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MEMORIAL LECTURE

EDWARD F. KNIPLING: TITAN AND DRIVING FORCE IN ECOLOGICALLY SELECTIVE AREA-WIDE PEST MANAGEMENT[1]

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ABSTRACT. Few entomologists have impacted insect pest management as profoundly as Edward F. Knipling (1909–2000). During WWII, Knipling and his colleagues developed highly effective measures to protect both military personnel and civilian populations from major arthropod-borne diseases. The sterile insect technique was Knipling's conception, and he successfully guided its development and use against the screwworm, *Cochliomyia hominivorax* Coquerel, and against various other pests. He inspired and guided the development of a wide range of ecologically selective methods of insect detection and suppression. Knipling became a leading proponent and theoretician of area-wide pest management and of the design of systems of pest population suppression to achieve synergism between control methods efficient at high pest population densities and those efficient at low densities. Knipling was convinced that many pest problems could be met without harm to the environment by the area-wide application of systems including the augmentation of natural enemies.

KEY WORDS Knipling, area-wide pest management, sterile insect technique, typhus, insecticide reduction

INTRODUCTION

I am deeply honored to join our Association in celebrating the life and work of Edward Fred Knipling. Throughout his life, Knipling was motivated powerfully by 3 concerns: (1) the well being of people throughout the world, (2) improving the compatibility of agriculture with natural ecosystems, and (3) a wholesome and happy family.

The legacy left by Knipling to entomologists includes (1) the use of biomathematical models as a research tool, (2) entirely new and ecologically selective methods of pest suppression, (3) principles for designing pest management systems, and (4) an advanced understanding of the pros and cons of major plans or strategies for managing pest populations. Knipling was appalled by the damage inflicted in agriculture and our environment by the widespread and repeated application of broad-spectrum pesticides against fractions of pest populations, while leaving reservoirs for immediate reinfestation. He believed firmly that, as in the case of mosquito control, the control of most major insect pests should be regarded as a community problem and not as an individual household or grower problem. Therefore, Knipling strongly advocated approaching major pest problems preventively by managing total pest populations.

Knipling had a clear vision. He was convinced that if major advances were to be made in coping with most of the important pest problems, then the tactics and strategies for managing such arthropods must change from the current limited-scale, reactive, broad-spectrum measures to rigidly applied, target-pest-specific preventive measures. That is, "selective suppressive measures must be applied against total pest populations in an organized and

Edward F. Knipling, 1943, while in charge of research on medical entomology at Orlando, FL.

[1] This Memorial Lecture was given at the 2001 Annual Meeting of the American Mosquito Control Association in Denver, Colorado.

coordinated manner at strategic times before—and not after—the populations have reached damaging numbers" (Knipling 1992).

Knipling possessed seemingly inexhaustible intellectual and temperamental staying power needed to convert his ideas into reality. Even though major honors were bestowed on Knipling, he remained a genuinely humble person, known merely as "Knip" to his professional associates, friends, and family.

CAREER SUMMARY

Knipling spent his entire career with one employer, the U.S. Department of Agriculture (USDA). For 7 decades, the USDA either directly employed Knipling or provided him with collaborator status. After Knipling graduated from Texas A&M at the age of 21, he began his entomological career in the USDA with a 3-month temporary job in Mexico in 1930, and from that time, his career trajectory in the Bureau of Entomology and Plant Quarantine was "straight up" (Perkins 1982). He went on to enroll at Iowa State University to pursue a graduate entomology degree, which was awarded in 1932.

For the first 10 years, Knipling's assignments included research on the common horse bot in Ames, IA, screwworm biology and control in Valdosta, GA, and Menard, TX, and mosquito biology and control in Portland, OR. Knipling was 33 years old when Pearl Harbor was bombed on December 7, 1941. Early in 1942, he was transferred from Portland to Orlando, FL, where he joined and then led a 20-member emergency research team mobilized to work with the military to invent control technologies for vectors of major diseases that threatened our armed forces, such as typhus and malaria.

After the war's end and after receiving a PhD in entomology from Iowa State University in 1946, Knipling served for the next 7 years in Washington, DC, as Director of Research on Insects Affecting Livestock, Man, Households, and Stored Products. In 1953, Knipling was promoted to Director, Entomology Research Division, Agricultural Research Service (ARS), a position he held until 1971.

