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How United States Agricultural Herbicides Became Military and Environmental Chemical Weapons: Historical and Residual Effects

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Abstract

Discoveries in Charles Darwin's laboratory led to modern herbicides. Darwin discovered the internal mechanism that directed plants to grow toward sunlight and sources of water. Scientists in Europe and America later called this mechanism a plant's hormone response system. Administrators and scientists, including Dr. Ezra J. Kraus, the Head of the Botany Department at the University of Chicago and a plant physiologist, suggested on the eve of WWII that weed killers had significant military value as chemical weapons. Dr. Kraus obtained access to a synthetic chemical, 2,4-D, and found that when the chemical was absorbed through the leaves of plants, it destroyed a plant's hormones. After exposure, the plant experienced rapid and uncontrolled growth, and then the leaves shriveled, died and fell off. Dr. Kraus obtained funding for his Department of Botany research program from Department of Defense (DOD) during World War II (WWII). Camp Detrick (Biological Weapons Laboratory) scientists later obtained samples of newly created 2,4,5-T which contained unknown amounts of the by-product dioxin TCDD. In the 1950s and 1960s, Fort Detrick military scientists formulated the herbicide Agent Orange, which was a 50 - 50 mixture of 2,4-D and 2,4,5-T. These dual purpose herbicides were used by DOD and USDA. American and European farmers in the 1940s used 2,4-D and 2,4,5-T to eliminate weeds from pastureland and cropland. After WWII, synthetic herbicides (and pesticides) development continued in tandem with production of synthetic fertilizers and breeding of high-yield plant varieties. These new agricultural products were then shipped worldwide to increase crop yields, as part of the Green Revolution. This new system of agricultural technologies was intended to eliminate global starvation and increase food security by increasing field and farm crop yields. In contrast, the goal of military use of herbicides, as chemical weapons, was to defoliate jungle forests and destroy food crops as a strategy to win battles and wars. The primary objective of this research study is to describe how agricultural herbicides became tactical chemical weapons. A current assessment will address the environmental impacts of military and environmental chemical weapons on the United States and Vietnam ecosystems and need for additional dioxin TCDD hotspot clean-up efforts.

Keywords

Agent Orange, Agent Blue, Dioxin TCDD, Cacodylic Acid, Arsenic, Environmental Weapons, Chemical Weapons, Ecocide, TIBA, 2,4-D, 2,4,5,-T, Ezra J. Kraus, Arthur W. Galston, Green Revolution, Agricultural Herbicides

1. Introduction

The origins of the herbicides 2,4-D (2,4-Dichlorophenoxyacetic acid) and 2,4,5-T (2,4,5-Trichorophenoxyacetic acid) begins with one of Charles Darwin's 1880 biological theories [1] on the power of plant movement. Through circumnutation (bending) important in the life of a plant in light (vs. darkness), plant cells begin to swell (turgesence) and re-direct the plant tip. The first published account of 2,4-D was produced by Pokorny in 1941 on the eve of WWII [1]. Dr. Ezra Kraus became aware of Dr. P. Zimmerman's 1942 pioneering agricultural research work at Boyce Thompson Institute, Ithaca, New York and asked him for 2,4-D samples [2]. By the way, Dr. Kraus did not tell him the real reason why he wanted the samples, but his request occurred after Pearl Harbor. The information on 2,4-D remained hidden (was not published in journals) during World War II (WWII).

When 2,4-D was combined with 2,4,5-T (and the contaminant dioxin TCDD) the herbicide Agent Orange was formulated. Agent Orange, used during the Vietnam War, was a synthetic plant growth regulator comprised of equal amounts of 2,4-dichlorophenoxyacetic acid $C_8H_6Cl_2O_3$ (2,4-D) and 2,4,5-trichlorophenoxyacetic acid $C_8H_5Cl_3O_3$ (2,4,5-T). TCDD, dioxin, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin ($C_{12}H_4Cl_4O_2$) was an unintended byproduct of the accelerated combustion process used in the manufacture of dual purposed herbicides containing 2,4,5-T [3]. Agent Orange has frequently been blamed for contamination of soil and sediment and long-term environmental and human health problems; however, the primary source of the harm was the by-product dioxin TCDD.

Dr. Kraus, a plant physiologist and Head of the Department of Botany at the University of Chicago, suggested in 1940 (on the eve of WWII) that weed killers had significant military value as chemical weapons. Being the first to recognize the military value of herbicides, even before United States (U.S.) military officers, Dr. Ezra Kraus was the father of the development of agricultural herbicides as chemical weapons. Zierler [1] proposed that "Dr. Kraus's idea might be better understood as a matter of political rather than scientific innovation. Kraus pushed the boundaries of the social and agricultural purpose of Plant Pathology. Weed killing herbicides initially developed as an agricultural strategy similar to insecticides (pesticides) were [2] used to raise the productivity of croplands".

The scientist and agricultural producer goals were to create optimal growing conditions for an agricultural field or a forest by eliminating undesirable plant species, which were diminishing the amounts of sunlight, water and soil nutrients available to the desired crop. The goals of military use of herbicides, as a chemical weapon, were to defoliate the jungle (forest) and to destroy the enemy food supply.

The primary objectives of this study are: 1) to describe how agricultural herbicides became military and environmental chemical weapons, 2) to determine the environmental impacts, in the United States and Vietnam, of the manufacturing, storage, transport and use of tactical herbicide (chemical) weapons in warfare, and 3) the need, after the American-Vietnam War ended, to safely utilize or dispose of existing herbicide weapon stock piles and the removal of these chemical weapons from U.S. military arsenal.

2. Scientists, Universities, Agencies, Chemical Companies and Institutions Who Helped to Convert Agricultural Herbicides to Military Chemical Weapons

2.1. First Agricultural Herbicides

The first modern synthetic herbicide, 2,4-D was discovered and synthesized in 1940 by Dr. W. G. Templeman [4] at Imperial Chemical Industries. His research on plant growth substances revealed that concentrations of specific acids produced different effects on the growth of different plant species [5]. Initial experiments showed chlorosis of the foliage and significant root damage in rape (*Brassica campestris* L.) when given different concentrations of nutrient solution containing 4-chloro-2-methyl phenoxyacetic acid. While rape was highly susceptible to this acid, spring oats was found to be highly resistant and corn (*Anthemis arvensis* L.) to be moderately susceptible. He concluded, "Growth substances applied appropriately would kill certain broad-leaved weeds in cereals without harming the crops".

Since the 1940s synthetic growth regulator discovery, the world's farmers have used a variety of herbicides and weed management solutions to control weed growth. Early weed control practices required human labor working long hours under difficult conditions. The synthetic growth regulator chemicals were introduced to protect crops from weeds that competed for water and nutrients. Current agricultural systems use digital tools and data science in making decisions about agricultural herbicides to reduce their environmental impact. Farmers today consider the crops to be grown, season, weather and weed pressure when selecting the type of herbicide and appropriate concentration to spray.

The technologies of the Green Revolution—synthetic fertilizers, pesticides, high-yield crop varieties, and mechanical machinery increased production of food grains during the 1950s and 1960s. For developing countries, this new approach to agriculture increased availability of food, prevented starvation for millions and reduced food insecurity while providing a good livelihood for their farmers. However, the use of chemical fertilizers and synthetic herbicides and pesticides and more intensive farming practices had unintended consequences for the environment, often increasing soil erosion and water pollution.

Agricultural herbicides have variable toxicity to farmers and the environment arising from both short-term and long-term uses. Some herbicides can cause a range of health effects ranging from skin rashes to death. The improper application of herbicides can result in direct contact with wildlife or people, inhalation of aerial sprays, or food consumption. Some water-soluble herbicides [6] can be transported via surface runoff and leaching to contaminate surface water resources and the groundwater.

It was not until the 1970s and the creation of the U.S. Environmental Protection Agency (USEPA) that herbicide products were regulated and they currently go through rigorous safety testing to assess impacts on human health. Farmers and those that handle and apply them are required to be trained and certified when using agricultural herbicides. All pesticides are now required to be labeled for formulation, uses, and toxicity rating; specific concentrations for specific crops and application practices to avoid over-applications and off-site drift; and personal protective equipment to shield the user from inhalation and skin exposure. Food and agriculture production has benefited from the use of herbicides when combined with high-quality seeds and the latest scientific developments in integrated agronomic and weed management approaches. Today, practices such as no-till use herbicides help farmers to grow crops that reduce soil erosion, improve soil health, increase soil moisture holding capacities and have less environmental impact. Herbicides, used properly can be beneficial to society. However, without widespread awareness of their potential to harm, appropriate use training, regulation and careful management they are harmful to humans and the environment.

2.2. Ezra J. Kraus, Botany, University of Chicago

Dr. Ezra J. Kraus, the Head of the Botany Department at the University of Chicago and a plant physiologist was the first to recognize the potential military value of herbicides before the official entry of United States into World War II (WWII). Scientists in Great Britain were also working on a dual claim of innovation: 1) of hormone herbicides as agricultural tools and 2) military chemical weapons. However, Dr. Kraus's military and environmental chemical weapons innovation claim predates the British claim by almost one year [1].

Dr. Kraus's idea appears to have been a political innovation rather than a scientific innovation. He proposed that herbicidal warfare required innovative thinking about environmental dimensions of warfare and national security. Military grade herbicides were stronger than agricultural grade herbicides and expanded the weed killing properties to all plant species [1]. As the Head of the Botany Department at University of Chicago, Dr. Kraus (**Figure 1**) was able to obtain expensive cutting-edge laboratory equipment due in part to a grant from the Rockefeller Foundation. In addition, Dr. Kraus was well positioned to grasp the military potential of herbicidal warfare [2]. He had inside access to the United States Department of Agriculture (USDA), Bureau of Plant Industry (BPI) located in Beltsville, Maryland, which he helped to create in the 1930s. By 1940, Dr. Kraus was overseeing collaborative research efforts on plant growth manipulation involving his department and USDA. He then placed his graduate students at USDA and BPI. Dr. Kraus and his colleagues recognized the herbicidal potential of synthetic growth compounds. He first discussed it publicly on August 1941 but earlier research reveals he formulated his ideas in 1940 [1], which pre-dated the U.S. official entry into WWII by almost a year.

After the attack by the Japanese on Pearl Harbor (**Figure 2**) on December 7, 1941, Dr. Kraus offered his services to the U.S. Government and Military [1]. Once again, Dr. Kraus was well situated to put Plant Physiology in the service of the public and the government. He was a founding member of a highly classified project on chemical and biological warfare under the National Academy of Sciences (NAS). At a top-secret meeting of the Biological and Chemical Weapons Committee of the War Bureau of Consultants (WBC) on Feb. 17, 1942 (just 9 weeks after Pearl Harbor), Dr. Kraus presented a paper on "Plant Growth Regulators Possible Uses" which included herbicides as military and environmental chemical weapons [1]. The abrupt entry of the U.S. into WWII gave Dr. Kraus an audience of U.S. military and political leaders at the highest governmental level [2].

Figure 1. Ezra Kraus, the father of herbicide (chemical) weapons, in his laboratory at the University of Chicago. Credit line: University of Chicago Library, University of Photographic Archive, Hanna Holbord Gray Special Collections. Individual groups, Informal 5, apfi-03586.

Figure 2. Arizona monument in Pearl Harbor, Hawaii. Credit line: U.S. National Park Service, Public document, https://www.nps.gov/perl/index.htm.

This new class of weapons that promised a tactical advantage on the battlefield was detailed in the presentation. Strategic utilization of herbicides could contribute, by defoliating Japanese held island forests (jungle) in the Pacific Ocean to help in locating hidden enemy troops. The killing of trees could reveal military weapon storage areas. Kraus also called for greater U.S. government funding of the field of plant growth manipulation as a "matter of national security" [1]. Dr. Kraus suggested the release of growth destroying chemical substances, in a dry, solid state, via aircraft over Japanese rice fields (this crop duster approach was already being used by American farmers to eliminate or kill weeds in U.S. croplands). This modified military operation would have been a way to destroy the rice crop and the stable food supply of the Japanese.

2.3. Significance of Dr. Ezra Kraus's Proposal

Three significant points about herbicides emerged from Dr. Kraus's work that had potential to transform on-the-ground war strategies:

1) While plant scientists and others were still doing basic herbicide research, their effects on different kinds of plants, and their use in improving agricultural productivity, Dr. Kraus proposed turning herbicides into military chemical weapons [1].

2) Dr. Kraus's conceptualization of the military value of herbicides was advanced far beyond knowledge gained from WWII testing and the current state of herbicide research. Additional testing had to wait until Operation Ranch Hand, which was implemented during the Vietnam War. Clearly, Dr. Kraus was a visionary who was 20 years ahead of his time [2].

3) Dr. Kraus suggested it would be easy to add herbicides as chemical weapons to the American arsenal. Low cost and easy accessibility of tactical herbicides meant that these chemical weapons were readily available to any nation [1].

Drs. Kraus and Mitchell (former Kraus graduate student) published a paper on growth-regulating potential of herbicides. This research attracted the interest of military officials who were impressed by the potential tactical advantage [1]. The U.S. Army included herbicide research as a cornerstone of chemical and biological research programs at Camp Detrick, Maryland. In the fall of 1943, Dr. Kraus acquired another synthetic chemical, 2,4,5-T with apparently unknown amounts of the contaminant dioxin TCDD, from Sherwin-Williams Chemical Company [1]. By 1944, Drs. Kraus, Mitchell and Hammer (another Kraus graduate student who had moved from USDA, BPI to Cornell University) established hormone response properties of different kinds of plants using a variety of herbicide application methods.

Dr. Kraus was a consultant to the Camp Detrick military scientists who continued simulating war conditions with military aircraft outfitted with crop-dusting equipment over Florida Everglades. The Everglades were thought to be similar to the tropical Pacific islands where herbicides were destined to be used. Dr. Kraus became the WBC's chief censor of all scientific publications with potentially sensitive herbicide information. Up until the end of WWII, the literature did not reveal that plant physiologists had joined the War effort. Hormone herbicides were the most valuable component of America's emerging biological and chemical program. The secrecy surrounding the program attested to the possibility of waging herbicidal warfare [1]. American chemical companies recognized the tremendous commercial potential of these dual purpose herbicides (initially formulated for use in agriculture, lawns and forests) and after WWII actively marketed them to agricultural producers and residential consumers. Civilian and military officials believed chemical (herbicide) weapons would be an effective addition to the military arsenal that could then be used, if needed, in the Pacific theater.

The U.S. military did not use tactical herbicides in the Asia-Pacific theater until 1961. The reasons included: 1) atomic blasts over Hiroshima (**Figure 3**) and

Figure 3. The WWII Hiroshima atomic bomb cloud. Credit line: Atomic Heritage Foundation National Museum of Nuclear Science and History. info@nuclearmuseum.org.

(**Figure 4**) and Nagasaki, which abruptly ended WWII before herbicide weapons, were ready, and 2) moral attitudes towards chemical and biological weapons after WWI (**Figure 5**) and during WWII (**Figure 6**) and (**Figure 7**) [2]. President Roosevelt stated that the United States would never be the first country to use chemical and biological weapons and would only consider chemical weapon use in response to any enemy use [1]. That suggests that these herbicide weapons would remain in the U.S. arsenal as a deterrent.

Figure 4. Visible destruction as a result of the United States dropping an atomic bomb on Hiroshima, Japan during WWII. Credit line: Atomic Heritage Foundation National Museum of Nuclear Science and History. info@nuclearmuseum.org.

Figure 5. WWI gas masks on soldiers in trenches. Credit line: Courtesy Alamy. HRHBWD. https://www.alamy.com/.

Figure 6. Railroad entrance to Auschwitz where WWII prisoners were taken to be eliminated. Photograph courtesy of Pam Olson.

Figure 7. Auschwitz memorial gas chamber rooms where prisoners were taken to be gassed during the Holocaust (WWII). Credit line: Auschwitz Memorial and Museum. Photograph courtesy of Scott Barbour.

