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Chemical Ecology: Studies from East Africa

Interdisciplinary studies at the ICIPE laboratories in Nairobi are yielding exciting chemical results.

Jerrold Meinwald, Glenn D. Prestwich
Koji Nakanishi, Isao Kubo

The difficulties associated with the control of insect and other arthropod pests by means of conventional insecticides are widely recognized. Environmental pollution, lack of species specificity, and the development of resistant insect populations are among the main factors that make it highly desirable to develop new methods of pest control. A rational approach to this worldwide problem, however, requires a greater understanding than we now have of the physiology, ecology, behavior, and chemistry of insects. Many laboratories are engaged in research programs aimed at obtaining a more detailed knowledge of insect endocrinology; insect defense and communication systems are also receiving considerable attention. Work in these areas may ultimately provide the basis for new, biologically sound control techniques that utilize insect hormones and pheromones or their analogs. Perhaps an even more promising avenue of investigation involves the examination of plants for naturally occurring secondary metabolites that may have insect-repelling, insecticidal, antihormonal, or antifeeding characteristics on which novel ways to influence insect behavior or development (or both) might be based. From a chemical viewpoint, our knowledge of many of these areas is still in an embryonic state.

One important motive behind the founding of the International Centre of Insect Physiology and Ecology (ICIPE) was to establish an interdisciplinary laboratory where biologists and chemists from all over the world could collaborate on fundamental studies of arthropods, and concentrate chiefly on species of agricultural and medical importance. An equally important motive, however, was expressed by Djerassi just ten years ago (*1*). At that time, he put forward an intriguing model for the accelerated ad-

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Summary. The International Centre of Insect Physiology and Ecology (ICIPE), in Nairobi, provides a laboratory at which a multinational group of scientists pursues interdisciplinary research. In collaboration with their colleagues in biology, ICIPE chemists have characterized the sex pheromones of the tick which serves as a vector of East Coast fever and have identified a termite queen-cell–building pheromone. The structure of many anthropod defensive chemicals have been determined; most interesting of these are the trinervitenes, structurally novel diterpenoids from nasute termites. Several highly active insect antifeedants were discovered using a simple bioassay to screen selected East African plants. These antifeedants may provide leads for the development of new insect-control techniques.

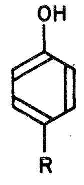
vancement of science in a developing country, based on the cooperation of an international group of established scientists coming together on a part-time basis to guide the work of a select group of young postdoctoral investigators in the study of some area of science that would be exciting, timely, and of significance both locally and internationally. There were many reasons for choosing Nairobi as the site for such a laboratory and for selecting insect physiology and ecology as its chief subjects. Djerassi's idea was quickly taken up by University of Nairobi entomologist Thomas R. Odhiambo, who had long been concerned with the philosophical basis for scientific development in East Africa, and who had independently suggested that an African center of excellence devoted to the intensive study of insect biology be established (*2*). It took a remarkably short time for these ideas to find their embodiment in ICIPE, with Odhiambo at its head. The first ICIPE research laboratory, a temporary building located on the University of Nairobi campus, was completed in May 1971, and a second building was added a year later. In 1975, the first permanent building was completed. There are now about 25 research scientists (all holding the Ph.D. degree), most of whom are biologists, working at ICIPE. The Chemistry Research Unit, which can accommodate up to four chemists, has facilities suitable for most standard chemical operations, including infrared, ultraviolet, and 60-megahertz proton nuclear magnetic resonance (NMR) spectroscopy, as well as gas-liquid and high-pressure liquid chromatography. In addition, the ICIPE laboratories are equipped with a gas chromatograph-mass spectrometer system (GC-MS). Even though this system is uncomputerized, it is the only one of its kind in all of East Africa, and it has performed valuable service from time to time for other laboratories in the area.