Knipling served as Science Advisor to the Administrator from 1971 until his retirement in 1973. Thereafter, until his death, Knipling remained associated with ARS as a science collaborator. During retirement, Knipling completed his comprehensive and classic publication "The Basic Principles of Insect Population Suppression and Management" (Knipling 1979) and his favorite book, *Principles of Insect Parasitism Analyzed from New Perspectives* (Knipling 1992).

During his active-duty career, Knipling published more than 225 technical publications relating to insects, and he continued to write and publish for 27 years after his retirement and even weeks before his death. He received numerous honors from heads of state, 3 U.S. presidents, agricultural organizations, publications, universities, and his peers. However, his favorite award was being named the first inductee into the Calhoun County Cattlemen's Association Hall of Fame in 1994 in his home town of Port Lavaca, TX, where he had grown up on his parents' farm.

UPBRINGING, EARLY FAMILY LIFE, MARRIAGE, AND PERSONAL INTERESTS

Knipling was born in Port Lavaca, TX, on March 20, 1909, as the 9th child in a family of 10. Knipling's grandfather, at age 17, had visited Texas in 1850 but returned to his village in the Province of Hamburg, Germany. The grandfather became alarmed by political events. In 1888, Emperor William II ascended to the throne. The young emperor was arrogant and impetuous. He dismissed Chancellor Bismarck, and Germany's foreign policy deteriorated dangerously. Thus, in 1891, at age 58, the grandfather, together with his family, immigrated to Texas and purchased a farm. There, in 1895, Knipling's father, Henry John, married Hulda Rasch, an orphan raised by prosperous foster parents.

In 1903, Knipling's parents moved to a 150-acre cotton farm near Port Lavaca. The family owned small numbers of dairy and beef cattle, swine, and chickens, primarily for home consumption. Mules and horses provided the draft power needed for farm operations and transport. Farm life was hard and without electricity, indoor plumbing, and natural gas for heating. At an early age, Knipling became accustomed to long hours of hard farm work (Anon. 1975). He learned to cope with mosquitoes, screwworms, ticks, boll weevils, snakes, and weeds.

Knipling's parents were hardworking, frugal, and strict but loving, warm, generous, and hospitable. On occasion, total strangers in need stayed overnight in the Knipling home. Each week, the entire family worked long hours from dawn on Monday until noon on Saturday. Saturday afternoon was set aside for social events, sports, and hobbies. On Sunday, the family attended services in the Lutheran Church and attended to farm chores. Within the home, a Low German dialect was spoken and High German was used in formal settings. This lack of English as the mother tongue presented a significant challenge when the children entered high school.

The children attended a 1-room rural school in which 1 teacher taught 6 grades simultaneously. For schooling beyond the 6th grade, the children were transported to a consolidated high school in Port Lavaca. Knipling's father served for many years on the Calhoun County Board of Education. School was difficult, but Knipling persevered and he loved to read. Knipling enjoyed good relations with his siblings. He and his brother Ernest were inseparable in playing marbles, mumblety-peg, swimming, baseball, hunting small game, fishing, and training dogs for hunting (Sellingsloh 2001).

Knipling's parents were progressive in that they provided financial support to each child to obtain 2 years of specialized training after public school. Knipling decided to study agriculture at Texas A&M College. Between the spring and fall semesters, Knipling returned to work on the family farm. His professors impressed on him the tremendous impact, both good and bad, that insects have on human welfare worldwide and that each year millions of people die from diseases borne by insects. Moreover, in the recent past, tremendous strides had been made in entomology. The citrus industry in California had been rescued through the introduction of the scale-eating vedalia beetle from Australia. L. O. Howard had triggered concerted area-wide application of oil to mosquito larval habitats in New Jersey in 1901, the forerunner of abatement districts. Mosquitoes had been shown to transmit the pathogens causing filariasis, malaria, and yellow fever. W. C. Gorgas had implemented highly effective area-wide programs against *Aedes aegypti* (L.) to eliminate yellow fever from Havana and from the Panama Canal Zone. Theobald Smith and F. L. Kilgore had proved that the *Babesia* cattle fever pathogen was vectored from sick to healthy animals by *Boophilus* cattle ticks. Shortly before Knipling was born, the epic program to eradicate *Boophilus* ticks from the USA was initiated by use of quarantines, arsenical dips, and keeping pastures free of hosts until ticks had starved to death. This difficult program was underway in Texas when Knipling was a student.