2.4. Arthur W. Galston, University of Illinois, Yale University

Arthur W. Galston's 1943 University of Illinois (Botany) PhD thesis (Figure 8) and (Figure 9) research focused on the use of the chemical TIBA (2,3,5-Triodobenzic acid) to increase flowering and grain yield of soybeans (Glycine max [L.] Merr.) [7]. Galston also noted that in higher concentrations, it would cause soybeans to lose leaves and kill the plant. Galston's discovery of TIBA was a precursor to creating the Agent Orange herbicide [7]. In 1943, Dr. Galston moved to the California Institute of Technology to work with Nobel Prize winner Dr. George Beadle on World War II defense-related (synthetic rubber) research. Galston joined the Navy in 1944 and served as a natural resources officer while stationed in Okinawa, Japan, until after World War II was over.

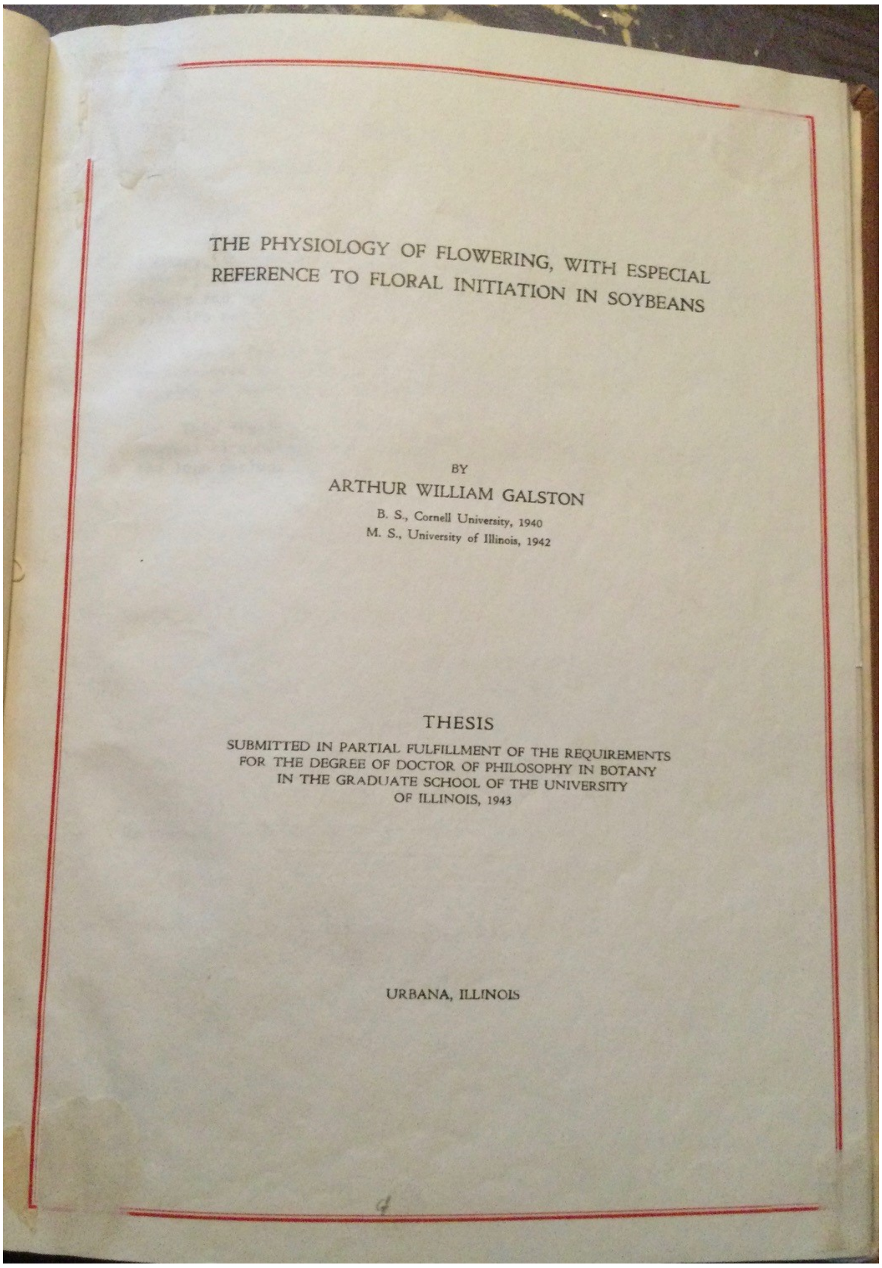

Figure 8. Arthur W. Galston 1943 thesis that contained the scientific discovery that leads to Agent Orange formulation by military scientists at Camp Detrick. Agent Orange adversely affected the lives of millions of U.S. Vietnam Era veterans, who were exposed to dioxin TCDD and/or arsenic and their children but had at least ten times more of an effect on the Vietnamese people and their offspring. The picture is of the title page of the Galston thesis. Credit line: University of Illinois Library. Cover picture taken by Pam Olson.

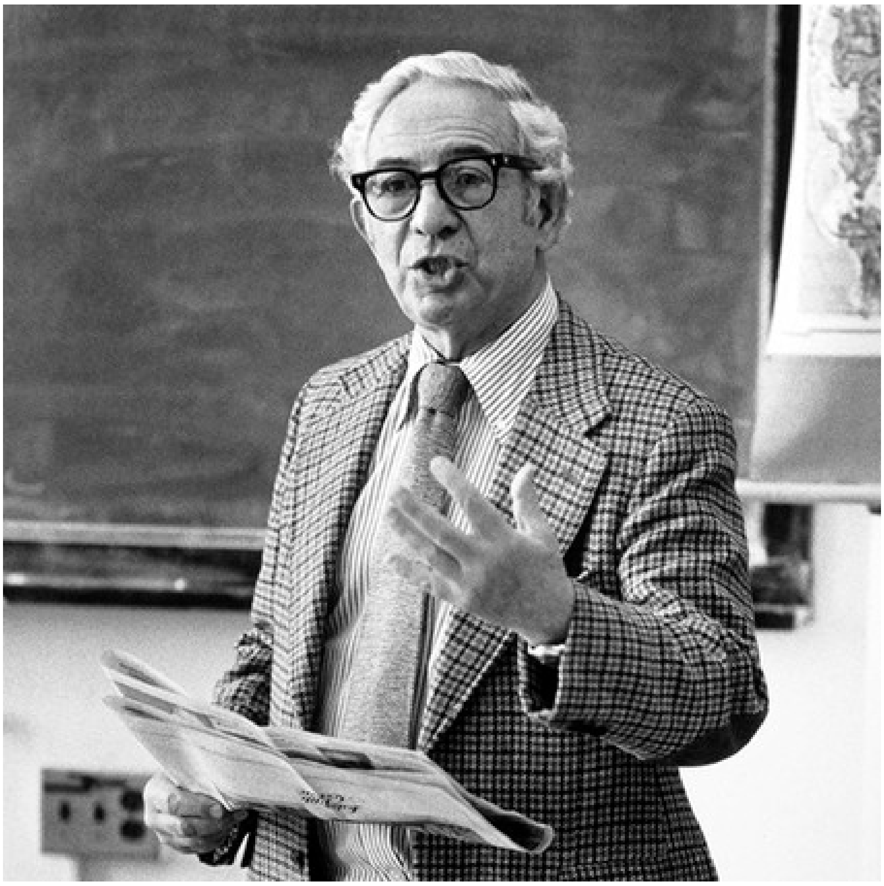

Figure 9. Arthur W. Galston picture taken during a lecture at Yale. Credit line: Yale Environment 360. Yale library. Beinecke Rare Books and Manuscripts library. https://beinecke.library.yale.edu.

Early in 1965, many scientific organizations, led by Dr. Galston (then a Botany Department Head and Professor at Yale University), warned the U.S. government against the continued use of military chemical (herbicide) weapons during the Vietnam War [7]. In all, 5000 scientists, including members of the Federation of American Scientists and American Association of the Advancement of Science (AAAS), along with 17 Nobel Prize winners, petitioned the U.S. military and government to stop the use of chemical and biological weapons. Dr. Galston strongly objected to the use of his early University of Illinois scientific research and discovery in the development of toxic herbicide weapons for use in the Vietnam War [8]. He thought it was a misuse of science stated in a California Institute of Technology Archives Oral History Project, "Science is meant to improve the lot of mankind, not diminish it—and its use as a military weapon was ill-advised." [9]. The University of Illinois Alumni Association finally recognized Professor Galston in 2004 for his scientific discovery and subsequent efforts to prevent its misuse by the U.S. Government and Military.

2.5. Camp Detrick, Biological Weapons Laboratory

Camp Detrick was initially a Maryland National Guard property located in Frederick, Maryland. It became a United States Army Medical Command installation, during WWII and was the center of the United States biological weapons program of Department of Defense (DOD) and Office of Strategic Services (OSS), which became the Central Intelligence Agency (CIA) in 1947, even before the area was officially named in 1952. It was designated a permanent installation for peacetime biological research and development shortly after World War II, but its status was not confirmed until 1956 when it was renamed "Fort Detrick" (**Figure 10**). However the post had been called *Fort Detrick* as early as 1952, after expansion of the installation had begun.

Initial interest in biological weapons by the Chemical Warfare Service (CWS) began in 1941. That fall, U.S. Secretary of War Henry L. Stimson requested that the National Academy of Sciences (NAS) consider under taking a study of U.S. biological warfare [2]. By the spring of 1943, a United States biological weapons program officially began under orders from U.S. President Franklin Roosevelt. Safety "S" Division was first activated (1943) to serve as a "Biological Protection Branch", for the large stockpile of biological agents and weapons. By 1946, production of U.S. biological warfare agents went from "factory-level to laboratory-level", with the establishment of the United States Army Biological Warfare Laboratories at Camp Detrick. This military element formed the nucleus for a suite of research laboratories and pilot plant centers that operated during the first half of the Cold War.

In 1942, biological warfare scientists at Camp Detrick, Maryland, began investigating the possible uses of defoliant herbicides based on Galston's scientific discovery while working with TIBA [4] and Dr. Kraus' on-going research. The U.S. Department of Army's Chemical Corps Biological Laboratories initiated a major program in 1952 at Camp Detrick, Maryland [10] to develop both the herbicide formulations and aerial spray equipment for potential deployment in

Figure 10. Fort Detrick Biological Weapons laboratory headquarters in Maryland. Credit line: Youtube. Photograph courtesy of by Andrew Dutton.

Korean Conflict. The Agent Blue (precursor reagent, cacodylic acid) was formulated by military scientists at Fort Detrick in 1957. A closer examination of Agent Blue and Agent Orange herbicides reveals their toxicity and effects when used as chemical weapons of war.

2.6. Chemical Companies and Manufacturing Sites of Agent Orange and Agent Blue

The U.S. Government passed the Defense Production Act in 1950. The government then had the authority, as a nation at war, to compel eleven companies to create, produce, and supply Agent Orange and Agent Blue to the military. From 1965 to 1969, eleven wartime government contractors manufactured Agent Orange and Agent Blue and produced it for the U.S. military [3]. These companies also continued to manufacture a very similar commercial products for agricultural use but with different product names [11].

These Chemical companies included Dow Chemical, Monsanto Company, Hercules Inc., Diamond Shamrock Corporation (previously Diamond Alkali) (**Figure 11**), Hooker Chemical Company, Riverdale Chemical Company, Ansul Chemical Company (**Figure 12**), Uniroyal Inc., Occidental Chemical Company, N. A. Phillips Chemical Company, and Thompson-Hayward Chemical Company. The U.S. government also specified how Agent Orange and Agent Blue would be formulated and manufactured and then controlled its transportation, storage, distribution, and use.

During the manufacturing process, the workers at the New Jersey Diamond Alkali facility on the Passaic River were exposed to dioxin TCDD [12] as was the Passaic River and Newark Bay (**Figure 13**). Agent Orange was stored on site at Diamond Alkali in 208-liter barrels painted with an orange stripe and then loaded on ocean-going vessels and shipped through the Panama Canal Zone [13]

Figure 11. Gravel parking lot of the former Diamond Alkali Company. The dioxin contaminated building was torn down and contaminated building materials were placed in a landfill. The contaminated soil was incinerated. The former chemical plant site was on the Passaic River bank. The site was made into a gravel parking lot [12] Journal of Soil Water Conservation, 75, 33A-37A. https://doi.org/10.2489/jswc.75.2.33A.

to the South China Sea and the coast of Vietnam. The barrels were stored on Vietnam military bases for spraying the jungle and food crops or stored on Navy ships for use on stream banks and mangrove forests.

Figure 12. Ansul chemical plant on the Menominee River. The ships can travel through Green Bay, Lake Michigan and then to the Atlantic Ocean via the St. Lawrence Seaway [21]. Published with copyright permission from Editor of Open Journal of Soil Science.

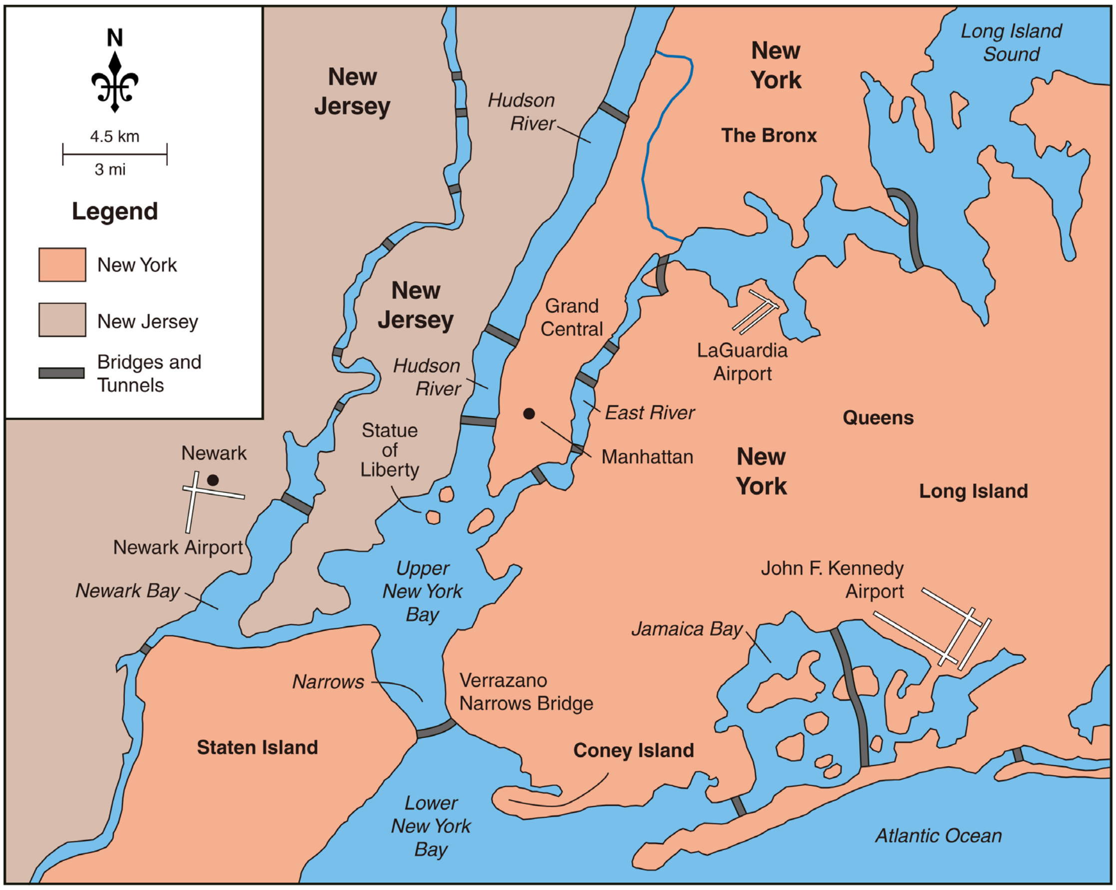

Figure 13. Passaic River near Newark and Newark Airport, Newark Bay and the Hudson River.