Chemists at ICIPE have had an opportunity that might be envied by natural products chemists almost anywhere in the world. The rich tropical insect fauna of East Africa provides a seemingly unlimited number of ecologically significant natural product problems, and the flora affords a wealth of interesting biological activities that invite investigation. While some of our studies have entailed the elucidation of rather complex structures, it is fortunate that it is not uncommon for structurally simple compounds to play significant biological roles as well. Since the more sophisticated techniques for the determination of chemical structures are not available in Nairobi, certain key experiments have had to be performed at appropriately equipped laboratories in the United States, chiefly at Columbia and Cornell. Also, the difficulty in obtaining a wide variety of organic chemicals whenever unforeseen needs arise has made it inefficient to attempt extensive work in organic synthesis at ICIPE. Nevertheless, these disadvantages have been more than compensated for by the presence of talented biological collaborators. It is their participation in the identification and collection of target species and their expertise in establishing bioassays which has often provided the critical element in a successful chemical ecological study. Overall, despite the absence of complex equipment, ICIPE has become a rewarding place for a chemist to work; availability of interesting arthropod and plant materials and the close relationship with biologists has permitted chemical and biological work to proceed simultaneously and interdependently. It is now 6 years since the first group of ICIPE scientists began their work. In this article, we present a somewhat informal account of the highlights of the research that members of the Chemistry Research Unit have carried out during the first half-dozen years of this laboratory's existence.

Arthropod Pheromones

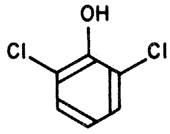
Research on chemicals isolated from arthropods at ICIPE has included studies of the sex pheromones of hard ticks, the building pheromones of a grass-feeding termite, and a variety of substances active as defensive agents. In pheromone research, the only detector available to monitor biological activity in the early stages of isolation and characterization is the *dudu* (Swahili for "insect") itself. By choosing locally available species, the collection, extraction, and isolation steps may be continuously monitored by behavioral or electrophysiological assays (or both).

In a collaborative study of this sort, ICIPE chemists and biologists characterized the sex pheromone of the hard (ixodid) tick *Rhipicephalus appendiculatus*, an economically important vector of East Coast fever in cattle (*3*). Simple ether washing of partially engorged female ticks, followed by partition experiments coupled with a straightforward two-choice bioassay, located biological activity in the weakly acid (phenolic) fraction. Analysis by GC-MS allowed rapid identification of phenol (**1**) and *p*-cresol (**2**) in the active fraction. Bioassay of these two compounds led to the conclusion that they constituted the natural pheromone system used by the engorged female ticks to attract males. Surprisingly, even the individual components taken alone showed biological activity, and therefore the chemical communication system of these ticks appears to be much less finely tuned than that of the insects from which most of our previous knowledge of pheromones comes. Finally, GC-MS analysis of extracts obtained from five other species of ixodid ticks showed phenols to be universally present, with 2,6-dichlorophenol (**3**), (*4*) and salicylaldehyde appearing as additional components. Interestingly, *R. appendiculatus* males responded well to **3**, even though this compound was not found in the secretion of their engorged females. Interspecific mating is known among ixodid ticks however (*5*), and it seems that phenols may serve as non-species-specific sex pheromones for this group of animals.



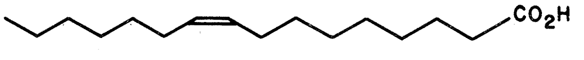
1 : R = H

2 : R = CH_3



3

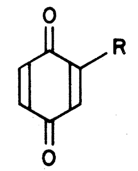
The existence of volatile stimuli capable of releasing various types of building behavior in termites was also established by a team of chemists and biologists at ICIPE. It was first discovered that a volatile compound emerging from the abdomen of the queen of the subterranean grass-feeding termite *Macrotermes subhyalinus* triggered construction of a replacement queen cell (Figs. 1 and 2) (*6, 7*). The principal bioactive component has been tentatively identified as palmitoleic acid [(*Z*)-9-hexadecenoic acid, **4**] a simple unsaturated fatty acid widely found in insect glycerides. The stereoisomeric palmitelaidic acid [(*E*)-9-hexadecenoic acid] was found to be completely inactive, as were most other homologs and analogs that were tested. Furthermore, termite workers could perceive the presence of **4**, and build in response to it, in amounts as small as 100 nanograms at a distance of 2 to 3 centimeters.



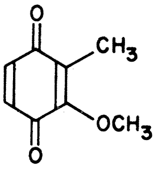
4

Chemical Warfare

The chemistry of arthropod natural products used in defense and alarm has constituted another primary interest at ICIPE (*8–10*). Early studies focused on the identification of the defensive compounds of millipedes. Quinones **5** to **9** were found to be oozed or sprayed by four species of African millipede (*11, 12*). One of these, ubiquinone-O (**9**), had not been isolated previously from a natural source (*12*). Other early work included the identification of 3-octanone and 3-octanol as the alarm pheromones in two species of *Crematogaster* ants (*13*), and the characterization of 20 aliphatic components in the defensive scents of eight species of East African hemipteran (true bugs) (*14*).