These heroic developments fired Knipling's imagination and filled him with enthusiasm. Knipling informed the family that he wanted to attend Texas A&M for 4 years to earn a degree in entomology. However, Knipling's father was reluctant to provide funding for 4 years because he had a strict policy of treating the children even-handedly. Fortunately, Knipling's siblings induced their father to loan the funds for the 3rd and 4th years (Sellingsloh 2001). Also, Knipling worked as a waiter, mowed lawns, and did other work part time in order to defray his costs. In spite of this heavy workload, Knipling was elected to the Texas A&M Scholarship Honor Society, and he received a BS degree in June 1930 (Scruggs 1975).

Knipling earned an MS from Iowa State University, where he met Phoebe Rebecca Hall. Phoebe was a remarkable woman by any standards, who by age 23 had earned a PhD in protozoology and parasitology at Iowa State University. Knipling and Phoebe married on July 21, 1934, and enjoyed a harmonious and synergistic relationship for 66 years until Phoebe's death. They had 2 daughters, 3 sons, 14 grandchildren, and some great-grandchildren.

Knipling invariably took advantage of award ceremonies to assemble family and friends. Allen (1967) recorded that "On February 6, 1967, Dr. Edward F. Knipling went to the White House to receive the National Medal of Science Award for 1966. The presentation was made by the President of the United States in the presence of government leaders and prominent fellow scientists. For most men in government service this day would have marked the pinnacle of their careers, but for Dr. Knipling this was simply the most recent in a long list of awards to recognize his achievements in science. However, he was especially pleased to receive this award because it provided the occasion for a family reunion."

Allen's account describes the arrival at the Knipling residence of family members and friends well in advance of the appointed day and the conviviality and warmth of the gathering. Further, Allen (1967) noted: "Amidst all this noisy activity Dr. Knipling sat at the kitchen table thoughtfully drafting a reply to a letter, pausing only now and then to hoist a giggling grandchild into the air. The kitchen is the hub of activity in the Knipling house, so the table functions primarily as a desk for Dr. Knipling and for 'Mrs. Dr. Knipling,' herself a holder of a Ph.D. in biology and Supervisor of Secondary Science for Arlington County Schools. It is often necessary to clear a space to eat, for books and papers are usually piled high on at least half of the table." Also, Allen (1967) stated that Knipling and Phoebe coordinated their hectic schedules, in part, "so that Dr. Knipling can be sure that his dog won't be left alone. His dog, . . . , is a faithful and jealous companion. 'Nophie' (named for the *Anopheles* mosquito) is the latest in a succession of family pets, all of whom were named for insects that figured prominently in Dr. Knipling's career."

About 1950, the Kniplings purchased a mountain property in the Shenandoah Valley of Virginia, where the family built a cabin. This cabin served to bring family and friends together on numerous weekends each year for outdoor recreation. The Kniplings set a high standard of warmth and informal hospitality. Each Christmas Eve, the Kniplings assembled between 50 to 60 family members and friends for a sit-down dinner. Knipling treasured opportunities to relate to family members, and to provide time for this, he deliberately avoided entanglements in elite Washington society.

Knipling was an avid hiker, archer, hunter, and fisherman. Knipling carved and painted his own fishing lures, and almost always caught more fish than anybody else. He jokingly attributed this to being able to think like a fish and outsmart them (E. B. Knipling 2000). Walker (2000) noted that Knipling, as a youth, had enjoyed hunting "with the conventional rifle and shotgun—but he discovered a more primitive form—the bow and arrow. He hunted deer with the bow, fascinated by the long odds of success and the challenge, stirred by the silent atavism of the past that lurks in humans. He was taken by the primitive nature of the bow.

And he was good at using it, bagging many deer across the years. . . . I remember him, too, as an outgoing hunting companion, . . . as a man who knew that somewhere out there . . . there was a seven pound small mouth bass waiting for him."

SELECTED ACCOMPLISHMENTS

Early in Knipling's career, the USDA posted him in Galesburg, IL, and then in Ames, IA, to work on the common horse bot and other pests of livestock. Knipling showed that when the mouth of the horse contacts fully developed eggs glued to the horse's hair, the warmth of the horse's mouth immediately causes the larva to hatch from the egg and to enter the mouth (Knipling 1934). Knipling and Wells (1935) showed that sponging the horse with warm water to cause the larvae to hatch harmlessly could readily control horse bots.

During the first decade of his career, Knipling (1969) was greatly interested in the taxonomy of dipterous larvae. In one publication, Knipling (1935) demonstrated that there are only 3 larval stages in *Hypoderma* warble fly larvae instead of 4 or 5, as had been described by others. This paper led to the generally held view that almost all Diptera have only 3 larval stages.