2.7. DOD Use of the Tacticial Herbicides Agent Orange and Agent Blue

After WWII, the United States and British military researchers continued to create and produce toxic defoliants. The British Air Force, in the 1950s, was the first to use defoliants during the Malayan Emergency. In the 1960s by the U.S. Air Force, Navy, and Army and Republic of Vietnam military began using tactical herbicides during the Vietnam War. Since the 1940s, the 2,4-dichloro phenoxy acetic acid, $C_8H_6Cl_2O_3$ (2,4-D), and 2,4,5-trichloro phenoxy acetic acid, $C_8H_5Cl_3O_3$ (2,4,5-T), herbicides were used in the United States [3]. Agent Orange, a 50:50 mixture of 2,4-D and 2,4,5-T, was used tactically by the U.S. military. Both of these herbicides have a relatively short half-life when exposed to sunlight. Unfortunately, the manufacturing process used to make 2,4,5-T created a by-product or contaminant dioxin TCDD, which has a much longer half-life (50 to 100 years or more) and is likely to persist in anaerobic soil and water environments for long periods [3]. The dioxin TCDD, when buried under anaerobic conditions in the subsoil or under water when attached to clay and organic matter particles transported in surface runoff and the sediment settled to the bottom of a river or lake. Initially, the dioxin TCDD contaminant levels in 2,4,5-T were in the range of 0.05 ppm [14].

2.7.1. Agent Orange

In 1961, U.S. President J. F. Kennedy approved a counter insurgency strategy for South Vietnam (**Figure 14**) and the U.S. Department of Defense and perhaps the CIA initiated a program to investigate herbicide use as a defensive weapon in guerrilla warfare [1]. Ambushes, sabotage, fast-moving small-scale raids and other guerrilla warfare tactics were used extensively by the Democratic Republic of Vietnam in their war against U.S. troops in South Vietnam. These hit-and-run tactics, dependent upon the element of surprise, were largely successful because the dense tropical vegetation hid military personnel, armed civilians, supply lines, and an extensive network of covert soil tunnels (**Figure 15**) [15].

The first shipment of herbicides to be used tactically arrived in South Vietnam on January 9, 1962 at Tan Son Nhut Air Base in 208-liter drums. The herbicides including Agent Orange were sprayed from low-flying C-123 Fairchild Provider aircraft (**Figure 16**) powered by either turbojets or propeller engines. Helicopters were refitted with 3800 liter chemical tanks, sprayers, and MC-1 Hourglass pump systems [16]. To maximize the contact of herbicide (**Figure 17**) with the forest and to minimize drift, the spray sorties were restricted to calm days and only sprayed early in the morning. Trucks, Navy boats and backpack sprayers were also used to spray herbicides.

The U.S. Vietnam herbicide campaign was called Operation Ranch Hand and was carried out by a close-knit group of pilots who aerial sprayed about 95% of the herbicide [16] [17]. From January 1962 (3 years before the official esculation of the American-Vietnam War) to January 1971, Operation Ranch Hand flew more than 19,000 combat sorties with jungle defoliation and crop destruction

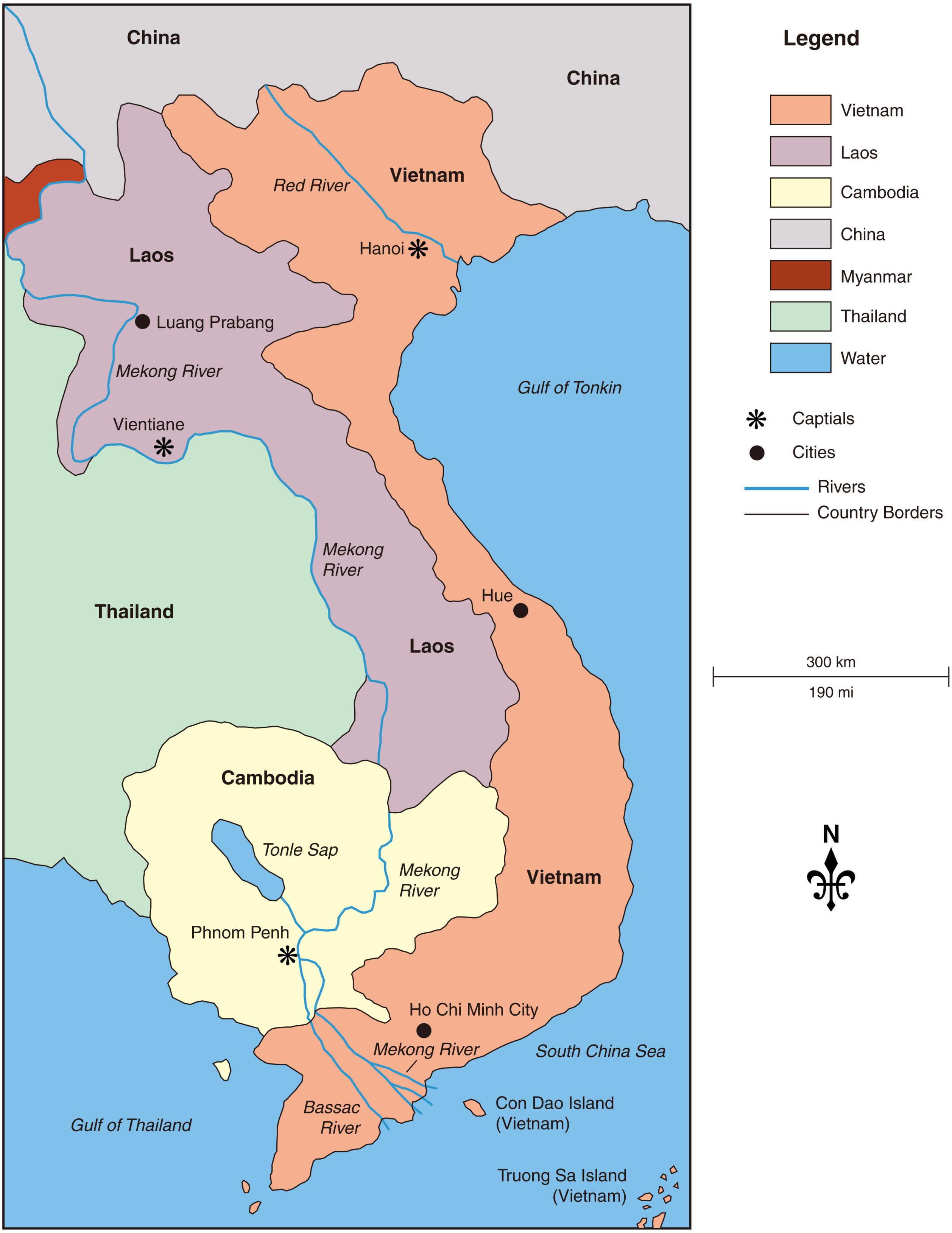

Figure 14. A location map of Vietnam relative to other southeastern Asian countries. The South China Sea is on the eastern border and Cambodia and Laos are the western border, the Gulf of Thailand is the southern border and China is on the northern border of Vietnam [41]. Map by Mic Greenberg. Reprinted from Journal of Soil and Water Conservation. 2018, 73:4:83A-89A.

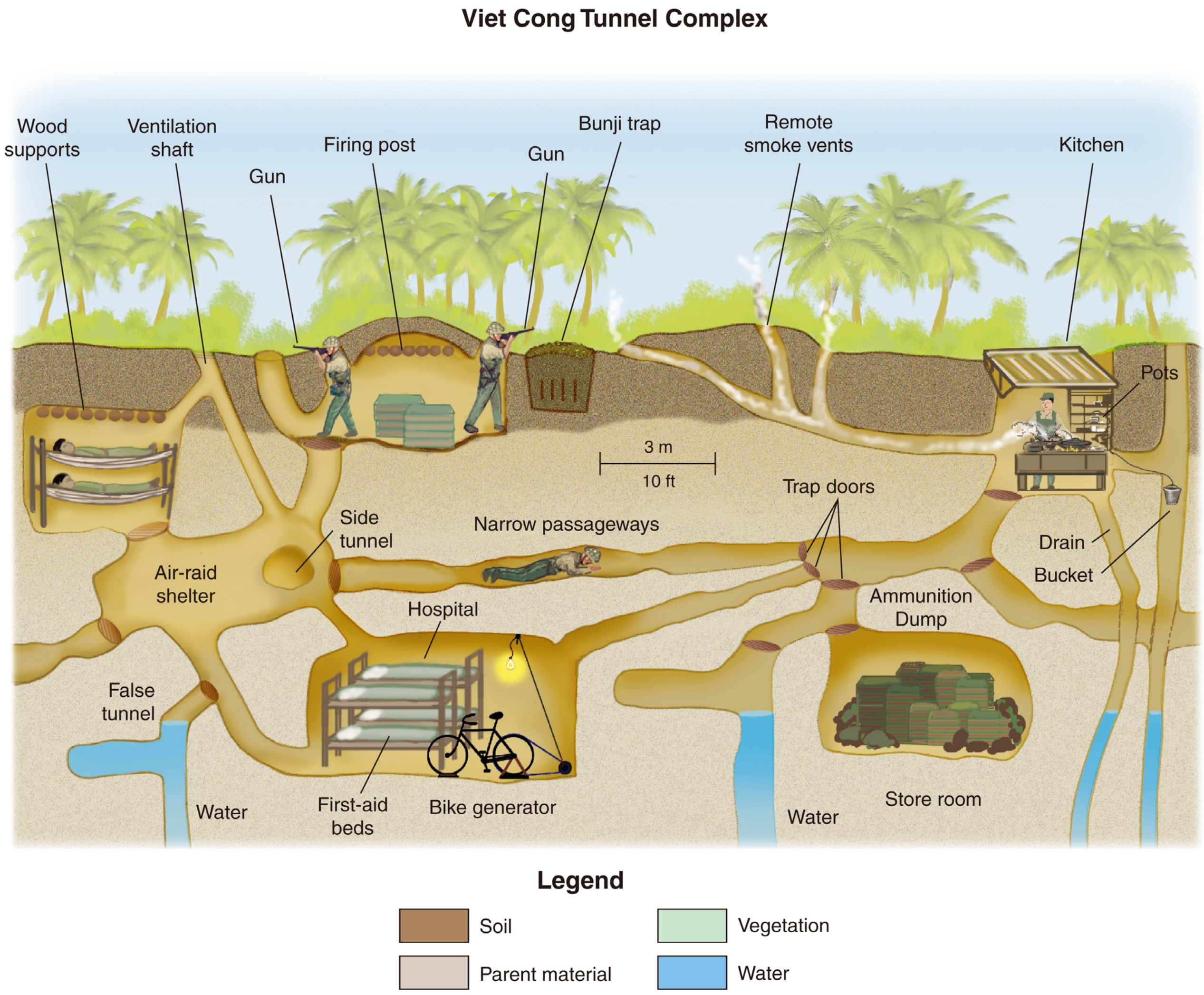

Figure 15. The Cu Chi and Iron Triangle tunnels were constructed in Old Alluvium soils which had high concentrations of ferric oxides and clays. Map by Mic Greenberg. Reprinted copyright permission from Editor of Open Journal of Soil Science.

Figure 16. C-123 Fairchild Provider aircraft that was used during the Vietnam War to spray tactical herbicides. Photo credit: Picture courtesy of Jim Lang.

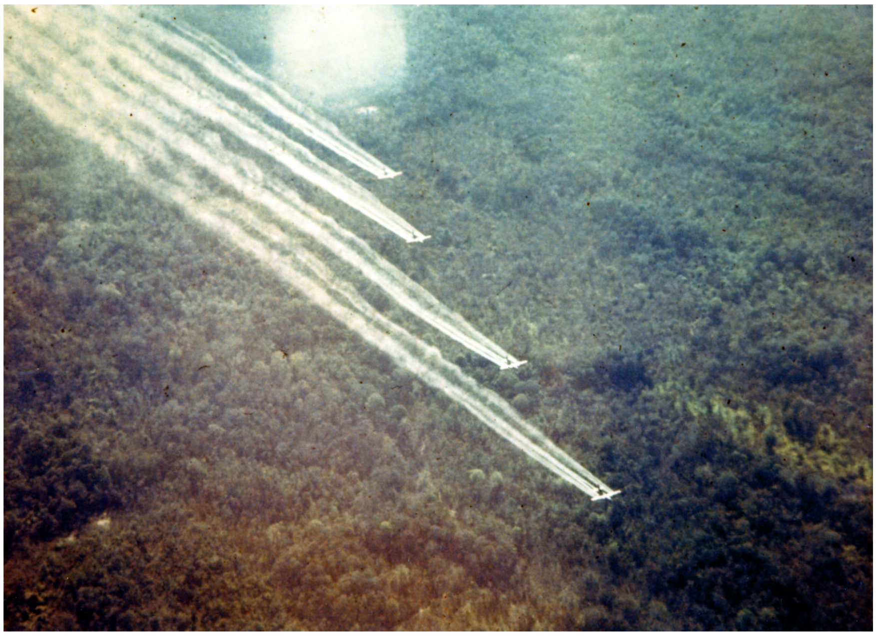

Figure 17. C-123 formation spraying tactical herbicides over southern Vietnam in the 1960s. Credit line: Photograph courtesy of National Museum of Air Force and Chronical on-line.

missions [18]. The amount of Agent Orange and other herbicides sprayed during each mission has been variously estimated at 105 - 119 kg [19] and 221 to 336 kg [20]. An unknown fraction of aerial spraying by the U.S. Navy was over river transportation corridors and coastal regions. Herbicides contaminated with dioxin TCDD could enter waterways and sediments via bank spraying as well as surface runoff and soil erosion from the sprayed areas [19].

U.S. Air Force records officially document 6542 spraying missions (**Figure 17**) covered 12% of the total area of South Vietnam by 1971. Between 1962 and 1971, more than 20% of southern Vietnam forests were sprayed one or more times [19] and approximately 10 million ha of agricultural land was sprayed (**Figure 18**) The defoliation campaign destroyed 20,000 km^2 upland forests and mangroves and thousands of km^2 of crops. Herbicides were applied at 13 to 20 times the recommended USDA rate. As a result the dioxin TCDD concentrations in the soil and water were hundreds of times above the levels considered safe by the newly created (1970) USEPA.

Vast areas of South Vietnam were stripped bare of vegetation (**Figure 19**) including U.S. military bases perimeter fences in Vietnam after receiving high concentrations of the dioxin contaminated Agent Orange and arsenic-based Agent Blue herbicides. The Ho Chi Minh Trail in Laos and Cambodia (**Figure 20**) also received high concentrations of dioxin TCDD and arsenic (via U.S. Air Force bases in Thailand). One of the most contaminated sites was the Cu Chi soil tunnels region (**Figure 21**) and agricultural and horticultural areas [15] located 40 km to the northwest of Ho Chi Minh City (formerly Saigon). Today, tourists can view and crawl through a portion of these Cu Chi soil tunnels

Figure 18. The Mekong River Delta region has an extensive system of canals, ditches, and dikes and polders built by the French in 1800s that was expanded for Vietnam troop movement and post-1970s by Vietnamese farmers to intensify agricultural cropping systems. Map by Mic Greenberg. Reprinted from Journal of Soil and Water Conservation. 2018, 73:4:83A-89A.

network. The Vietnam Memorial Park shows a 40-year old black and white film of Vietnamese women picking fruit near Cu Chi in what was once known as the Garden [15]. A variety of trees, jungle undergrowth) (**Figure 22**), and bamboo have grown up in the bomb craters of Cu Chi during the last 45 years and rubber tree plantations (**Figure 23**) have been recently been established.

Figure 19. Agent Orange and other tactical herbicides we sprayed by low and slow moving flying C-123 aircraft over the Vietnam jungle and rural landscapes. Most of these tactical herbicides had short-half lives of hours, days and a few weeks; and vegetation regrowth required additional applications. Photo Credit: Picture taken by U.S. Army Flight Operations Specialist 4 John Crivello in 1969. Stream banks vegetation a few weeks after being sprayed with tactical herbicides.

