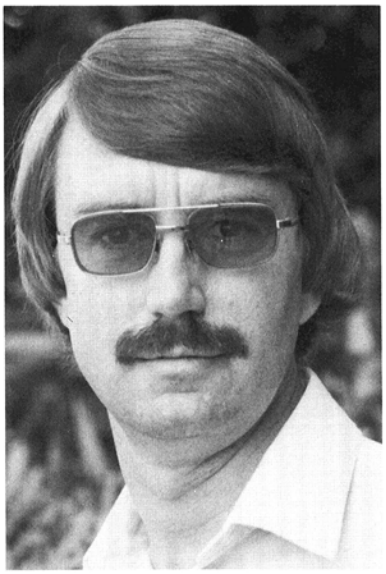

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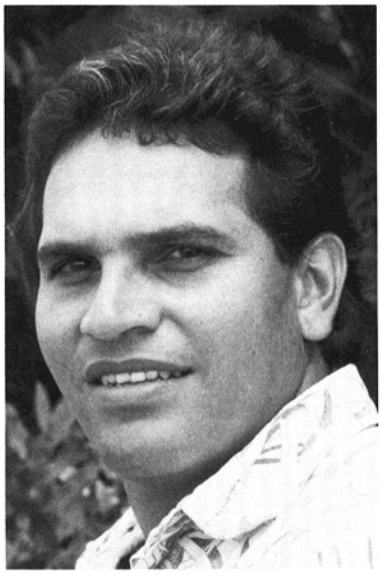

Stephen A. Ferreira

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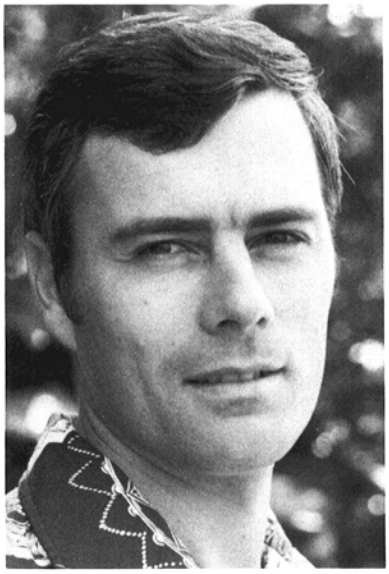

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