Wounds infested with screwworm larvae had to be treated a number of times to remove and kill the larvae, prevent additional egg laying, and promote healing. Thus, a wound treatment was needed that would accomplish this with a single application. At Valdosta, GA, and subsequently at Menard, TX, Knipling conducted wound treatment studies and concluded that the effectiveness of larvicidal and repellent materials could be improved by means of a wetting agent such as turkey red oil (Knipling to Cushing 1941). Indeed, based on these studies, Knipling's colleagues developed Smear 62, with which a wound could be treated satisfactorily by a single application (Melvin et al. 1941).

In 1940, Knipling was transferred to Portland, OR, and placed in charge of investigations on mosquitoes. Since 1892, when L. O. Howard had first demonstrated that culicine mosquitoes could be controlled by applying oil to larval habitats, the treatment had been largely unchanged. Knipling, Gjullin, and Yates (1943) soon found that, by the addition of spreading agents and emulsifiers, the amount of oil required to treat 1 acre could be reduced up to 7-fold—from 35 gallons to just 5 gallons. Oil alone did not kill pupae, but the combination of the wetting agent plus oil was highly effective in killing this stage.

Immediately after the attack at Pearl Harbor, December 7, 1941, the U.S. military requested emergency research to combat vectors of explosive diseases, such as typhus, malaria, and plague. In most wars prior to WWII, such insect-vectored diseases caused more deaths of service personnel than did combat. A team was assembled by the USDA to develop technologies to destroy disease vectors and transfer these technologies to the U.S. military and our allies. Initially, W. E. Dove directed the work, but he was reassigned to Washington and replaced by Knipling (Cushing 1957, Knipling 1948).

Within 6 months, the team had developed a synergized pyrethrum louse powder designated MYL. The MYL controlled body lice, head lice, crab lice, fleas, bedbugs, and chiggers. The MYL louse powder was used to break a typhus epidemic in Naples, Italy. This was the first time in history that a typhus epidemic had been halted abruptly (Bushland et al. 1944).

In November 1942, the laboratory obtained a preparation from the Geigy Company containing the synthetic chemical DDT. A 10% DDT powder was found to control lice for many weeks. The Food and Drug Administration concluded that DDT dust was entirely safe for human use. In May 1943, the Laboratory recommended DDT to the armed services as a louse powder and as a clothing impregnant. DDT was used with astonishing effectiveness against lice in the North African War Theater and widely against mosquitoes (Knipling 1945).

Most of the effort of the Orlando laboratory was devoted to mosquito larvicides, adulticides, repellents, and aerial pesticide application technology. The greatest single advance in the control of insects of medical importance was the development of the residual treatment concept of mosquito and mosquito-borne disease control. Because many mosquitoes readily enter buildings and rest on walls or ceilings, it was found that they could be killed by applications of insecticide to interior surfaces of buildings. The DDT residual treatment was recommended to the armed forces, and later it became the basis for global malaria control (Knipling 1948).

In the years following WWII, Knipling continued to guide the development of insecticides. However, between 1947 and 1953, Knipling noted a number of alarming developments. By 1947, resistance to DDT had developed in house flies, and this insecticide had been found to be secreted in the milk of cows fed fodder containing DDT residues (Smith et al. 1948). A related pesticide, DDD, was applied several times to Clear Lake, CA, to suppress a gnat that bothered tourists (Knipling 1950). DDD was found to be biomagnified up to 80,000-fold in the food chain and to kill western grebes. The DDT applied to elm trees became sufficiently concentrated in earthworms to kill robins. These developments caused Knipling to think and take action. Later, DDT was linked to egg shell thinning in fish-eating birds (Carson 1962).

In 1953, Knipling was selected to be Director of the Entomology Research Division of ARS. Soon thereafter, he reached the conclusion that pest control programs had become too dependent on the use of broad-spectrum chemicals. He recognized that broad-spectrum insecticides needed to be retained but used much more judiciously. His division at the time was devoting fully two thirds of its resources to the development of conventional insecticides. In 1954, Knipling and his team leaders identified new and existing research programs that needed to be strengthened (Knipling 1954). Within a few years, the Division had shifted to a strong emphasis on ecologically selective methods to control major insects and to relevant basic research. Knipling initiated this shift 7 years before the appearance of Rachael Carson's book *Silent Spring* (Hoffman 1970). When Congress reacted to *Silent Spring* with major funding for alternative methods of insect pest control, Knipling's foresight was rewarded with significant resources for the scientific cadre that he had already put into position.