The targeting of food crops began in October of 1962, but the U.S. public was not made aware of this DOD and USDA action until 1964. More than 40% of all herbicide spraying targeted the destruction of food crops (the original military objective). Members of the U.S. Congress were told in 1965 that crop destruction was the most important purpose of the herbicide campaign, but media reports focused only on jungle defoliation in support of ground combat. Post-war analyses show that nearly all of the destroyed food crops were grown for the rural civilian population and not for the guerrillas. Crop destruction left hundreds of thousands of Vietnamese people malnourished or starving and contributed to widespread famine in rural southern Vietnam and movement of the Vietnamese population (at least 2 million) to the slums of Saigon and other cities.

U.S. planes and helicopters sprayed Agent Orange and other herbicides over the Ho Chi Minh Trail jungle canopy to expose and bomb enemy forces and their supply bases. After the 1968 Tet Offensive, the Cu Chi and Iron Triangle agricultural and forested areas were defoliated and used as a free strike zone [19]. The demilitarized zone at the 17th Parallel was frequently sprayed to eliminate vegetation. As a result, "thousands of acres of jungle were transformed into the tropical equivalent of a winter forest" [20].

Other targets for defoliation were low-lying wetlands at the interface of uplands, rivers and canals. The extensive U Minh mangrove forest in Ca Mau Peninsula, headquarters for communist resistance fighters, and other remote locations known to house opposing troops were also defoliation targets. Herbicides were heavily sprayed on both sides of perimeter fences of U.S. military bases in

Figure 20. The Ho Chi Minh Trail through the mountains and jungles of Vietnam, Laos and Cambodia was a system of trails and paths controlled by the Democratic Republic of Vietnam (1959-1975) used for transporting food, military equipment and North Vietnamese soldiers into southern Vietnam during the Vietnam War [3]. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2017, 7: 34-51. Published with copyright permission from Editor of Open Journal of Soil Science.

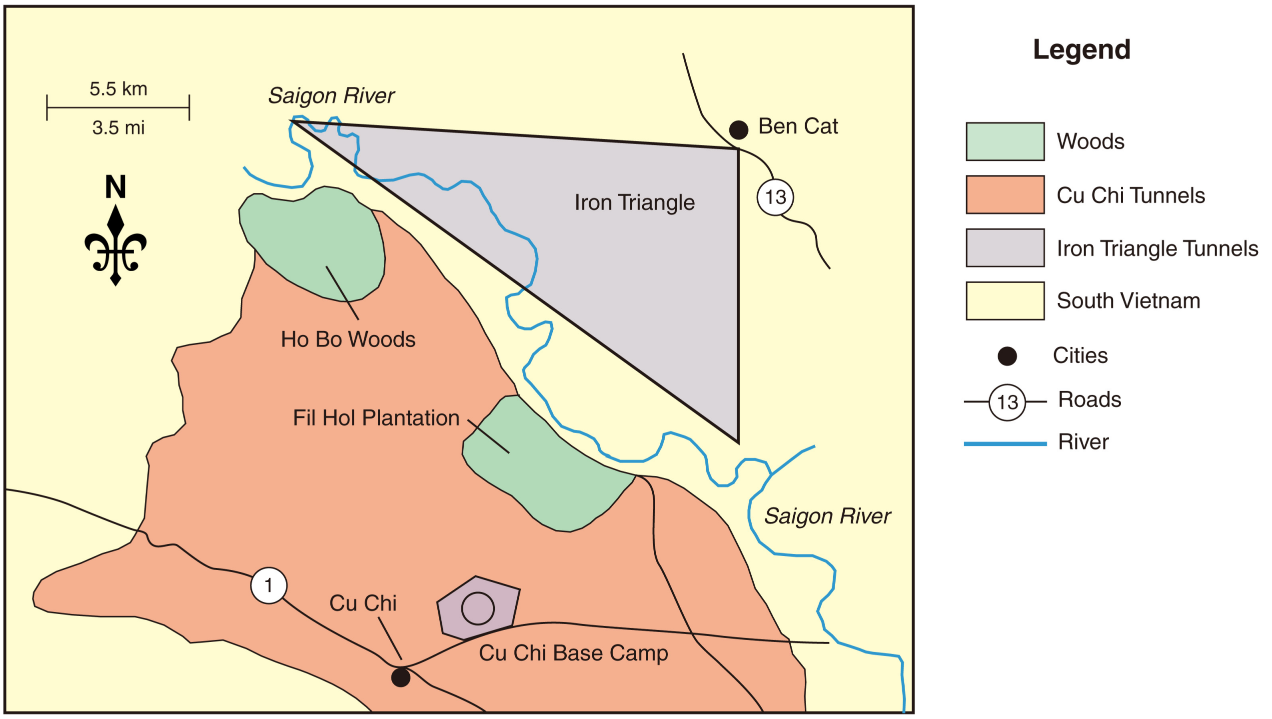

Figure 21. The heavily forested Cu Chi and Iron Triangle jungles were frequently sprayed by U.S. military with herbicides to expose tunnel entrances and North Vietnamese guerillas [3]. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2017, 7: 34-51. Published with copyright permission from Editor of Open Journal of Soil Science.

Figure 22. Agent Orange was sprayed in 1970 over the Cu Chi tunnels area to help in the target bombing of the tunnels. In the last 50 years the vegetation has regenerated naturally but the trees are slowly growing and will take many more years to reach a mature forest [3]. Photo Credit: Picture courtesy of Ken Olson taken in 2016 at the Cu Chi Vietnam War Memorial Park. Published with copyright permission from Editor of Open Journal of Soil Science.

Figure 23. Rubber tree plantations have been planted on the Old Alluvial terraces between Ho Chi Minh City and Cu Chi. Photo Credit. Photograph courtesy of Ken Olson. Picture taken in 2016.

southern Vietnam to ensure visibility and alert military base security of pending raids and sabotage. U.S. military personnel were unintentionally exposed to highly concentrated mixtures of herbicides with dioxin TCDD [21]. A third target, rice and other food crops were sprayed primarily with Agent Blue shortly before the rice matured. Agent Blue, the arsenic-based herbicide, was intended to kill or eliminate the food supply for the soldiers, coming down the Ho Chi Minh Trail, and fighting in southern Vietnam. This led to high levels of food insecurity in the rural civilian population.

2.7.2. Agent Blue

In 1957, scientists at Fort Detrick (formerly Camp Detrick) started to test the activity of cacodylic acid (**Figure 24**) used in Agent Blue on rice. Cacodylic acid in mixtures with 2,4-D and 2,4,5-T was tested in Maryland (1956), Dugway, Utah (1959) and Fort Drum, New York (1960) [21].

The first tactical herbicide barrels started arriving in Vietnam in 1961. Herbicide Blue liquid (later called Agent Blue) was a yellowish-tan liquid that was insoluble in diesel fuel but soluble in water [21]. One gallon (3.9 liters) of Agent Blue contained 1.4 kg of the active ingredient cacodylic acid. Agent Blue contained both cacodylic acid as a free acid and sodium salt cacodylate. The active ingredients were 65% cacodylic acid and 70% of salt sodium cacodylate. Agent Blue ($C_2H_7AsO_2$) was first used in southern Vietnam on the north side of Route 15, northwest of Saigon on 12 January 1962. In addition to Ranch Hand aircraft, the Vietnam Air Force (VNAF) used several H-34 helicopters, and one C-47 aircraft to evaluate applications of the herbicides [21]. These flight records were not recorded and if recorded were not maintained. It appears the spraying was not done as part of Operation Ranch Hand or it would have been recorded and the records would have been maintained. Some tests were conducted on the Ca Mau Peninsula [22]. Rubber vats or fuel bladders filled with Agent Blue were

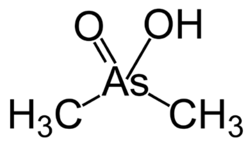

Figure 24. Cacodylic acid chemical formula. Drawing by Mic Greenberg.

apparently dropped from helicopters on the rice paddies to increase the rice-killing efficacy.

In 1961, the Kennedy administration approved the use of the tactical herbicides (1961-1971) program, which led to formal use of herbicides including Agent Blue during the Vietnam War. Herbicides had two primary military objectives: 1) to destroy the food crops available to the enemy, and 2) defoliate trees and plants to improve military observation of enemy activity. The program was initially used against both the South Vietnamese civilians and the National Front for the Liberation of Southern Vietnam (NLF).

The effects of defoliation were studied by comparing soil properties (**Figure 25**) in defoliated and non-defoliated mangrove areas northeast of Nam-Can (Ca-Mau Peninsula). The only positive effect was that mangrove area spraying made the areas safer from the NLF by denying cover from within and was easier to clear land for irrigated fields. However, woodcutters recognized that their primary wood resource was being eliminated [21].

Within the 10 years, the land impacted or damaged by Agent Blue, primarily rice paddies, totaled nearly 400,000 ha in South Vietnam, mostly near Da Nang and Saigon with over 51,000 ha of forest defoliated at least 4 times. Approximately, 27,000 ha of mangroves, mostly along the South China Sea, were completely destroyed, as were 300,000 ha of rice paddies in the Mekong Delta and Central Highlands [20]. The official Operation Ranch Hand records and flight maps show little activity in the Mekong Delta, the primary rice growing region. Why? Perhaps the official records are incomplete. The removal of the local food supply for the enemy was the primary military objective between 1962 and 1965 (before the esaclation of the American-Vietnam War) and not defoliation of the jungle vegetation. There is evidence that 2 million people from the Mekong Delta moved to the slums of Saigon and other cities. Why did Vietnamese leave the Mekong Delta and their food rich (rice and fish) sources? The main driver was the political policy of Republic of Vietnam (RVN) to relocate the people into "strategic hamlets" which the government (Diem) felt were easier to defend, than a few families scattered in small villages, from the influence of the insurgents.

2.8. National Academy of Sciences and Agent Blue

For the last 47 years, the NAS [7] Part A: Summary and Conclusion report appears to have been the "final word" on the fate of Agent Blue and its active component cacodylic acid [10]. Cacodylic acid breaks down in the soil and is hypothesized to bind tightly as arsenate (+5) to soil compounds. In an earlier

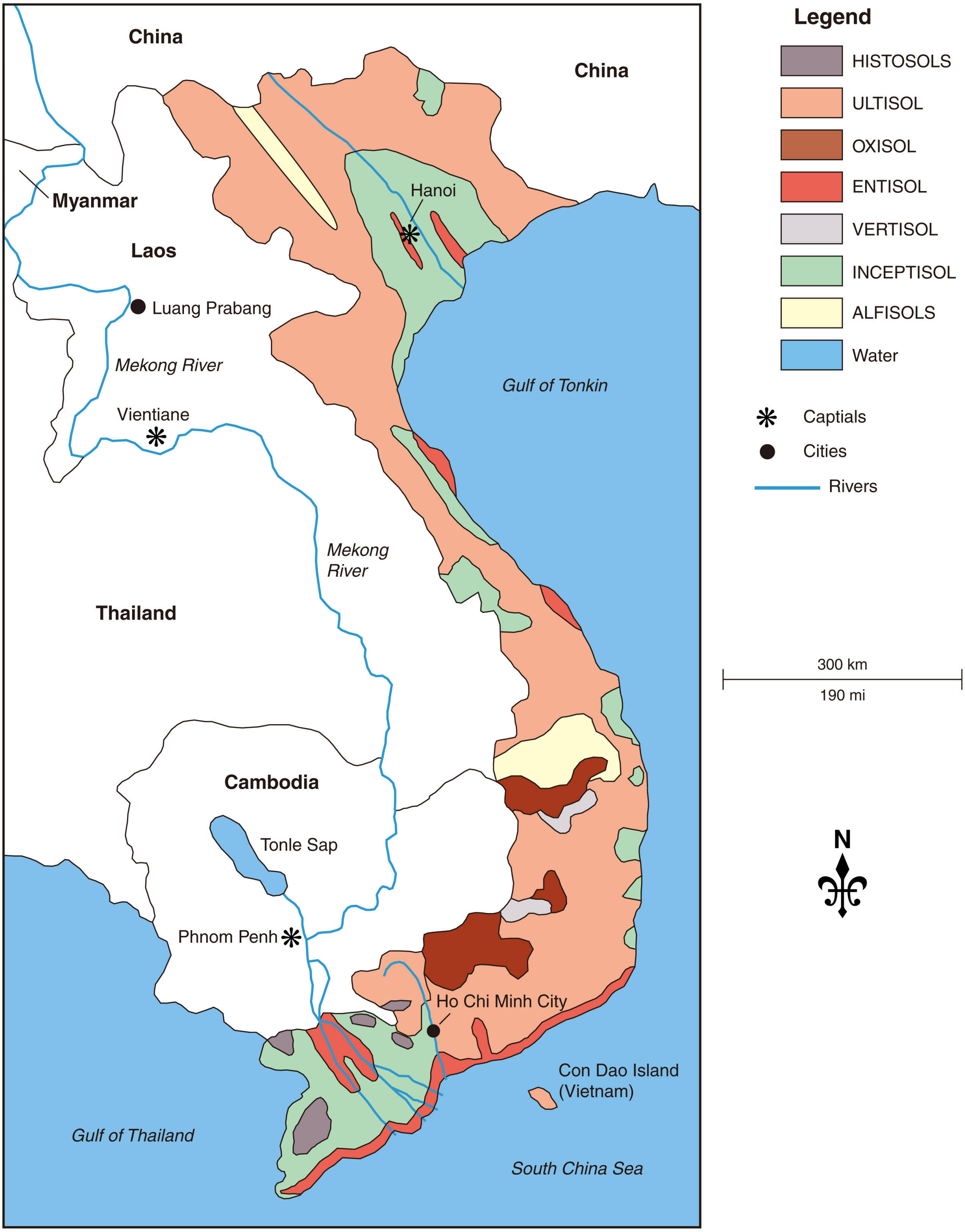

Figure 25. Soil map of Vietnam. Based on FAO/UNESCO [preliminary definitions, legend and correlation table for the soil map of the world. World Soil Resources Report no. 12. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2019, 9: 1-34. Published with copyright permission from Editor of Open Journal of Soil Science.

paper [21], we explained that arsenic exists in four forms. Two forms are water soluble, arsenite (+3) and arsenate (+5). The latter, are water-soluble arsenic salts. These two water-soluble forms of arsenic are not tightly bound and can leach from water into plant root zones as well as potentially contaminate groundwater. For example, arsenic-rich groundwater (from natural and anthropic sources) in Southeast Asia is frequently pumped back to the surface (after 1975) by hundreds of thousands of tube wells (**Figure 26**). The water is then used for rice paddies, shrimp ponds and to meet the drinking water and household water needs of 15 million Vietnamese living on the Mekong Delta and in the Central Highlands.

During August and September of 1970, Dr. Matthew S. Meselson (**Figure 27**), a Harvard geneticist and molecular biologist, led a scientific team in the Republic of Vietnam to conduct a pilot study of the ecological and health effects of the military use of herbicides, on behalf of the American Association for the Advancement of Science (AAAS). Upon returning to Cambridge, he and his students developed an advanced mass-spectrometric method for the analysis of the toxic herbicide contaminant dioxin TCDD and applied it to environmental and biomedical samples from Vietnam and the United States [1]. While in Republic of Vietnam, Dr. Matthew Meselson tested Vietnamese for arsenic and found little evidence in 1970 of any health effects (A personal communication during virtual Zoom session at the April 2021 Vietnam War conference (**Figure 28**) hosted by the Vietnam War Archive in Lubbock, Texas).

Figure 26. Tube wells in the Mekong Delta. Photo credit: Photograph courtesy of Somnath Chakraborty. https://www.anandabazar.com.