5 : R = H
6 : R = CH_3



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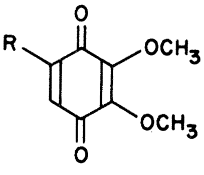


8 : R = H
9 : R = CH_3

More recently, investigations into the substances used in chemical warfare by termite soldiers have revealed a particularly wide range of structural variation. The basic weapons available to the soldier termites are their mandibles and their defensive chemicals. Quennedey has described three types of defense by which termite soldiers may repel, kill, or immobilize an attacking ant: (i) biting, generally with the addition of a toxic or irritant chemical secretion from the frontal gland reservoir; (ii) daubing, in which a brushlike, elongated labrum is employed in the topical application of a toxic mixture from the frontal gland; and (iii) squirting, in which a sticky, gluelike secretion is fired by the soldiers from a distance of up to 10 centimeters (*15*).

Among those using the technique in the first category are the soldiers of the subfamilies Termitinae, represented by the genera *Amitermes*, *Cubitermes*, and *Noditermes*, and the Macrotermitinae, represented by *Odontotermes badius* and *Macrotermes subhyalinus* (*7*). Soldiers of the subterranean, fungus-growing termite *Odontotermes badius*, a common garden and house pest in Nairobi, were found to bite with the concomitant expulsion of an aqueous mixture of proteins and benzoquinone (**5**) from salivary glands opening into the mouth (*16*). Major and minor soldiers of the related macrotermitine species *Macrotermes subhyalinus* (*7*) exhibited an interesting glandular dimorphism. In minor soldiers, the frontal gland is nearly absent (volume, 0.03 mm^3), whereas in major soldiers, a massive 14-mm^3 reservoir containing 2.6 mg of paraffins and olefins is present. We have identified the major components of this secretion as *n*-tricosane (**10**), *n*-pentacosane (**11**), 5-methylheptacosane (**12**), (*Z*)-9-heptacosene (**13**), and (*Z*)-9-nonacosene (**14**). Soldiers of this species release their secretion into wounds inflicted by their powerful razorlike mandibles. Ants thus injured were less able to recover than ants similarly wounded without the application of the hydrocarbon mixture (*17*).

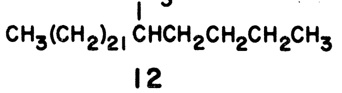
Soldiers from five species of *Cubitermes* have been examined and were shown to possess frontal glands containing mixtures of from four to eight diterpene hydrocarbons. At least one of these diterpenes appears to represent a new skeletal type, but the elucidation of all of the diterpene structures has not yet been completed (*18*).

Termitines of the genus *Amitermes* vary widely in their defensive chemistry (*10, 19*). *Amitermes unidentatus* produces principally a mixture of 2-alkanones (**15**); *A. messinae* utilizes a mixture of 10 percent limonene and 90 percent 4,11-epoxy-*cis*-eudesmane (**16**); *A. lonnbergianus* has no volatile, hexane-soluble secretions at all. Finally, soldiers of *Noditermes wasambaricus* possess a secretion consisting of two still unidentified sesquiterpene hydrocarbons in a 1:3 ratio (*10, 19*).

$CH_3(CH_2)_nCH_3$

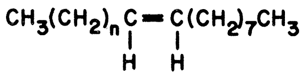
10: n = 21

11: n = 23



$CH_3(CH_2)_{21}\overset{CH_3}{\overset{|}{C}}HCH_2CH_2CH_2CH_3$

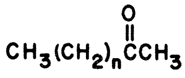
12



$CH_3(CH_2)_n\underset{H}{\underset{|}{C}}{=}\underset{H}{\underset{|}{C}}(CH_2)_7CH_3$

13 : n = 16

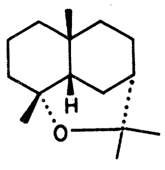
14 : n = 18



$CH_3(CH_2)_n\overset{O}{\overset{\|}{C}}CH_3$

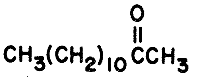
n = 8, 10, 12, 14

15



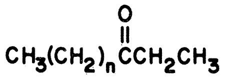
16

Among termites using the second group of defensive techniques are the soldiers of the wood-eating species *Schedorhinotermes lamanianus*. Colonies of this termite develop a strikingly pungent, peculiar odor when disturbed. This odor is due to a mixture of ten aliphatic ketones present in large amounts (up to 10 percent of the body weight) in both major and minor soldiers. The ketones were assigned the structures **17** to **20** on the basis of GC-MS data, and these