In 1937, both Knipling and Bushland had been transferred to Menard, TX. Bushland had developed a procedure for rearing the screwworm on an artificial medium. He maintained hundreds of adults in cages in which Knipling observed the males to be extremely aggressive sexually. Thereupon, the great idea was born in Knipling's mind that "if a wild population could be overflooded with sexually sterile males, they would mate with most of the wild females, and the population would decline precipitously." In this preventive way, livestock could be protected without having to treat wounds (Scruggs 1975). Next, Knipling developed a simple mathematical model of the annual buildup and decline of the screwworm population and of how the release of sexually sterile males might suppress the population. However, neither Knipling nor Bushland knew of a means to induce sexual sterility (Knipling 1985).

Further development of the sterile insect concept could not be pursued until after WWII. In 1950, Knipling learned that X-rays had been used to induce sexual sterility in *Drosophila,* and Bushland quickly determined the appropriate doses for sterilizing the screwworm. Bushland found irradiated males to be competitive with untreated males in mating with females in cages and verified Knipling's theoretical model (Bushland and Hopkins 1953).

Next, Bushland and his team attempted to determine whether sterile males could be used to eradicate a wild population. They released sterile screwworms on Padre Island, TX, and again on Sanibel Island, 2 miles off the west coast of Florida. But they were frustrated by the apparent movement of screwworm flies from the mainland to nearby islands that prevented eradication.

Vieques Island seemed sufficiently isolated to prevent the influx of wild screwworm flies from Puerto Rico, but naval gunnery created too great a risk for researchers (Meyer and Simpson 1995, Baumhover 2002). At this bleak moment, it was Knipling's incredibly good fortune that B. A. Bitter, an animal health officer on the Dutch Island of Curacao, contacted him about screwworm control. Curacao lies 40 miles off the coast of Venezuela. In cooperation with The Netherlands, the USDA conducted a pilot eradication experiment on this island of 456 km^2. Sterile flies were produced in Orlando, FL. In 1954, 150,000 sterile screwworm flies per week were released over Curacao, and within 3 months—the time needed for 4 generations to mature—the screwworm had been eradicated from the island (Baumhover et al. 1955, Lindquist 1955). Seventeen years of delay and experimental failure had elapsed from conception to proof of concept! Also, taking the enormous political risk of spending taxpayers' dollars on a foreign resort island on a "screwy" idea had paid off.

The Florida livestock industry soon demanded an eradication program in the southeastern USA. The Florida Legislature appropriated $3 million, which was matched by the U.S. Congress. An aircraft hangar in Sebring, FL, was converted into a "fly factory," and by 1958, it was producing 50 million sterile flies per week. While livestock owners treated all wounds with insecticide smears, a fleet of 20 aircraft dropped sterile flies over the infested area. The screwworm was eradicated from the southeastern USA by the end of June 1959, 18 months after the beginning of the project (Meadows 1985).

Next, the Southwest Animal Health Research Foundation raised $3 million to initiate a program in the southwest. A mass rearing facility was built at Mission, TX. As soon as screwworms had been eliminated from overwintering areas north of Mexico, the sterile flies were deployed to create a barrier along the U.S.–Mexico border to protect against reproduction by invading flies. In this way, the parasite was largely excluded from Texas, New Mexico, Arizona, and California (Bushland 1985). During 1966, no screwworms could be found in the USA for several months, and the state governors persuaded the U.S. Secretary of Agriculture to declare the screwworm eradicated from the USA. This declaration caused the screwworm to be considered a foreign pest, and thus the federal government became solely responsible for costs incurred when screwworms reappeared in the USA (Scruggs 1975).

Eradication of the screwworm to the Isthmus of Tehuantepec was the long-range goal, but the program could not move into Mexico because the governments of Mexico and the USA took a decade to negotiate an agreement and organize a joint program. The strategy of eradication had to be replaced with area-wide population management as a static holding action along the entire border with Mexico. During this decade, many difficulties arose. The deer population in Texas exploded, and many ranchers reduced the number of cowboys needed to treat wounds. Screwworm cases occurred each year. In 1972, the program performed badly and 95,000 infestations occurred. Critics charged that the screwworm program had failed and that it should be scuttled (Graham 1985). Moreover, a movement arose to prohibit not only eradication programs but also area-wide programs in general (Perkins 1982). This uninformed negative view created a problem of towering proportions for Knipling in his quest to mount a sterility-based program to eradicate the boll weevil from the USA and later in his quest to develop the use of parasitoid augmentation on an area-wide basis. But by 1982, the screwworm had been removed from northern Mexico, and by 2000, all the way to Panama.