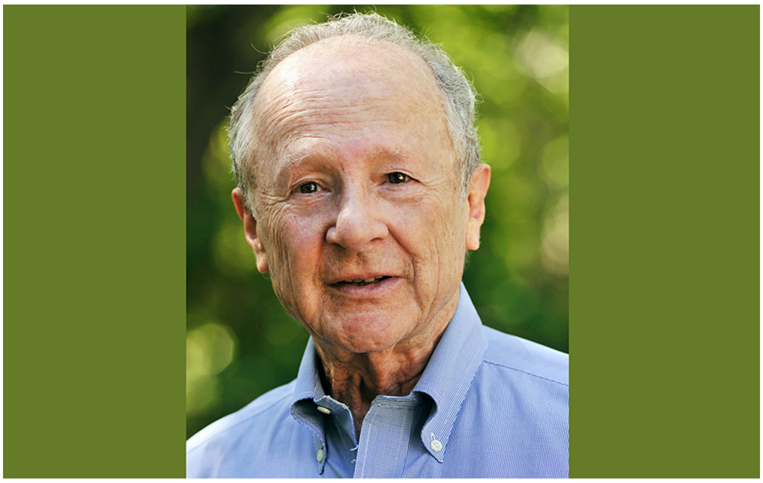

Figure 27. A picture of Matthew S. Meselson, a Harvard geneticist and molecular biologist, emeritus professor, who led a boots on the ground AAAS study in 1970 (during the American Vietnam War). Harvard University Library. Photo Credit: Janet Montgomery, 31 Aug. 2010.

Figure 28. Texas Tech Library is the home to the U.S. Vietnam War Archive which is located in Lubbock, Texas. Photograph courtesy of Ken Olson. Picture taken in April, 2018 during the Annual Vietnam War Conference in Lubbock, Texas.

The 1974 National Academy of Sciences report Part A: Summary and Conclusions (**Figure 29**) report [10] states: "Cacodylic acid, the active component in Agent Blue, is a non-selective herbicide capable of killing a wide variety of herbaceous plants. It is a non-volatile, highly soluble organic compound, which is

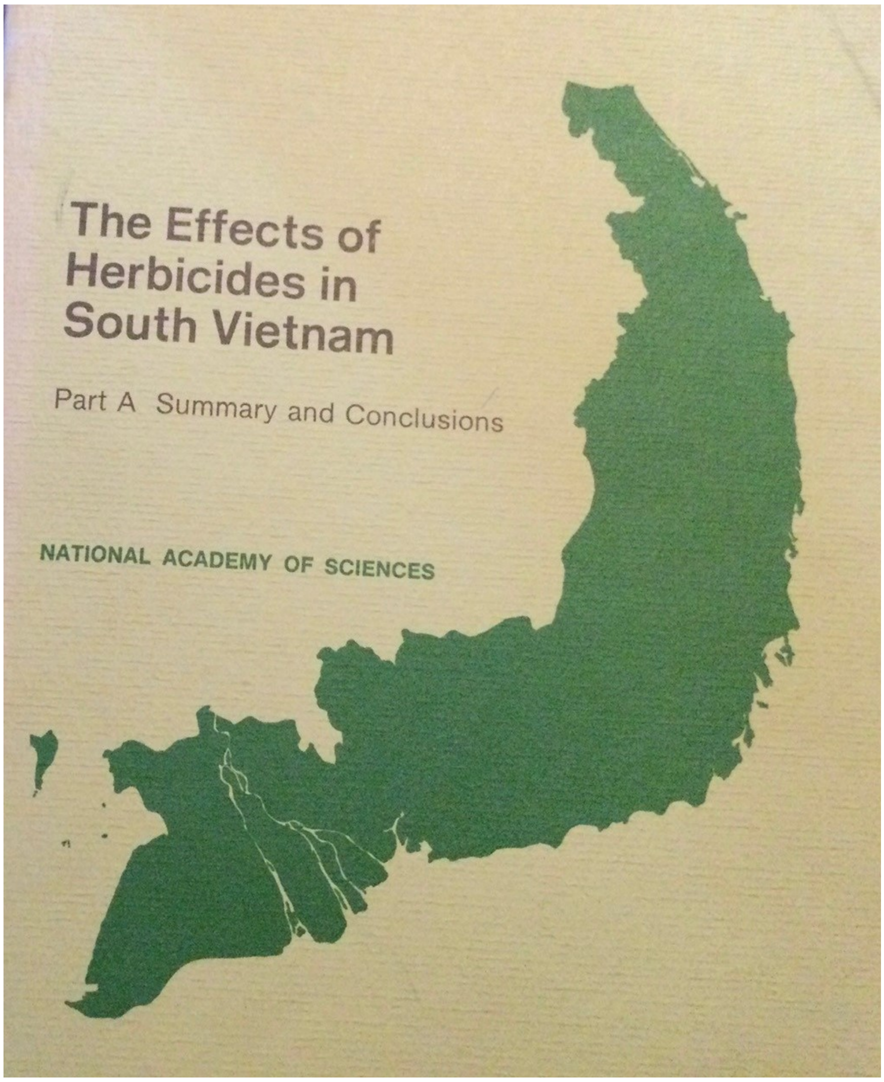

Figure 29. Picture of the 1974 National Academy of Sciences report. The NAS study was conducted during the Vietnam War years of 1971 and 1972. Photo credit: Cover picture taken by Pam Olson.

broken down in soil by microflora, mostly to inorganic arsenate bound as insoluble compounds, which also exist naturally in the soil. Acute and chronic toxicity studies in a variety of animals indicate a low to medium toxicity rating. No teratological studies nor toxicity studies in man seem to have been reported".

While co-authors of this paper have great respect for the National Academy of Sciences (NAS) and their fieldwork and research in southern Vietnam, its scope was limited to the on-going American-Vietnam War and its findings are now dated. This NAS study (1971-1972) (**Figure 29**) was conducted, after DOD ordered the stopping of Agent Orange spraying in 1970 and all tactical herbicide spraying in 1971. President Nixon signed the Paris Peace Accords on January 27, 1973 ending the direct U.S. involvement in the Vietnam War. Furthermore, the scientific study was conducted from aerial observations due to the unstable political environment on the ground. This gave little chance for boots-on-the-ground scientists to gather first-hand soil, water and vegetation samples and observe herbicide use effects on the landscape or the Vietnamese people close-up. Subsequent research and re-assessments of the fate of Agent Blue, cacodylic acid, and arsenic including both water soluble and inorganic arsenate and arsenite make it clear that NAS conclusions were inadequate. It is now time new assessments and a fresh look at past data and current conditions [21].

For example, arsenic-rich feed had been used to make chickens more marketable (plumper, redder and prevent certain chicken diseases) [23]. There has been recent research [24] studying the effects of feeding chickens organic arsenic (non-toxic) supplements and their ability to convert it into inorganic arsenic (toxic Group-A carcinogen). Because of these findings, chicken producers started eliminating the use of organic arsenic rich feed from 1999 to 2004. The use of organic rich arsenic feed was banned in the United States in 2013 by Food and Drug Administration (FDA). Arsenic is a heavy metal and thought to be a carcinogen.

2.9. Historical USDA Role in Agricultural Herbicide Program and Partnership with DOD in the Military Chemical Weapons Program

From the 1940s to the 1970s, federal agency and civilian herbicide use was under the control of USDA, BPI. The United States Military controlled the manufacture and use tactical herbicides under secrecy and worked closely with USDA before, during and after the Vietnam War. USDA was a key partner in Operation Ranch Hand.

Dow Chemical and Monsanto, two of the largest chemical manufacturers of Agent Orange did discover ways to manufacture Agent Orange faster and cheaper (to help support the war effort) by raising the temperature 9 degrees F [3]. These Chemical Companies apparently delayed [25] [26] [27] telling the U.S. Government and Military about the manufacturing process modification (liability issues as a consequence) since dioxin TCDD levels increased dramatically [3]. However, once the military officers were told by the chemical companies [25] about the "manufacturing process contamination problem and harmful effects of dioxin TCDD", the U.S. Military officers opted for the faster and cheaper manufactured product, with higher levels of dioxin TCDD contaminate. At that time the U.S. military was running low on Agent Orange and needed more herbicides for use in the Vietnam War [28].

The Agent Orange stored at Kelly Air Force base (**Figure 30**) was manufactured after the early Agent Orange had been used up and the military had to substitute Agent White to meet the demand. If Agent White, which did not have any 2,4,5-T, use had been continued it would have reduced the long-term environmental and human health impacts on both our military (*boots on the ground*) and the Vietnamese (*living in rural southern Vietnam*). The later military Agent Orange product was formulated the same (50% 2,4-D and 50% 2,4,5-T) the same as the earlier Agent Orange product. However, the Agent

Figure 30. Kelly Air Force Base in Texas. This was the command headquarters for shipping tactical herbicides through the Panama Canal Zone. Agent Orange and Agent Blue were stored at the base. Credit line: Photograph courtesy of Kelly Heritage and the Houston Chronicle.

Orange mixture was manufactured at higher temperatures and with a much higher levels of the by-product contaminant dioxin TCDD [13]. Were the dioxin TCDD levels of each batch of the Agent Orange measured and recorded? The field testing of Agent Orange was done in the early and middle 1960s when there was less dioxin TCDD in Agent Orange mixture.

It is very important to understand the following "key points" before one can begin to assess the environmental impacts and human health effects of Agent Orange with unknown quantities of dioxin TCDD. The FIFRA (Federal Insecticide, Fungicide, and Rodenticide Act) approved formulation for Agent Orange for commercial and military use and were likely identical. When Agent Orange was initially approved for use, the dioxin TCDD by-product was not a consideration. Later in the Vietnam War, the military needed more Agent Orange so the chemical companies increased the temperature used in the manufacturing process to speed up the manufacturing process and make it cheaper. This resulted of significant more Agent Orange being produced with significantly higher amounts of the byproduct dioxin TCDD. Later in the Vietnam War the Agent Orange formulation was still the same but the faster manufacturing process (higher temperatures) used to make the Agent Orange faster and cheaper was not. The Agent Orange left in Kelly Air Force base chemical storage, in 1972, were military supply chain remnants after DOD unexpectedly stopped the spraying of all tactical herbicides on 30 June 1971 and was no longer needed in South Vietnam [29]. The Agent Orange produced near the end of the Vietnam War would have been manufactured using a manufacturing process with a higher temperature and would have contained higher amounts of the contaminate dioxin TCDD. Both the DOD and USDA should have known by the late 1960s that later batches of Agent Orange had more dioxin TCDD but it was a secret. DOD and USDA should have also known about the human health effects of dioxin TCDD [3] [25] [26]. When the USDA, Forest Service decided to accept the transfer of the DOD stockpiled of Agent Orange stored at Fort Kelly, the Forest Service may have assumed the Agent Orange had the same formulation, was same product, and would have the same environmental impact as commercially available Agent Orange and components. This was not the case due to higher dioxin TCDD levels in the Agent Orange manufacture for DOD in the later 1960s. This increase the human health risks associated with potential drift onto private lands when the USDA, Forest Service and partners sprayed it on the public forest in the Western United States.

2.10. Utilization and Disposal of Tactical Herbicide Stockpile after the Vietnam War Ended

2.10.1. Agent Orange

After President Nixon signed the Paris Peace Accords on January 27, 1973, the herbicide known as "Agent Orange" still remained in the Kelly Air Force base (**Figure 30**) chemical stockpile [29]. DOD transferred the Agent Orange to the USDA, Forest Service for brush and broad leaf weed control. This Kelly Air Force base chemical stockpile was likely one of the primary sources of Agent Orange used by the USDA, Forest Service and partners in the Western United States in the 1970s to control the brush and broadleaf weeds after clear-cutting. This was the subject of a 2021 PBS documentary Independent Lens on "People vs. Agent Orange" [30] and a 2021 Vietnam Veteran News podcast 2086 by Mack Payne [31]. The DOD transfer of Agent Orange to the USDA, Forest Service would not have been an issue since Agent Orange (a 50:50 mixture of 2,4-D and 2,4,5-T) components created was formulated for dual military and agricultural uses. The excess, Vietnam War Agent Orange and components, stored at Kelly Air Force base, San Antonio, Texas, were transferred by DOD to the USDA, Forest Service for use in the Western United States forests. As stated in the 1959 Armed Services Procurement Act and subsequent Department of Defense directives make the use of coordinated Federal and Military mandatory for the procurement of items, materials and service, meaning all materials could be used at any Federal installation. Agent Orange "Federal Specifications" were formulated and approved by Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) for use by the U.S. military or any federal agency. The USDA, Forest Service and timber and chemical company partners in the Western United States to prevent shrub and broadleaf weed regrowth competition with planted trees on clear-cut public forest lands using these same chemicals used before, during, and after the Vietnam War.

The USEPA Region 10 reported on the Federal Use of Pesticides, for the years 1984 and 1985, by 17 federal agencies in Idaho, Oregon and Washington (but not for Alaska) [32]. Fifteen of the federal agencies provided the requested information. Only the USDA, Agricultural Research Service (ARS) and the Justice Department (DOJ), Drug Enforcement Administration (DEA) failed to submit reports. The DEA failed to respond to requests to provide pesticide use data for national security reasons. It appears USDA, ARS uncooperative response to the request for EPA's pesticide use/disposal information fostered suspicions that the ARS must be using pesticides in a manner which would have been disapproved by the EPA. National and regional level federal agency staffs were especially sensitive about providing pesticide disposal information. Many Agency staffs either did not have a good understanding of what happened at the application/disposal level or did not wish to provide disposal information. The typical responses were: 1) certified, private contractors were responsible for disposal activities, 2) pesticide containers are disposed of as directed on the pesticide container label, and 3) no excess pesticides existed. Or the pesticides were all used up. Many agencies reported the use of large quantities of pesticides, which were water soluble and a potential risk to groundwater as contaminants, to the EPA's Office of Pesticide Programs [32].

Federal agency pesticide record keeping systems varied greatly. Some agencies tracked pesticides when used while other agencies record systems consisted of filing and storing pesticide use proposals submitted by field offices. Once approved the field offices can apply for any quantity up to the maximum amount listed on its proposal. Some agencies had up-to-date data while others had data which had not been updated for several years. Record keeping was by month, fiscal year, or calendar year. Pesticide quantities, target species, and/or application locations were not always provided or were provided with varying degrees of precision [32].

The herbicide 2,4,5-T was banned in 1985, the year these survey reports were requested by USEPA Region 10. The EPA requested records for 1984 and 1985. The critical data for the early 1970s were not included in the EPA request for information. In the early 1970s the DOD transferred USDA Agent Orange, 2,4,5-T and perhaps Agent Blue, the arsenic based herbicide, from the Kelly Air Force base chemical stockpile that was left over from the Vietnam War or had remained in the supply chain. The Department of Navy had quantities of 2,4,5-T and DDT which could have been commercially purchased. However, the Bureau of Indian Affairs (Warm Springs Agency-Oregon) still had 14 gallons of a mixture of 2,4-D and 2,4,5-T left over after previous spraying. This mixture was not commercially available for federal agencies to purchase. Therefore, it had to have been mixed by agency staff or it was residual Agent Orange herbicide from the 1970s DOD transfer of the Kelly Air Force base transfer to the USDA and then to the Bureau of Indian Affairs. If the Agent Orange and/or 2,4,5-T herbicides were transferred from the DOD to the USDA to the Bureau of Indian Affairs in the early 1970s there should be records [32].

The USDA, Forest Service manages 18 million hectares in Idaho, Oregon and Washington which did not include Alaska which is also in USEPA Region 10. Nor does it include forest lands in other Western USEPA regions. The pesticide data was only for FY 1984 and 1985 and did not include previous 1970s data. Due to a Federal Court injunction Federal agencies were prevented from spraying pesticides in Oregon in 1984 and 1985 (*most likely as a result of Agent*

Orange vs. People legal action) [13]. The Bureau of Land Management (BLM) pesticide use, in its 1984 and 1985 noxious weed control program, was reduced dramatically from 1983 pesticide spraying levels. The real reason for the reduction was a federal court injunction issued on Dec. 2, 1984 which prohibited BLM and other federal agencies from spraying pesticides in Oregon. After that date BLM was required to prepare a "worst case analysis" before it could resume pesticide spraying.