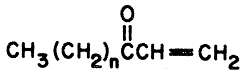
$CH_3(CH_2)_{10}\overset{O}{\overset{\|}{C}}CH_3$

17



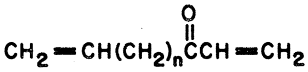
$CH_3(CH_2)_n\overset{O}{\overset{\|}{C}}CH_2CH_3$

18: n = 8, 10, 12



$CH_3(CH_2)_n\overset{O}{\overset{\|}{C}}CH{=}CH_2$

19: n = 8, 10, 12

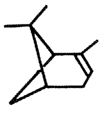


$CH_2{=}CH(CH_2)_n\overset{O}{\overset{\|}{C}}CH{=}CH_2$

20: n = 7, 9, 11

assignments were confirmed by synthesis (*20*). The three α,ω-dienones (**20**) are previously unknown natural products. This ketonic secretion is exuded from the frontal gland through a small hole, the fontanel, and flows down an extended grooved labrum terminating in broad brushlike hairs. The soldier termite grasps an ant with its mandibles while spreading the secretion over the surface of the ant. No wound is necessary for the toxic effect to appear. It is likely that the long hydrocarbon chains in these molecules provide high lipid solubility and facilitate cuticle penetration; we have speculated that the conjugated enone function may act as a Michael reaction acceptor for a biological nucleophile once the compound is inside the ant (*20*).

Almost all of the defensive compounds discussed so far have had relatively simple structures. From an organic chemist's viewpoint, some particularly interesting results have been obtained with termites belonging to the third group, which possesses nasute soldiers. In these species, colony defense against predacious ants is effected by the ejection of a viscous, sticky secretion from a specialized elongated rostrum called the nasus. We first identified several well-known monoterpene hydrocarbons (α- and β-pinene, camphene, myrcene, and limonene, **21** to **25**) in the secretions of major and minor soldiers of the grass-eating termites *Trinervitermes bettonianus* and *T. gratiosus* (*8, 10, 19*). Dissolved in these terpenes is a series of previously unknown crystalline diterpenes, whose structure determination provided a considerable challenge. In collaboration with Clardy's research group at Iowa State University, we were able to establish structures **26** to **31** for these new diterpenes (*21*). We christened these substances "trinervitenes"; their unprecedented tricyclic, cembrene-related skeletons are intriguing both biosynthetically and phylogenetically.



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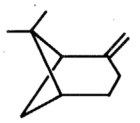

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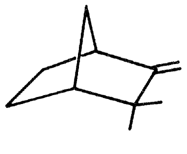

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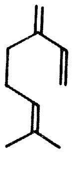

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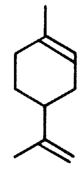

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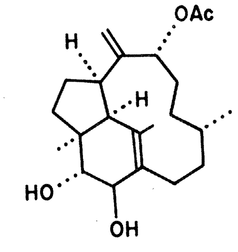

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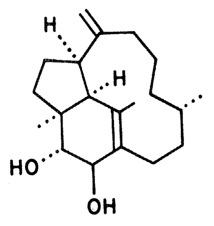

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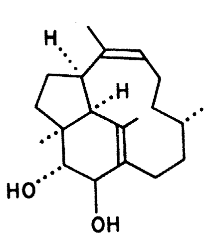

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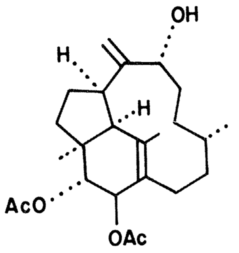

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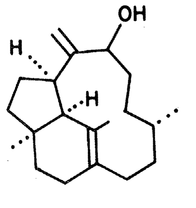

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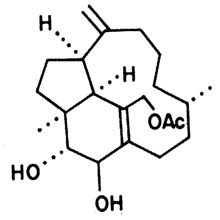