Knipling worked hard to advance the use of the sterile insect technique to cope with other pests (Knipling 1964). Sterile males were used to cope with the Mediterranean fruit fly in California, Florida, and many countries (Klassen et al. 1994). The sterility technique was used to eradicate the melon fly from Okinawa and all of the southern islands of Japan.

To combat tsetse flies with sexual sterility, Knipling visited Africa in 1960 and 1962, and in 1964, assigned David Dame to Salisbury, Rhodesia (now Zimbabwe), where Dame pioneered the use of sexual sterility to combat tsetse (Dame and Schmidt 1970). This program was transferred to Tanzania, where the feasibility of eradication was demonstrated (Williamson et al. 1983). In 1997, tsetse was eradicated from the main island in Zanzibar Island (Vreysen et al. 2000).

Presently, the sterility principle is being used to combat the pink bollworm in California and the codling moth in British Columbia.

Knipling, with the support of the National Cotton Council, was determined to eradicate the boll weevil from the USA. A third of all insecticides used in U.S. agriculture was used at this time just to control this pest on cotton, and highly insecticide-resistant boll weevil populations had emerged. Newsom and Brazzel, at Louisiana State University, had discovered that, in the fall of the year, the boll weevil enters a reproductive diapause and hibernates in trash along the edges of cotton fields. Brazzel showed that the number that survives the winter is reduced 90% if insecticides are applied just before diapausing weevils leave the fields. Moreover, Knipling's model showed that, if insecticide sprays were targeted to kill also the generation producing individuals going into diapause, then the number overwintering would be reduced by more than 99% (Knipling 1963, 1968). Knipling's model was verified, and this ignited great interest in eradication of the boll weevil. Toward this goal, an effective pheromone-baited trap was developed for detection, and weevils were sexually sterilized with the antileukemia drug busulfan.

In 1971–73, a large pilot field experiment to assess the feasibility of eradication was centered in southern Mississippi. The eradication zone was surrounded by 3 buffer zones. Intensive suppression was implemented in the 2 inner zones, and farmers were encouraged to practice diligent control in the outer zones, although some grew cotton simply to qualify for government payments and with no intention of harvesting a crop. Only one application of the suppressive system was made because of a shortfall in appropriations. Nevertheless, the boll weevil was suppressed below detectable levels in 203 of 236 fields in the eradication zone. All of the 33 lightly infested fields were located in the northern third of the eradication zone and less than 40 km from substantial populations farther north. In the southern two thirds of the eradication zone, no reproduction could be detected in any of the 170 fields (Knipling 1979). Knipling and some others concluded that the available technology was sufficiently effective to achieve eradication. Their experience with the screwworm indicated that eradication could be accomplished iteratively, following an application of the suppressive system to clear the pest from most of the target zone. Then surviving populations would be delimited and similar suppressive measures could be applied to them. In this iterative fashion, the aggregate range occupied by the pest would be reduced progressively toward zero (Klassen 1989). However, some felt that eradication could not be accomplished unless a single application of suppressive measures would eliminate all weevils in the target zone (Perkins 1982).

A National Academy of Sciences (NAS) cotton study team drafted a very negative interpretation of the results (Perkins 1982). Since Knipling was a member of the NAS, he had access to this draft, and he wrote a strong rebuttal. Therefore, the study team toned down their negative appraisal but continued to express strong reservations about the feasibility of eradicating the boll weevil. However, they agreed that a new trial eradication program in North Carolina should be conducted (NAS 1975). Thus, the NAS team grudgingly legitimized the concept of continuing large-scale eradication experiments but suggested that they would probably fail (Perkins 1982).

The new trial program, started in 1978 in Virginia and North Carolina, was highly successful. Subsequently, individual programs have removed the boll weevil from about 1.8 million hectares in 8 states, significantly reducing national pesticide usage. Boll weevil eradication efforts are continuing, and the job is about half done. However, the corrosive effect of the NAS report persists. Congress reduced the share of federal funds to less than 30% of the cost, and the process is being conducted piecemeal with a minimum of technology (Dickerson et al. 2001).

Although the concept of total population management has deep historical roots, Knipling (1966) appears to have been the first to fully grasp the decisive advantages of area-wide pest management versus field-by-field pest management. Knipling (1972) noted, e.g., that apple growers achieve almost 100% control of the codling moth in their orchards, yet they often neglect a few abandoned orchards and unattended dooryard apple trees. These relatively few neglected host trees serve as a reservoir to reinfest all orchards each year. Using a population simulation model, Knipling showed that more than sufficient moths are produced in the small neglected areas to rapidly reinfest the total area. By contrast, moderate suppression of the total population has a persistent effect.