2.10.2. Agent Blue

What was the fate of Agent Blue, the arsenic based herbicide, stored at Kelly Air Force base after the end of the American Vietnam War? GAO records also show that approximately 173,910 gallons of the herbicide Agent Blue [13] containing the active ingredient cacodylic acid (with arsenic) (**Figure 24**), in addition to the Agent Orange and components, was stored at Kelly Air Force base. It is not clear how this massive amount of arsenic-rich Agent Blue was utilized or disposed of after President Nixon signed the Paris Peace Accords, ending direct U.S. involvement in the Vietnam War, on January 27, 1973. Agent Blue, with its active ingredient cacodylic acid, was a dual purpose herbicide developed during WWII, could also have been transferred to USDA, Forest Service, for weed and grass control in clear cut in Western United States forests. If the USDA, Forest Service and their partners applied Agent Blue, arsenic, which does not have a half-life, arsenic would have remained in the Western United States forest soils [13]. At this time, how and where the herbicide, Agent Blue with the active ingredient cacodylic acid (As), was utilized or disposed of is not clear. Was it transferred, along with Agent Orange, by the DOD from Kelly Air Force base chemical stockpile to USDA, Forest Service after the end of the Vietnam War? The USDA, Forest Service goal was to control grass, weeds and brush in recently clear-cut and re-planted Western United States forests. Agent Blue was known to be effective in the eradication of grass and narrow leaf weeds [21]. If Agent Blue was not used on Federal lands in Western United States, then what happened to the 173,910 gallons of Agent Blue that were stored at Kelly Air Force base after the herbicide was no longer needed in southern Vietnam? Perhaps the herbicide was applied to the Western United States forest. Was the herbicide applied to the Western United States forest?

3. Environmental Impacts of Agent Orange (Dioxin TCDD) Manufacturing in Newark, New Jersey

The Passaic River parallels the Hudson River (**Figure 13**) and was an industrial river, with chemical plants that manufactured Agent Orange that was used in the Vietnam War in the 1950s and 1960s [12]. Stretches of Passaic River in Newark, New Jersey are post-industrial abandoned landscapes and the sediment in the Passaic River near Newark Bay remains contaminated with dioxin TCDD, PCBs, and Hg. The USEPA designated this 27 km stretch of the Passaic River as a Superfund site.

3.1. Agent Orange Environmental Impacts in United States and Cleanup of Passaic River

The Passaic River parallels the Hudson River and was an industrial river, which included chemical plants that manufactured Agent Orange that was used in Vietnam War in the 1960s. The Passaic River is one of the most polluted hotspots in the United States and site of one of the largest cleanup efforts ever. In 1983, sampling of soils and sediments, by the State of New Jersey and U.S. Environmental Protection Agency (USEPA) near 80 Lister Avenue in Newark (**Figure 11**) and the adjacent Passaic River west of Newark Bay, revealed high levels of dioxin TCDD [12]. There were also high levels of PCBs and Hg as a result of the manufacture of other chemical products. In 2001, the USEPA, in partnership with New Jersey and other federal agencies, cleaned up the Lister Avenue manufacturing site (**Figure 11**) on the Passaic River near Newark, New Jersey (**Figure 13**). The buildings were torn down and hauled to a landfill, and the site became a gravel parking lot (**Figure 11**); the dioxin-contaminated soil was removed and incinerated.

Today, only a gravel lot remains as part of an abandoned industrial complex (**Figure 31**). The remediation actions taken in the Passaic River included a pre-1998 floodwall and subsurface treatment system. The contaminated sediment in the river, originating from the Lister site and neighboring lots, was capped to prevent additional release of dioxin TCDD to the river. The site has been monitored by Occidental Chemical Corporation [33] [34]. In 2005 the State of New Jersey sued Maxus Energy Corporation (the U.S. unit of Argentina's oil giant YPF Sociedad Anomima) and OxyChem over a delay in the cleanup. The

Figure 31. Newark abandon industrial site adjacent to the former Diamond Alkali Chemical Plant site. Credit line: De glossed. L5FNO.jpa, https://i.imgur.com.

US$220 million that the state spent cleaning up a section of the river was recovered from Maxus and OxyChem partnership under terms of a court settlement [31]. Cleanup activities by the partnership in 2012 and 2014 included the removal and disposal of dioxin TCDD, PCBs, and Hg-contaminated sediment from two areas along the Passaic River [35]. The most concentrated inventory of dioxin TCDD contaminated sediment, in the river adjacent to the Lister Avenue site, was dredged by Tierra Removal. At river mile marker 10.9 the concentrated inventory of highly contaminated mudflat on the east bank of the river near Lyndhurst was dredged and capped [36] [37].

In 2014 the USEPA announced a US$1.7 billion plan to remove 3.2×10^6 m^3 of toxic sediment contaminated with dioxin TCDD, PCBs, and Hg [12]. The sediments in the lower 13 km of the Passaic River were found to be a major source of the contamination in other sections of the Passaic River (a tidal river) and Newark Bay (**Figure 13**). In March of 2016, a remedy was chosen for the contaminated sediment of the lower Passaic River which included an engineering cap being installed from riverbank to riverbank. In an attempt to avoid increasing future Passaic River flooding hazard and to maintain the navigation channel, part of the dioxin TCDD-contaminated sediment had to be removed to make room for the cap. The removed dredge material was dewatered and transported by barge to a sediment permitted processing facility on the banks of Newark Bay for disposal [12] [38] [39]. The estimated cost was US$1.38 billion. The USEPA estimated the cost of the cleanup of the lower 27 km of the Passaic River and Newark Bay to be US$6 billion, in addition to US$6 billion in earlier natural resource damages.

Cleanups for the remainder of Newark Bay and lower Passaic River are still being planned [32] [35]. Exposure to even low levels of contaminants through crab and fish consumption may have long-lasting health effects on people living along the lower Passaic River. The USEPA alerted the public about the prohibitions and advisories on harvesting crabs or fish in the tidal Passaic River and Newark Bay. The advisories and prohibitions, based on levels of Hg, PCBs, and dioxin in tested crabs and fish, are difficult to enforce.

In 2013, several corporations agreed to pay New Jersey US$130 million for ecological damages related to the Passaic River pollution [35]. To date, US$1.38 billion has been spent on cleanup. The USEPA estimated the remaining cost of cleanup of the lower Passaic River and Newark Bay at US$6 billion in addition to US$6 billion needed for past natural resource damages. After 50 years, U.S. companies, such as Diamond Alkali (now Diamond Shamrock), stopped manufacturing Agent Orange with the by-product dioxin TCDD. However, the contaminant with a very long half-life when attached to sediment under anaerobic conditions remains an environmental problem in the tidal Passaic River and Newark Bay. To this day, fish and crabs from the Passaic River are too contaminated with dioxin TCDD for human consumption and remain a threat to the food supply and human health [12].

3.2. Environmental Clean-Up of Vietnam War Dioxin TCDD Hotspots

The fate of TCDD in the environment can best be understood by studying the movement of dioxin at hotspots including Thailand (Figure 32) and Vietnam Air Force bases (Figure 33) and land beyond their perimeter fences [40]. The most contaminated site in Vietnam is Bien Hoa Air Force base (Figure 34) [3] just 30 km northeast of Saigon (Ho Chi Minh City) with a population of over 800,000 living in an adjacent airbase city, Bien Hoa City.

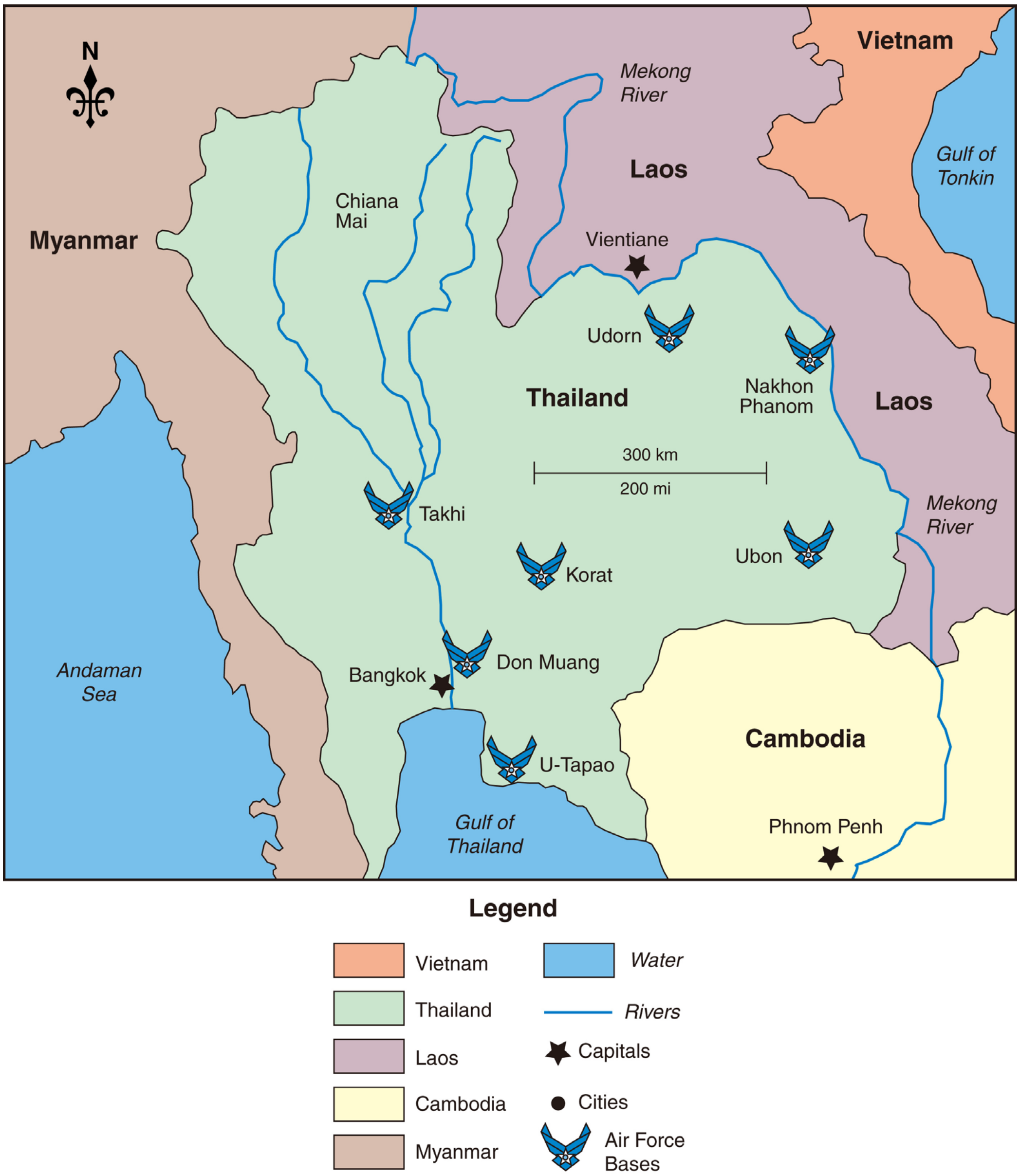

Figure 32. There are seven hotspot airbases in Thailand with dioxin-contaminated soils where the dioxin contaminated herbicides were stored and handled [3]. Agent Orange was sealed in 208-liter barrels that were shipped to Thailand air bases for use in Laos and Cambodia by C-123 aircraft during the Vietnam War. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2019, 9: 1-34. Published with copyright permission from Editor of Open Journal of Soil Science.

Figure 33. There are 10 Agent Orange hotspot airbases in Vietnam with dioxin-contaminated soils and sediments. These U.S. Airbases handled most of the Agent Orange coming into Vietnam and were the collection sites for shipping of Agent Orange for at-sea incineration [3]. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2019, 9: 1-34. Published with copyright permission from Editor of Open Journal of Soil Science.

Figure 34. Picture of active Bien Hoa Air Force Base taken in the 1960s during the Vietnam War. Credit line: Photograph courtesy of Vietnam War Commemoration. https://vietnam50th.com.

Ten Air Force bases in Vietnam were the primary hotspots of dioxin contamination. A 2016 report, "Environmental Assessment of Dioxin Contamination at Bien Hoa Air Force Base" funded by United States Agency for International Development (USAID) [35], extensively detailed TCDD contamination at Bien Hoa. The study was conducted approximately 41 years after the Vietnam War ended and 43 years after the stockpile of Agent Orange barrels were removed from Vietnam and shipped to Johnston Island (**Figure 35**) in South Pacific for eventual incineration in 1977 [18].

To address the residual contamination at the Bien Hoa Air base the USAID contracted with CDM International and Hatfield Consultants to address the Requirements of Title 22 of US Code of CFR, Part 216. The scope of the work [41] included: 1) addressing adverse health-related environmental and social issues associated with remediation activities of dioxin contaminated soil and sediment to meet Government of Vietnam (GVN) standards, 2) supplemental investigations, sampling and analysis, the site conceptual model, 3) evaluation of remediation alternatives and environmental consequences of implementing remediation, 4) consequences to social resources from implementing remediation approaches for environmental mitigation if they are indirectly affected through changes in physical and natural environment and 5) resettlement and monitoring.

Bin Hoa Air Force base was well known as a dioxin TCDD mega hotspot in Vietnam. Eleven studies characterizing the dioxin contamination at Bien Hoa Air Force base were conducted between 1990 and 2015. In 2016, USAID [41] funded a 12th study and reported findings in a comprehensive 870-page report. The study found multiple areas of contamination on the airbase and outside the perimeter fence (**Figure 36**). Examination of the historical soil and sediment sampling data revealed that dioxin contaminated soil and sediments in the area

Figure 35. Tactical herbicides being stored on Johnston Island in Pacific Ocean in early 1970s and were incinerated at sea in 1977. Credit line: Photograph courtesy of Department of Veterans Affairs.
https://velshq.com/herbicide-test-usage-storage-Vietnam/vetsHQ.

Figure 36. The defoliated perimeter of an airbase fence after being sprayed with Agent Orange in the 1960s. Credit Line: Picture taken by U.S. Army Flight Operations Specialist 4 John Crivello in 1969.

continued to be contaminated with dioxin more than 45 years later [41]. This high concentration was the result of how Agent Orange and the other herbicides were disposed of, handled, and stored. The hydrophobic water insoluble dioxin compounds attached to the organic fractions of Bien Hoa Air Force base soils and sediments. Contaminated surface soils and sediments spread from sites within the military base by leaks from storage tanks and spillage as well as outside the perimeter fence. The dioxin TCDD contaminated soil was transported and released by natural and human mechanisms: water and wind erosion; precipitation runoff, transport, and deposition in water as sediment [3].

Soil samples were collected from 76 different locations within Bien Hoa Air Force base and surrounding areas (**Figure 34**) during field sampling in 2014 and 2015, almost 45 years after Agent Orange use in Vietnam. There were 1300 composited soil and sediment samples tested for potential dioxin content, and 100 samples analyzed for soil, sediment, ground water and biota for various chemical and physical properties [41]. This was the largest dioxin TCDD sampling program ever undertaken in Vietnam [41]. About 550 of the 1300 composite dioxin soil and sediment samples when compared to the Vietnamese Ministry of National Defense standards were found within accepted levels based on current and likely future land uses. However, the other 750 soil and sediment samples had contaminated dioxin levels above accepted standards. The report estimated that between 408,500 m^3 and 495,300 m^3 of contaminated soils (75%) and sediments (25%) were found both on and off the Bien Hoa Air Force base.

Contaminated soil and sediments on and off Bien Hoa Air Base were used to estimate the bioaccumulation of dioxin within fish and other aquatic organisms and bio-magnification in the food chain from sediments, zooplankton and small fish to human consumption. The raising, harvesting and transport of contaminated fish and other aquatic animals both inside and outside the Bien Hoa Air Force base continued to have high potential for dioxin contamination even after 45 years [3]. All but one of the fish tested for dioxin were contaminated. Although raising and selling fish for consumption has been banned, the ban has not been effective and consumption of fish and aquatic animals from this region continues to present a high risk to human health [40]. The only other soil or sediment contaminant found in the analysis was arsenic. A few water samples contained dioxin at or above the 10 parts per quadrillion (ppq) standard, but overall drinking water samples on and off site were found to be safe [41].