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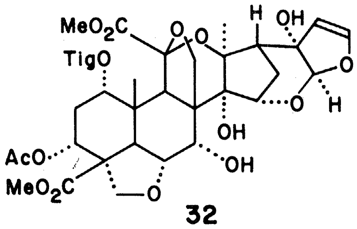
As a result of establishing these structures, it became possible to describe completely the defensive secretions of *T. gratiosus* soldiers (*22*). It has now been found that nonsympatric populations of this species possess chemically distinguishable secretions (*23*). Thus, GLC analysis of soldier secretions may be of chemotaxonomic value to termite ecologists. In recent experiments, it has been shown that the trinervitenes serve to enhance and prolong the irritant and toxic effects of the monoterpene hydrocarbons in the secretion. Furthermore, the high concentration of these unusual dome-shaped molecules in a monoterpene hydrocarbon solvent results in a viscous, gluelike material that remains tacky for several days (*24*).

Insect Antifeedants from Plants

In the early days of ICIPE, the Chemistry Unit embarked on a few projects that could be pursued independently of some of the more entomologically oriented studies. These chemist-initiated projects focused on the rich Kenyan flora, which was examined at first as a possible source of new compounds with insect molting hormone activity (phytoecdysones). Dr. D. Elder (*25*), the first research scientist to work at ICIPE, started this work by examining the leaves of the common Indian neem tree (*Azadirachta indica*) in which he became interested on the basis of a report from a Kenyan lady that she used the leaf and berry saps of this tree for keeping pest insects out of her garden. It was soon found that the leaf extract produced pronounced morphological changes in the coffee bug, *Antestiopsis*, upon topical application. Although the factor responsible for this developmental activity is still unknown, attempts to characterize it led to the isolation of azadirachtin, an unstable, amorphous triterpenoid which had been shown to act as a powerful feeding deterrent to locusts (*26*) as well as a systemic growth disrupter (*27*). In spite of extensive studies, previous workers had been unable to elucidate the structure of azadirachtin. Since the compound has not been crystallized, it was unsuited for x-ray crystallography. However, by the simultaneous use of partially relaxed Fourier transform (PRFT) and continuous-wave decoupling (CWD) ^{13}C NMR spectroscopic techniques, it was possible to characterize azadirachtin as **32** (*28*). While this compound is far too complex for a practical synthesis, the yield of **32** from the berries themselves is high (800 mg from 300 g of the seeds).



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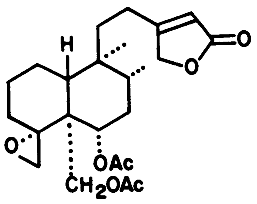
Since azadirachtin is not generally toxic (the berries are a favorite food, for example, for some birds), interest in the cultivation of the neem tree (*29*) and in further chemical study would appear to be justified (*30*).

As a result of the initial success with azadirachtin, a systematic search for other insect antifeedants was undertaken in mid-1974. This program uncovered a large number of active compounds, some of which were previously known and some of which were unknown. The screening program relied chiefly on leaf-disk and electrophysiological assay techniques, which guided the isolation work (*31, 32*). The potential antifeedants were tested chiefly against larvae of two species of African armyworm, the monophagous *Spodoptera exempta* and the polyphagous *S. littoralis*, both major crop pests. Not surprisingly, the antifeedants found in this program turned out not to be uniformly active against all insects but appeared to have some species specificity. Thus, warburganal (**41**), which is one of the most potent antifeedant compounds against armyworms, is almost without effect against *Manduca sexta* (tobacco hornworm) and *Schistocerca vaga* (vagrant grasshopper) (*31–33*). In contrast, some compounds are active against the Mexican bean beetle, *Epilachna varivestis*, but do not affect the feeding of armyworms.

Among the new natural products found in this screening program were three moderately strong antifeedants, ajugarin I, II, and III (**33, 34, 35**), which were isolated from the leaves of *Ajuga remota* (Labiateae), a plant which is not attacked by African armyworms. These diterpenoids, whose structures were determined on the basis of extensive spectral analysis (*34*), are especially interesting because their absolute stereochemistry is opposite to that of the previously characterized clerodane-based diterpenes (such as caryoptin and 3-epicaryoptin, which are also insect antifeedants) (*35*).