From this model, Knipling (1972) derived his basic principle that "Uniform suppressive pressure applied against the total population of the pest over a period of generations will achieve greater suppression than a higher level of control on most, but not all of the population, each generation."

Knipling (1966, 1979) formulated principles of integrating various control methods into effective systems of suppression: (1) when possible, use highly selective control measures because they spare beneficial organisms, (2) first apply control methods that are effective against high-density populations because the cost effectiveness will decrease as the pest population is decimated, and (3) next apply a control method that is effective against low-density populations because its cost effectiveness will increase progressively as the pest population declines. Knipling (1972) defined the principle that "the integration of two non interacting suppressive measures that differ in their effectiveness at high and low densities will be more efficient when combined than either method employed alone."

Knipling (1992) felt that parasite augmentation could be an especially desirable preventive measure because the release of host-specific parasites poses no danger to humans, other organisms, or the environment. Knipling regarded his book *Principles of Insect Parasitism Analyzed from New Perspectives* as his most important contribution to science. He was convinced that highly misleading conclusions had been drawn from past augmentation experiments because the experiments were done in small, nonisolated areas. Most pest arthropods and parasites or predators are highly mobile. Therefore, meaningful results can be obtained only if augmentation experiments are conducted over large areas.

Knipling noted that even though many species of natural enemies have developed efficient host finding by following odor plumes of kairomones emanating from the host, under natural conditions, the level of parasitization does not threaten the host with extinction. On the other hand, augmentative releases can cause extinction. Augmentation utilizes the host resources in nature to produce large numbers of parasite progeny. If done properly, parasite augmentation—for several generations—can become a self-perpetuating suppression measure. Like an atomic breeder reaction, augmentation causes progressive increases in the rate of parasitism with each succeeding parasite generation, provided that the initial rate of parasitism is above 50%.

Knipling's analysis indicated that the parasite augmentation technique is much more effective in suppressing pest populations than the sterility technique. The higher the release ratio, the greater is the advantage of parasite releases. Thus, a ratio of 4 parasites to 1 host can be expected to be more than 3 times as effective as a ratio of 4 sterile males to 1 wild male during the generation of release. Also, if host-specific parasites and sterile males are released in the same host generation, then the 2 techniques will interact synergistically to suppress the pest population much more strongly than either method alone. In addition, a host-dependent species will tend to distribute itself proportionally to the distribution of its host. No other method of insect control has the characteristic of concentrating its suppressive action where it is most needed. Knipling's models indicate that area-wide augmentation has great potential against various pest species.

METHODS USED BY KNIPLING FOR VISIONING AND LEADERSHIP

Throughout his adult life, Knipling used certain methods to develop concepts and to exert leadership. These methods are summarized below.

Knipling was always concerned with 2 questions: How does nature work? And how can the workings of nature be modified to better meet human needs?

To get answers, he constructed thousands of models. This intense logical process was a key ingredient in Knipling's approach to problem solving and to developing his vision. It gave him tremendous confidence.

Knipling was a very keen and thorough observer, and he asked penetrating questions. He attempted to visit every scientist in his division at least every 2 years. With pencil and pad in hand, he would meet with the scientist, together with the scientist's entire team (technician, laborers, and student helpers). He would ask the scientist to explain the objectives of the program, the results obtained, and experiments underway.

He did not give directives, but he asked numerous questions that caused one to consider a new experimental approach or a new way of analyzing data. Knipling deeply respected the ideas of the technicians, students, and laborers, and he was always eager to obtain their views.

After having visited individually with all of the scientists in a laboratory, Knipling would conduct a fully participative and spirited round-table discussion involving the entire scientific cadre. Knipling was never dogmatic and was always ready to revise his positions in accordance with new facts. He was open to advice from all directions and was future oriented and enthusiastic. Knipling would inform the scientists of new developments, needs, and priorities and share his thoughts on the issues that needed to be addressed in the coming year. He revealed himself as a bold thinker and shrewd risk taker.

Knipling always found time to meet scientists at all career stages. He would analyze data and make constructive comments. He mentored many young scientists and faculty in conducting collaborative studies and coauthoring publications.

Knipling constantly searched for new ideas for meeting insect problems. He was excellent at synthesizing information and defining hypotheses and experimental approaches. Between 1953 and 1971, Knipling developed his appraisals into at least 65 unpublished manuscripts, which he circulated freely within the USDA and to colleagues in other institutions. He organized numerous workshops.