To address the Bien Hoa hotspot, between 347,800 m^3 and 414,400 m^3 of dioxin contaminated soil and sediments will need to be treated [41]. The 2016 USAID assessment report suggests eight approaches to remediate the Bien Hoa Air Force base site.

1) No action—at a cost of $0.00.

2) Containment soil and sediment above approved dioxin limits in Passive or Active Landfill—at a cost of $126,000,000.

3) Containment using Solidification/Stabilization—at a cost of $202,000,000.

4) Treat soil and sediment above 2500 ppt—at a cost of $226,000,000.

5) Treat all soil and sediment above 1200 ppt—at a cost of $377,000,000.

6) Treat using incineration/thermal—at a cost of $666,000,000.

7) Treat using thermal conductivity heating—at a cost of $539,000,000.

8) Treat using Mechano-Destruction—at a cost of $600,000,000.

Incineration appears to be the best alternative treatment of TCDD contaminated soil and sediment. While the treatment is the most expensive technology currently available, it would eliminate dioxin rather than confine it to a landfill and would not require future maintenance or treatment. Incineration (oxidation of dioxin contaminated material) is a mature and tested technology and one of the most commonly used technologies [41] having been used to treat soils at more than 150 superfund sites, including on the Passaic River near Newark, New Jersey (**Figure 13**) [12].

Incineration involves temperatures between 870 to 1200 degrees C generated in rotary kiln incinerators. This method volatilizes dioxin in contaminated soils and sediments and then oxidizes it into the gaseous phase. The incineration process requires significant quantities of fuel to generate the temperatures needed to fully burn contaminated soils and sediments. The contaminated soils and sediments would first need to be excavated and transported to stockpile areas near designated incineration locations. Several different types of incinerators have successfully destroyed dioxin [41] such as rotary kiln incinerators similar to those used in the US to remediate contaminated soil. Rotary kiln incinerators have an extremely high (99.999%) destruction efficiency (DE). Incineration costs are expensive but the process would be effective and likely acceptable to the Government of Vietnam (GVN).

Contaminated material is dried using a rotary drum dryer to lower moisture content and then placed in a kiln for 40 to 60 minutes. Following treatment, the soil material is stockpiled for other uses including back filling. Confirmatory sampling and testing would be necessary prior to using the treated soil; and the ash from the incinerator once cooled must be stockpiled separately from treated soils. A secondary combustion chamber processes the off-gas separately to ensure that all organics are destroyed. These gases pass through particulate separators, acid gas scrubbers and quenchers to remove particulates and vapor contaminants and to reduce temperature before discharging into atmosphere [41].

The excavated areas of the Bien Hoa Air Force base can be refilled with the treated soil and placed as clean fill into soil decision units (DU). Treated sediment should never be used as backfill to avoid the risk of contamination. Land use at restored sites should not be changed from industrial area to farmland or aquaculture with lower acceptable dioxin levels. Drainage at the remediated site should be monitored to manage future erosion of materials, transport and deposition into lakes. Treatment of the Bien Hoa Air Base contaminated soil and sediment (estimated to be at least 408,000 m^3) would take about eight years of one incinerator system operating continuously (24 hours per day). Two separate incineration units could reduce the time to 5 years. However, there would be startup time required for design, permitting and contractor procurement. This would reduce dioxin concentrations to or below GVN cleanup standards; and ash generated by the incinerator would require offsite disposal.

Incineration of dioxin contaminated soils and sediments would lower Bien Hoa Air Force base dioxin concentrations and prevent continued off-base leaching and transport. Further, protected tourism and cultural and heritage resources would again be safe. Potential concerns during remediation are that the movement of contaminated soils and incineration could affect surface water quality from material handling and air quality because of dust from construction activities. Noise from heavy equipment operations might also be a temporary nuisance problem since almost 900,000 Vietnamese live nearby. There may also be a risk of recontamination of the airbase and adjacent lakes. Since incineration involves treating contaminated soil and sediment materials on the airbase, there is little long-term risk associated with climate change. Potential China Sea level rise and inundation and increased frequency and intensity of extreme weather should be manageable if airbase drainage is maintained.

3.3. Environmental Impact of Agent Blue and Clean-Up Costs to Date

3.3.1. Agent Blue Environmental Impact in United States

The Menominee River flows into Lake Michigan via Green Bay (**Figure 37**). The Ansul Chemical Company at Marinette, Wisconsin (**Figure 38**) and (**Figure 39**) manufactured the Agent Blue, an arsenic containing herbicide, used in the Vietnam War during the 1960s and 1970s. The Agent Blue was shipped via Green Bay and the Great Lakes (**Figure 40**) and the St. Lawrence Seaway to the Atlantic Ocean. Almost all (98%) of the Agent Blue used in the Vietnam War from 1961 to 1971 was manufactured at Ansul Chemical plants on the Menominee River in Michigan and Wisconsin [21]. The contaminated surface water and sediments near Ansul manufacturing plant flow into the Menominee River. The groundwater and the river bottom sediments are heavily contaminated with arsenic, which was released by Ansul Company from 1957 to 1977 resulting from the manufacture of Agent Blue. Ocean going ships then passed through the Panama Canal (**Figure 41**) and the Pacific Ocean on the way to the South China Sea.

Figure 37. Aerial view of the former Ansul company chemical plant on Menominee River in Marinette, Wisconsin (L) and Menominee, Michigan (R). The Menominee River flows into Green Bay [21]. Published with copyright permission from Editor of Open Journal of Soil Science.

Figure 38. Seagoing ship being loaded with chemicals at the former Ansul company plant in Marinette, Wisconsin [21]. Published with copyright permission from Editor of Open Journal of Soil Science.

Figure 39. Bulk storage of raw materials, where the arsenic ash for making Agent Blue was stored at Ansel Chemical plant on Menominee River in Marinette, Wisconsin during the 1960s and 1970s [21]. Published with copyright permission from Editor of Open Journal of Soil Science.

Fewer 208-liter barrels of Agent Blue with a blue stripe were sent, via ocean going ships through the Panama Canal [13], to South Vietnam than Agent Orange barrels with an orange stripe. Between 1962 and 1971, the U.S. used an estimated 7.8 million liters of Agent Blue herbicide (1,132,400 kg of arsenic) applied as a chemical weapon for "crop destruction and defoliation". Agent Blue was applied primarily on the mangroves, rice paddies [42], and the surrounding forest of South Vietnam. Agent Blue was eventually also used in Laos along the Ho Chi Minh trail (**Figure 20**) to kill crops and upland rice in the Central Highlands in order to deprive the North Vietnamese communist insurgent troops a food source (**Figure 42**). The Agent Blue was applied at the average rate of 2.83 kg As/ha for the total rice paddy and forest area (**Figure 43**). Many areas were

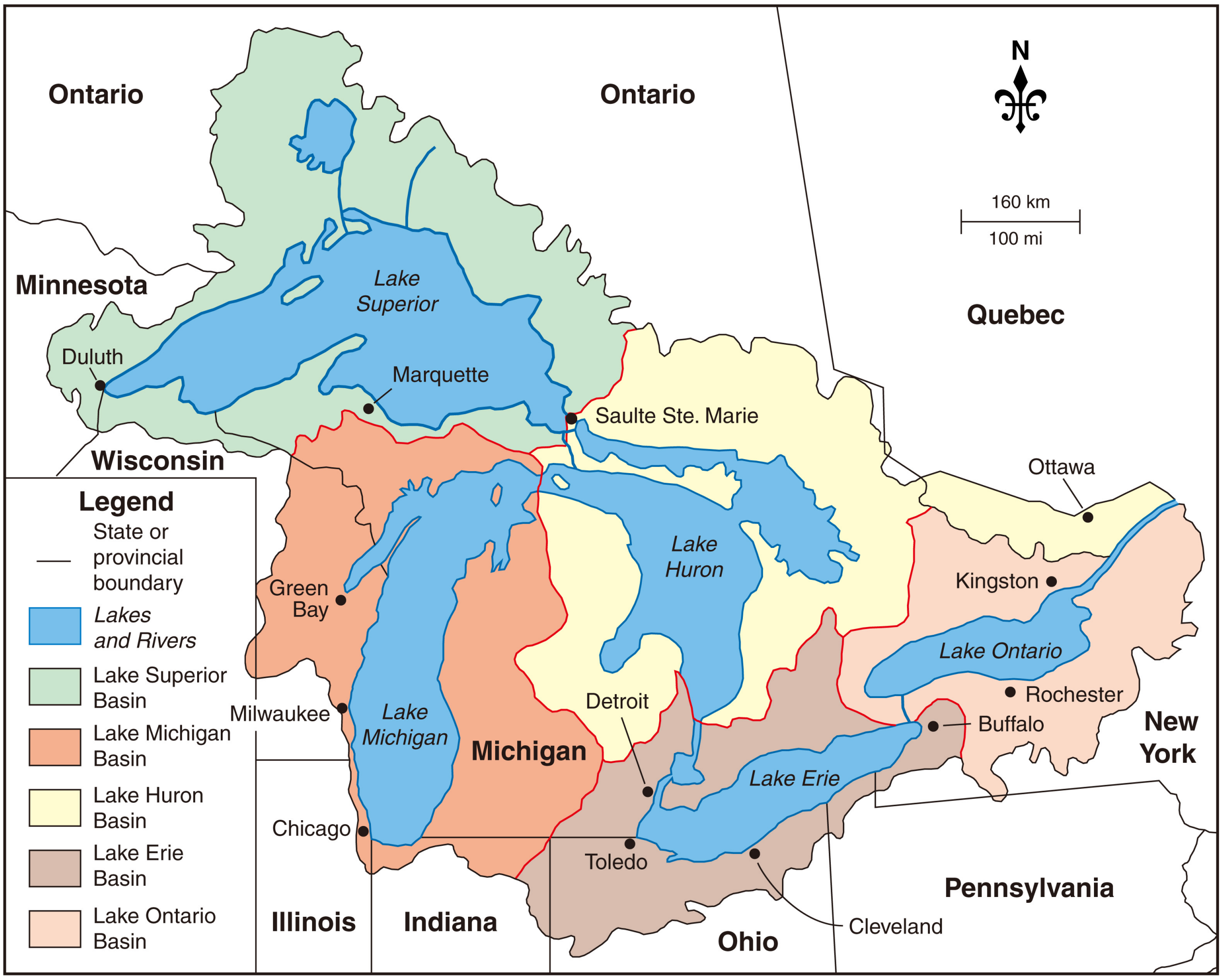

Figure 40. St. Lawrence Seaway and the Great Lakes. Map by Mic Greenberg. Published with the copyright permission from Editor Journal of Water Resource and Protection.

Figure 41. Loaded ship coming through a lock on the southern entrance to the Panama Canal [13]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Figure 42. Vietnamese and Montagnard rice growing in the Mekong Delta of Vietnam. Irrigated rice [11]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Figure 43. Tactical herbicides being sprayed on rice paddies and mangrove forests [21]. Published with the copyright permission from Editor of Open Journal of Soil Science.

sprayed only once while other areas received four or more applications. The forest and mangrove areas were usually sprayed (**Figure 43**) at a different rate than the rice paddies. Unable to control the guerrillas access to their food supplies or eliminate their grassroots village support, the U.S. military response was simple: "If you cannot control it, kill it" [28] [42].

Agent Blue destroyed food crops (rice) by desiccation of the green vegetation making the crop unable to maintain normal photosynthetic activity thereby desiccating the crop and making it susceptible to destruction by burning. The application of arsenic based herbicide was required to overcome the incredible resistance of rice to conventional methods of burning. Herbicides destroyed the food crop fields in 2 - 4 days and left the soil unsuitable (**Figure 44**) for further planting within a month. In this way, the Republic of Vietnam and United States militaries ultimately destroyed at least 300,000 ha of food crops (rice) [28] [43].

Agent Blue, a "tactical herbicide" used by the United States military during the Vietnam War, was inspired by the British use of herbicides and defoliants applied during the Malayan Emergency (1950s) to provide a precedent for its use. Destroying rice to prevent its consumption by the enemy was a U.S. and Republic of Vietnam military strategy at the very start of U.S. military involvement in Vietnam War.

Initially, Republic of Vietnam and United States soldiers attempted to blow up dikes and raised borders around rice paddies to dry them up by using mortars and grenades. However, mature rice grains are very durable and not easily destroyed even if the rice plant is deficient of water due to paddy drainage. Every grain of rice that survived became a seed to be collected and re-planted. The U.S. military discovered that rice grain is one of the most difficult plant materials to destroy [21]. However, if an herbicide like Agent Blue was applied by spraying before the rice plants were mature, it could mean a 60% to 90% rice crop loss. If subsequently burned, the immature rice seeds could be destroyed. However, the burning of arsenic treated vegetation resulted in the release of volatile arsenic containing aerosols and ash into the atmosphere. Surviving rice was contaminated, as well, with trace amounts of arsenic. Rice grown in the Vietnam to this day is still tainted by trace amounts of arsenic probably from both anthropic and natural sources.

Figure 44. Rice residue in dried out fields similar to the rice paddies sprayed with Agent Blue in the 1960s and 1970s [3]. Published with the copyright permission from Editor of Open Journal of Soil Science.

At the end of 1967 an International War Crimes Tribunal stated that: "The soldiers discovered that rice is one of the most maddeningly difficult substances to destroy; using thermite metal grenades it is almost impossible to make it burn and, even if one succeeds in scattering the rice, this does not stop it being harvested by patient men." The U.S. and South Vietnamese military went to "bigger and better" options that would actually destroy entire rice paddies [2].

"Ranch Hand", was the military code name for spraying of herbicides by U.S. military aircraft in Vietnam and Laos from 1962 through 1971 [43]. In this case, the widespread use of Agent Blue by the Republic of Vietnam and United States militaries was an attempt to take away the enemy's food supply by depriving them of food resources.

Agent Blue was primarily used to desiccate and kill narrow-leaf plants and trees such as bamboo, grass, rice, and bananas. The rice plant is highly dependent on water to survive. Spraying Agent Blue on paddies can destroy approximately 60% of an entire rice paddy and leave it unsuitable for intermediate re-planting. After the war, the Vietnamese people would then harvest and eat the tainted rice, fish, and shrimp for the next 55 years [21].

3.3.2. Agent Blue Field Studies and Application in Southern Vietnam

A study done by Watson *et al.* [44] found that life expectancies of animals (**Figure 45**) exposed to Agent Blue were reduced. For rats the lethal concentration of Agent Blue was 3.5 μg/L. Soldiers with prolonged exposure to Agent Blue had a garlic odor in their breath, which is one of the common noticeable symptoms of arsenic poisoning. Research shows the human liver absorbs 40% of the cacodylic acid [23] [45]. The extreme levels of arsenicals and high bioaccumulation of arsenicals in the body are detrimental to crops and human health.