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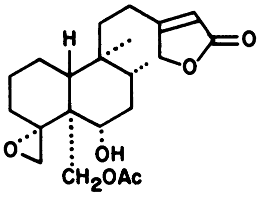

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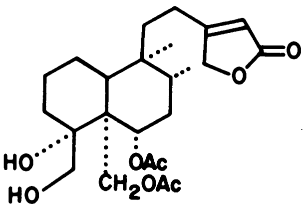
Another plant that is insect resistant and widely used in various folk remedies is the East African shrub *Harrisonia abyssinica* (Simarubaceae), known as "msabubini" or "mpapura-doko" in Swahili. The chopped root bark (650 g) of the shrub, collected near the Kenyan seaport of Mombasa, gave about 70 mg of an unknown crystalline antifeedant (active at 20 ppm), named harrisonin (*36*), along with about 20 mg of the well-known bitter triterpenoid obacunone (which, however, is not a feeding deterrent) (*37*). The structure of harrisonin (**36**) was established on the basis of extensive spectroscopic measurements, in particular ^{13}C NMR spectroscopy (*36*).



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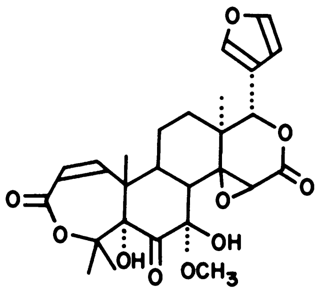

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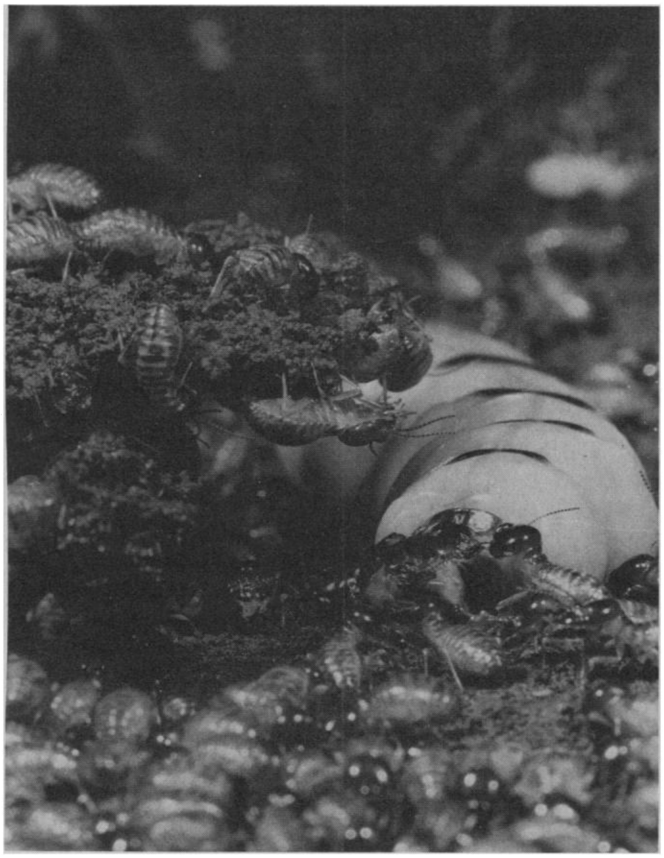


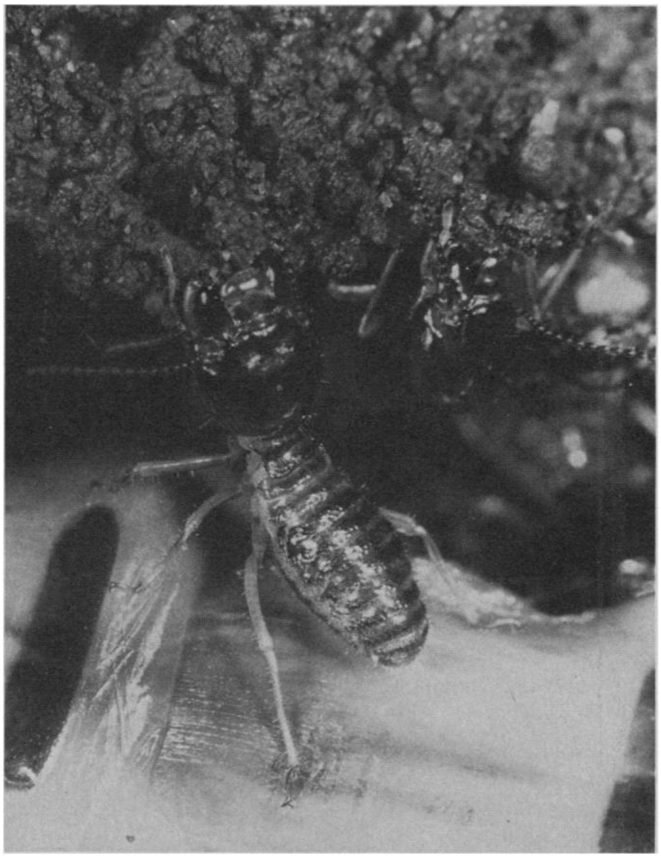
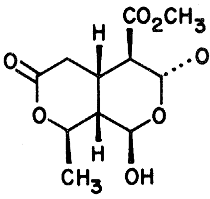