Knipling encouraged, helped plan, and facilitated highly promising investigations. He established an annual research contingency fund of $1 million to defray partially the costs of critical research needs. He established an annually recurring fund of $1.6 million for pilot testing of alternative insect control methods. Knipling supported extramural research with 10–15% of the division's resources. The division's program was greatly facilitated by research conducted in universities, and graduate students were trained in specializations needed to fill vacancies in the division.

Knipling gave inspirational and seminal talks at high-visibility occasions, such as award ceremonies.

Knipling was a master of the art of delegation. Dr. Clarence Hoffman, a competent and efficient associate director, freed Knipling from routine administrative chores and allowed him to focus on science. Each day, Knipling and those in the director's office had lunch together and discussed a wide range of issues. Therefore, every member of the team was well informed. Knipling developed 3 highly effective administrative officers. One of them, Ray Rhodes, related an incident shortly after he joined. Knipling had asked Rhodes to take the lead in procuring 5 gamma irradiators. After Rhodes had received bids from several vendors, he brought the bids to Knipling for an in-depth discussion of the pros and cons of each bid and for Knipling's decision. Knipling, who was working on a manuscript, said, "Rhodes, around here all of us make decisions." Then Knipling resumed work on the manuscript. From that point forward, Rhodes made numerous timely decisions on Knipling's behalf, and this greatly facilitated the division's operations.

Knipling acquired many state-of-the art facilities and competent scientists. Rainwater and Parencia (1981) stated, "During Knipling's tenure as Chief and as Director, he emphasized the need for a balance between basic and applied research and presided over the change to large, well-equipped laboratories. The Division grew rapidly under his supervision, and the science of entomology in ARS reached its zenith."

The combined effect of all of Knipling's actions was to arouse morale and to align the energies of his colleagues and subordinates in a shared focus on strategic tasks.

THE LAST YEARS

Knipling enjoyed robust health, but on May 2, 1993, he suffered cardiac arrest while driving at 65 mph on I-66 in Virginia. Phoebe brought the vehicle to a halt. A group of young adults from a Presbyterian Church and a Virginia highway trooper arrived instantly. The young adults rendered CPR and the trooper called an ambulance. A passing medical doctor stopped to help. The ambulance had a defibrillator, and it restarted Knipling's heart. At the hospital, he was deemed clinically dead and certainly not having more than 5% chance of living. However, within 24 h, Knipling was sitting up and talking (Kleinberg 1993).

A year later, the family arranged an event to thank those who had rescued him. At this re-birthday party, Knipling (1994) stated, "It has been said that TIME is our most valuable commodity. I fully appreciate that this is true. It means time to live, time to enjoy, time to accomplish. . . . It has given me time to complete 3 or 4 projects. . . . I believe these projects will make significant contributions to humankind and to a more healthy environment. All this I owe to you who saved my life a year ago." Further, Knipling stated, "I know the time will come when life will end for me—just as it will for all of us. But until that time comes, I hope to take full advantage of the added time that you have given me. I can say that this has been the happiest year of my life because for the first time I truly appreciate the value of time. May God bless you as he has blessed me all the years of my life. Once more I thank you for the time you have given me."

Knipling received his highest recognitions during his last decade. These were awards from the Food and Agriculture Organization of the United Nations, World Food Prize, and the Japan Prize. After the cardiac arrest, Knipling wrote 35 significant manuscripts, of which 4 have been published. He traveled to Okinawa and Tokyo and gave a series of lectures. He gave a major address to the Florida Entomological Society on the 40th anniversary of the eradication of the screwworm (Knipling 1998).

Knipling lived with one eye on the present and the other on the future. Until the very end, he was deeply concerned about the looming challenges in meeting world food needs and in restoring the environment. Knipling believed in young people and in the vital importance of higher education. Thus, he donated fully half of any prize moneys before paying taxes to universities.

Knipling hoped fervently that many academic entomologists would set aside their aversion to the area-wide pest management strategy because some of the most effective tactics can be used only on an area-wide basis. Knipling hoped that legislators would appropriate ample funds for area-wide pest management research, especially on augmentation. He hoped that policy makers would take timely action to forestall problems posed by the booming global population.

Knipling died of cancer 3 days before his 91st birthday. Virtually to the end, Knipling's mind was youthful, continuing to be full of new ideas and enthusiasm and looking ahead to making ever-greater contributions.

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