Fig. 1 (left). Responding to volatile building pheromones emanating from the abdomen of the queen (right), workers of the African grass-eating termite *Macrotermes subhyalinus* construct an arch of saliva-coated soil particles Fig. 2 (right). Standing atop the queen's abdomen, a worker of the African grass-feeding termite *Macrotermes subhyalinus* cements a saliva-coated soil particle into position. A new queen cell is being constructed in response to volatile building pheromones emanating from the queen. [Photographs by Glenn Prestwich, a former research scientist at the International Centre of Insect Physiology and Ecology, Nairobi, Kenya]

It seems likely that the hemiketal function in ring B of **36** is generated from the corresponding α-diketone by addition of methanol during the extraction procedure. This α-diketone is a stronger antifeedant than harrisonin itself (*38*).

Xylomollin, an antifeedant whose structure (**37**) proved of interest from a biosynthetic viewpoint, was isolated and characterized for the first time from a *Xylocarpus* sp. (Meliaceae), another East African tree widely used in folk medicine (*39*). The ripe fruits of this tree, weighing about 200 g each, are sweet, but the unripe ones (reputed to have aphrodisiac activity) are bitter. The bitter principle, xylomollin, could be extracted from the flesh of unripe fruits and constitutes about 0.1 percent of its wet weight. Besides its activity as an antifeedant, xylomollin inhibits respiration in rat liver mitochondria (*40*). Since the bitterness of these fruits disappears rapidly with ripening, it is clear that xylomollin is transformed into other products. In view of the key role played by secologanin (**38**) in indole alkaloid biosynthesis (*41*), it is conceivable that xylomollin is the precursor of some still undetected alkaloid contained in the ripe fruits.



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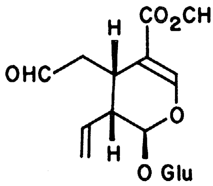

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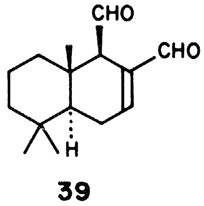
Some of the most potent antifeedants to be found up to now in our survey of East African plants are members of a group of closely related sesquiterpenoids that we isolated from the medicinal plants *Warburgia stuhlmannii* and *W. ugandensis* (*31, 32*). The ground bark of these plants, used not only in folk medicine but also as a spice for food, yields four antifeedants highly active against the African armyworm. Two of these are the known polygodial (**39**) (*42*) and ugandensidial (**40**) (*43*). The other two are the previously unreported warburganal (**41**) (*31*) and muzigadial (**42**) (*32*). Of these four substances, warburganal and muzigadial are by far the most potent. Thus, leaves of *Zea mays* that were dipped in solutions (0.1 ppm) of warburganal were not eaten by *S. littoralis* or *S. exempta* larvae. Electrophysiological studies of the sensilla of these armyworms showed that their sense of taste does not recover after the sensilla are brought into contact with the impregnated leaves a few times. Such armyworms are, therefore, irreversibly affected; their feeding is inhibited to the point of starvation (*44*).



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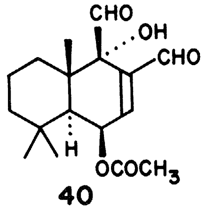

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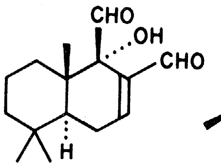

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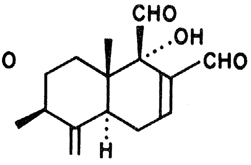

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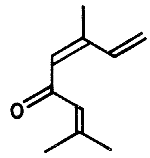
It is conceivable that, with proper development, some of these antifeedants may provide another method of controlling pest insects in the field or during crop storage. In any case, it is becoming increasingly apparent that many plants have evolved biosynthetic machinery for the production of a wide variety of highly functionalized terpenoids that are capable of providing effective defense against insect attack.

Some Other Efforts

There are a number of research projects involving ICIPE chemists which do not fall into any of the above categories, or which have been initiated but require further work. Dr. T. Gebreyesus, an organic chemist who was among the first to join ICIPE, had begun the characterization of a very elusive termite trail pheromone (*8*). This study is still being pursued. Dr. A. Maradufu, a current member of the Chemistry Unit, has been engaged in the isolation of the aggregation pheromone of the soft tick, *Ornithodorus moubata*, the vector of human relapsing fever and of swine fever (*10*). In this work, he collaborates with Christine Mango, a member of the tick biology group. He has also been concerned with a study of the Mexican marigold (*Tagetes minuta* L.), which is widespread in East Africa, especially in the highlands. The leaves of this plant are popularly used for repelling mosquitoes and safari ants. Maradufu succeeded in isolating a mosquito (*Aedes aegypti*) larvicide contained in the leaves of this extensively studied plant and has identified it as (*E*)-ocimenone (**43**) (*10, 45*), one of the major constituents of this plant and one which has already been synthesized (*46*). High-pressure liquid chromatographic analysis showed **43** to co-occur with at least 50 other compounds. A solution (40 ppm) of **43** effected 100 percent mortality of mosquito larvae within 24 hours (*45*).



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Concluding Remarks

Despite its relatively short history and the inevitable frustrations inherent in the embryonic stages of institutional development, ICIPE has now established itself as a unique and vigorous scientific institution. Scientists of the most diverse national and educational backgrounds interact at ICIPE in the pursuit of a wide variety of interdisciplinary research problems. In addition to its on-site research programs, as exemplified in this article for the Chemistry Research Unit, the Centre also fosters collaborative studies and discussions which involve the many scientists who visit Nairobi annually (*47*). Of course, the Centre is not without its problems. Nevertheless, it may be fair to regard it as a small miracle that the revolutionary concept which was committed to paper only in 1968 (*1*) has transcended an unusual array of political and financial difficulties and transformed itself into a functional entity. With the continued devotion of all of its people, we are optimistic that ICIPE will one day grow into one of the world's outstanding laboratories for the study of insect-related problems.

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48. In addition to those colleagues who have been directly engaged in the studies outlined here, we thank the ICIPE scientists and supporting staff who have devoted their time to the operation and management of this institute. We are particularly thankful to J. Jivanjee for his helpfulness. The studies described here have been supported by the United Nations Development Program (administered by Dr. W. Mashler) and by NIH grants AI 10187 and AI 12020. A grant to I.K. from the Japan Society for the Promotion of Science and an NIH postdoctoral fellowship (AI 05076) to G.D.P. are also gratefully acknowledged. Finally, J.M. thanks the John Simon Guggenheim Foundation for fellowship support.

Foreign Aid Support of Science and Economic Growth

Support of chemistry in Latin America, and scientific and economic growth in that area, are reviewed.

H. Harry Szmant

The ultimate objective of any foreign policy is to win friends and influence people outside of one's political boundaries in order to increase the security and improve the economy of one's own country. Since the advent of the postcolonial era, and especially in the case of the United States, foreign policy has become heavily dependent on foreign aid programs that were designed to raise the economic level of the less developed countries. This policy follows the premise that international support, cooperation, and friendship become meaningful when the partners share an interest in promoting a similar level of economic well-being rather than when the relationship rests only on formal pacts of friendship and mutual defense treaties. Except for foreign aid earmarked to insure national security, the bulk of foreign aid programs has been designated to provide funds for a variety of needs that create the infrastructure essential for economic growth, that is, adequate means of transportation and communications, adequate sanitary conditions and health care, the buildup of local agricultural, mineral, and energy resources, and the organization and modernization of elementary and vocational education. Because of the impressive technical character of World War II and the surge of technological contributions to the postwar economy (*1*), the support of science in the less developed countries became an important ingredient of the more recent foreign aid programs. This intent has taken a variety of forms: the establishment of educational ties between individual U.S. academic institutions and those located in the less developed countries, an exchange of visiting lecturers and research scientists, the organization of conferences, courses, and symposia, and so on. All programs also included the availability of scholarships that enabled persons from the developing countries to acquire tech-

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