Military personnel applied Agent Blue by using hand sprayers on backpacks, trucks, and riverboats or sprayed from helicopters on rice paddies and adjacent canals. In some cases, Agent Blue was also used to kill bamboo (**Figure 46**). The military personnel were told that the herbicides including Agent Blue were harmless and the herbicide handlers including Vietnamese soldiers and civilians did not need to wear protective gear such as facemasks, googles, gloves and suits. Agent Blue often contacted the exposed skin of the military personnel (**Figure 47**) who were spraying [21] [45]. The military personnel involved in Operation Ranch Hand were in three risk categories separated by the level of potential danger to herbicides including Agent Blue. Navigators, co-pilots, and pilots were thought to be at low risk for exposure and contamination [24]. The moderate risk group included the military personnel who loaded or re-drummed the herbicides (**Figure 48**), the crew chiefs, the mechanics and personnel who repaired the tanks and spray equipment [24]. The high-risk group included the flight engineers who operated the spray equipment. However, often unrecognized herbicide included the crews of fire support and escort aircraft which often had to maneuver around the spray aircraft to suppress ground fire and ended up flying through the spray stream or spray drift without protective gear. The empty

Figure 45. Water Buffalo in a rice paddy in Mekong Delta of Vietnam [21]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Figure 46. Bamboo growing in the Mekong Delta [3]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Figure 47. Tactical herbicides sprayed from a M113 Armored Tracked Personnel Carrier [21]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Figure 48. Repacking herbicide barrels and recovering buried barrels leaking into the ground [3]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Agent Blue barrels were washed and poured out on the ground by hand often without protective gear and then re-purposed for improvised showers, to store drinking water or even as barbeque pits or sold to locals. The rinse water from cleaning the barrels was poured on the soil surface and either leached into the soil and groundwater [46] or was transported off-site during monsoon rains into the waterways [21].

Agent Blue harmed village food supplies and forced many rural villagers into the "strategic hamlets" or urban slums after destroying hundreds of paddies with arsenic laced Agent Blue. Alain C. Enthoven, assistant secretary of the defense (DOD) for systems analysis, reviewed the RAND report and concluded, "existing wholesale food crop destruction program was counterproductive because it alienated the affected South Vietnamese population without denying food to the communist insurgents." However, others responsible for U.S. military strategists did not agree [21].

3.3.3. NAS Damage Assessment of Tactical Herbicide Spraying—Study and Findings [10]

An Act of Congress, Public Law-441, and Fiscal Year 1971 Military Procurement Authorization Act Section 506-9c authorized a NAS study. The Secretary of Defense was required to make arrangements with the NAS to conduct a comprehensive study (Sep. 1971 to Sep. 1973) and investigate physiological and ecological dangers in inherent use of the defoliation program by Department of Defense in South Vietnam [10] (**Figure 43**) [15]. NAS scientists spent 1500 scientist days working in Vietnam during the Vietnam War and found it impossible to determine whether arsenic found in the rice paddy soils was from the herbicide spraying of Agent Blue, from other sources, or was present naturally in the soil prior to the spraying.

The NAS overflight was conducted on January 27, 1972 of the Song-Re Valley, Quang-Ngai Province. This over flight of an area, which was sprayed with Agent Blue on August 9, 1970, found that rice fields and vegetable plots appeared normal from the low flying aircraft. NAS [10] analyses of a small number of samples of fish, rice, shellfish (**Figure 49**), worms, soils and water collected near a community in Rung Sat, which was subjected to Agent Blue missions between 1964 and 1969 found the arsenic levels within the normal ranges.

NAS scientists studied the effects of Agent Blue on settlements by interviewing the villagers and reported their findings in a report entitled "Effects of Herbicides on Humans" [10]. Human reactions to military spraying of tactical herbicides were documented [47]. Herbicide spraying including Agent Blue resulted in the displacement of people from their rural homes into government sponsored villages as part of the Diem government's "strategic hamlet" policy and urbanization movement into the slums of Saigon and other larger cities. Only one of 18 rural areas increased in population during the 1960s. After spraying of tactical (Rainbow) herbicides and subsequent burning of crops, individuals in every community interviewed reported on who became ill or died after the

Figure 49. Shrimp farming in the Mekong Delta of Vietnam that was developed after 1975 [21]. Published with the copyright permission from Editor of Open Journal of Soil Science.

spraying, or because of eating of herbicide-treated plants or drinking contaminated water. The NAS report [10] (**Figure 29**) was translated into Vietnamese for the locals to read. Vietnamese had to live with the consequences and had to undertake remedial action. Financial and technical support from the U.S. (funds and training for Vietnamese workers), lent professional technical personnel, and equipment.

Herbicide damage effects included: 1) loss of potential production at the plant stage before growth and grain production became economically valuable, and, 2) loss of commercial products such as grain, timber and fruit and lack of young plants including seedlings and seeds required maintaining food production. The effects of crop damage were revealed primarily from studies of rural settlements and interviews with villagers. The results were reported under the "Effects of Herbicides and Humans." Human reactions to military spraying of tactical herbicides were included in studies on mangrove forests and Vietnamese and Montagnard rice paddies, coconut plantations, gardening, and upland crop areas [10]. The tactical herbicides were destructive to health and livelihoods of the people whose land was sprayed.

The arsenic-laden Agent Blue herbicide was used to kill rice food crops and bamboo. Spraying Agent Blue added a significant amount of water-soluble arsenic to the rice roots, rice grains, water, and soil. The United States and Republic of Vietnam militaries sprayed and dumped Agent Blue on the rice paddies to desiccate rice plants and then burned the rice residue and seeds. As a result, toxic As-containing aerosols and smoke were released to the atmosphere.

The goal was to clear out crops and foliage to improve military intelligence, achieve enhanced security, increase availability of troops used for combat, reduce cover for enemy resistance, and reduce United States personnel casualties [3]. Between the first test in Kontum base in southern Vietnam on August 10, 1961 and the last spraying in October 1971, tactical herbicides including Agent Blue were shipped to and sprayed all over South Vietnam. U.S. and Vietnam public ongoing concerns: did the extensive use of tactical herbicides including Agent Blue modify the environment of Vietnam beyond the point of recovery? Agent Blue did not raise the arsenic levels in the groundwater above the 1970s drinking water standards [10].

There were many spikes in the arsenic levels (above WHO standard) in the Mekong Delta groundwater. Arsenic was bio-accumulated in the Vietnamese because of elevated arsenic levels in the drinking water and food supply. Medical evidence collected from U.S. veterans and Vietnamese and their offspring during the next 50 years suggests there was significant genetic damage [45] [47]. Documented effects of herbicide damage were: 1) the loss of potential food crop production at a stage before maturity and crop becomes economically valuable, and 2) the loss of commercial products such as grain, timber, fruit, seedlings and seeds required maintaining food production.

Subsequent industrial development and wastewater treatment plants have contributed to dangerous bio-available arsenicals in the surface and groundwater of the Mekong Delta. During the last two decades, thousands of government-subsidized shallow tube wells have been built. Shallow groundwater has become the major source of arsenic rich water for irrigation and drinking in Vietnam. Groundwater arsenic in concentrations has measured as high as 3050 ug/L. The Vietnam War's "Operation Ranch Hand" contributed to the crisis of arsenic contamination in South Vietnam upland and lowland rice paddies (**Figure 50**). However, the NAS [10] findings suggest arsenic levels were still below WHO standards. Fortunately, southern Vietnam farmers had not yet started pumping the groundwater to the surface for rice paddies or shrimp ponds.

3.3.4. Impacts on Mangrove Forests

NAS [10] studied the effects of defoliation by comparing soil properties (**Figure 25**) in defoliated and non-defoliated mangrove areas northeast of Nam-Can (Ca-Mau Peninsula). The only positive impacts recognized came from the spraying of the mangrove area (**Figure 18**), which increased security from the NLF because it was easier to clear land for irrigated fields. However, woodcutters recognized that their primary resource was being eliminated.

3.3.5. Cleanup of the Menominee River Adjacent to the Ansul Company Chemical Plant

In 2009, the Ansul Company operated under two consent orders for environmental mitigation; one from the Wisconsin Department of Natural Resources and another from the U.S. Environmental Protection Agency (EPA) [21]. In

Figure 50. As the Mekong and Bassac Rivers flow south, through the Mekong Delta they water a diverse landscape bringing freshwater to the lowlands around the flooded mountains; to saltwater river regions in the wet season; and sediment loads that replenish the fertility of rice fields. Coastal dunes along the South China Sea are high points in the landscape. Farmers in the uplands of Vietnam grow coffee, rubber, fruit and nut trees. Map by Mic Greenberg. Reprinted with permission from Open Journal of Environmental Protection 2018, 9: 4: 431-459. Published with the copyright permission from Editor of Open Journal of Environmental Protection.

September of 2009, Ansul Company agreed to spend an estimated $28 million on:

1) Removal 56,600 m^3 of arsenic-contaminated sediments from the Menominee River;

2) Construction of an impermeable barrier to bedrock for about 160,000 m^2 of sediment;

3) Cap or remove 17,000 m^2 of surface soils contaminated with arsenic levels above 16 - 32 ppm;

4) To pump and treat contaminated groundwater;

5) The total remediation costs were: 1976-1984, $11 million to pump and treat contaminated groundwater at the southern property border and to install a groundwater interceptor trench [21] in 1998-1999, $12.4 million to remove arsenic-contaminated sediment from the 8th Street section of the Menominee River and

6) An impermeable barrier system was installed to bedrock near the 8th Street slip and adjacent salt vault.

In 2012-2013, approximately $25 million was spent to dredge and then cap contaminated river sediments due to an EPA order of the removal of 190,000 m^3 of sediment from the main channel. The project cleanup began in July of 2012 after Ansul (Tyco) Company hired Stevenson Environmental Services of New York as the general contractor.

3.3.6. Cleanup of the Panama Canal Zone

A recently released report of the United States Government Accountability Office (GAO) focused on the actions needed to improve the accuracy and communication of information regarding storage and testing locations of Agent Orange outside of Vietnam including Kelly Air Force Base in Texas [25]. The GAO report confirmed that the Military Sea Transportation Service directly chartered merchant vessels to carry tactical herbicides through the Panama Canal during the Vietnam War. These tactical herbicides, including Agents Blue and Orange, were stored vertically on pallets in internal storage compartments on the vessels. There is no official evidence to show the tactical herbicides were ever offloaded in Panama Canal Zone [48]. However, there are other documents [49] [50] [51], that support the presence of similar formulated commercial herbicides 2,4-D and 2,4,5-T containing unknown amounts of dioxin TCDD. A December 1976 Environmental Sampling Report for the Panama Canal Zone showed chlorophenoxy herbicides were detected in the soil samples from the Canal Zone [52]. Chlorophenoxy herbicides are identified by the Centers for Disease Control and Prevention as 2,4,5-T based herbicide containing unknown amounts of dioxin TCDD [52]. In the 14th Annual Meeting of U.S. Army Corps of Engineering report on the "Aquatic Plant Control Research Program" a section notes the June 1978 initiation of large-scale testing of 2,4-D on water hyacinth [53]. However, not all of the test site locations have been provided. Since commercially available 2,4-D was used on military bases in Panama Canal Zone this herbicide would have been available for use on the hyacinth problem in Lake Gatun; however, no official records have been found that the Lake Gatun was used as a test site [18] [29] [54]. Was Lake Gatun used to test 2,4-D on hyacinths? If so were the findings of the "Aquatic Plant Control Research Program" published? If Lake Gatun was not used as a test site, why not?

Herbicides with 2,4,5-T with dioxin TCDD contaminant were shipped through the Panama Canal Zone. The U.S. Government and Military have for more than 60 years asserted those tactical herbicides such as Agent Orange and Agent Blue were neither off loaded in the Panama Canal Zone [47] nor aerially sprayed on the Tropical Forests of the Panama Canal Zone" [18]. Many Panama Vietnam Era Veterans have claimed that they handled and/or were exposed to toxic chemical sprays [49] [55] [56] have over the years challenged this official military statement [49]. Panama veterans who claimed to have been exposed to commercial herbicides including 2,4,5-T containing unknown amounts of dioxin TCDD, have filed for VA benefits but have been repeatedly denied benefits [51] since the tactical herbicides were not officially offloaded and/or applied to the Panama Canal Zone landscape [49]. However, commercial herbicides containing 2,4,5-T with an unknown amount of dioxin TCDD were used on the U.S. military base grounds [57] [58].

These commercial herbicides were very similar (composition and strength) but often have lower dioxin TCDD contents [59] [60] than the restricted use tactical herbicides being transported through the Panama Canal Zone to the South China Sea for use during the Vietnam War. The U.S. Government and Military declared, on the official record [48], that tactical herbicides were never used in the Panama Canal Zone [49] [50]. However, DOD was not really claiming that "unrestricted commercial herbicides" were never requisitioned, offloaded, handled, and applied by military personnel to the military base grounds and perimeter fences [55] [56] [57] at the direction of the Base Civil Engineer Commanders. It is also assumed that any aerial spraying done by aircraft only involved commercially available herbicides including 2,4-D and 2,4,5-T containing unknown amounts of dioxin TCDD [13]. However, three C-123 (**Figure 16**) aircraft that were used to spray Malathion in the Panama Canal Zone may have been previously contaminated with tactical herbicides, containing dioxin TCDD and arsenic, in other theaters of operation including South Vietnam. After DOD announced that the use of Agent Orange was suspended in on April 15, 1970 the military started to ship C-123 aircraft back to U.S. territories [13].

In 1970, three C-123 aircraft previously used to spray tactical herbicides in Vietnam [13] and contaminated with tactical herbicides (including Agent Orange and Agent Blue) residues (dioxin TCDD and arsenic) in their spray tanks, were relocated via a transport ship in 1970 to Howard Air Force base in Panama. These TCDD and arsenic contaminated C-123 airplanes (**Figure 16**) were used from 1970 to 1973 to spray Malathion in the Panama Canal Zone [13]. This may have resulted in trace amounts of tactical herbicide Agent Orange (dioxin TCDD) and Agent Blue (arsenic) [21] being added to the soils and water of the Panama Canal Zone.

The herbicides 2,4-D and 2,4,5-T containing low levels of TCDD were commercially available and thus could be ordered and used separately by any Federal Agency (including the military and USDA) and shipped to and used on the Panama Canal Zone military base grounds [56] [57]. While there are no official documents which prove tactical herbicides, such as pre-mixed Agent Orange, were ever off-loaded in Panama Canal Zone [49] and/or sprayed on the tropical forests and islands in the Panama Canal Zone. There are commercial ship transport records which show commercial herbicides, Orange, Ester-Butyl, 2,4-D and 2,4,5-T containing the contaminant TCDD were used on military bases in the Panama Canal Zone [55] [56]. Even if tactical herbicides were never off-loaded and sprayed in the Panama Canal Zone, the commercial herbicides including 2,4,5-T by-product containing unknown levels of TCDD were used on the military base grounds and perimeter fences by military base personal to control the vegetation and insect pests and would have added TCDD to the Panama Canal Zone environment. There is evidence that DDT and Malathion (first registered in 1956) [13], 2,4-D and 2,4,5-T with the contaminant dioxin TCDD were sprayed on Panama Canal Zone highways, structures, military grounds, and perimeter fences using sprayers mounted on trucks in the Panama Canal Zone.

The extent of the current chemical and pesticide contamination on former Panama Canal Zone U.S. military base grounds and in Lake Gatun and the Panama Canal channel (**Figure 51**) is unknown [13]. Systematic soil sampling of former military bases, chemical disposal sites, and sediment sampling of the Lake Gatun or the Panama Canal sediments is needed to determine if mitigation is still required.

3.3.7. Disposal of Chemical Weapons Including Agent Blue (Davis-Monthan Air Force Base)

Historically, most of the world's chemical weapons were disposed of at sea. This included the arsenic-based chemical weapons [16]. These chemical weapon disposal sites were not well documented. Once dumped into the sea, the chemicals leaked because of the corrosive action of seawater on steel barrels and containers. Davis-Monthan Air Force Base, near Tucson, Arizona is the home of the U.S. aircraft boneyard where retired military aircraft are stored (**Figure 52**). After DOD stopped the spraying the tactical herbicides including Agent Blue the excess stocks were removed from Vietnam by 1972 [18]. Most of these tactical herbicides, used during the Vietnam War and containing dioxin (TCDD) herbicides, were transported to Johnston Island in the Pacific Ocean for eventual incineration at sea [3] [21]. The stockpile of tactical herbicides in South Vietnam were transported to Bien Hoa Air Force base, re-barreled in 1971 and 1972, and shipped to Johnston Island in the Pacific Ocean. Twenty thousand barrels of tactical herbicides were shipped and stored for 5 years on the Johnston Island beach and then incinerated on a ship in 1977.

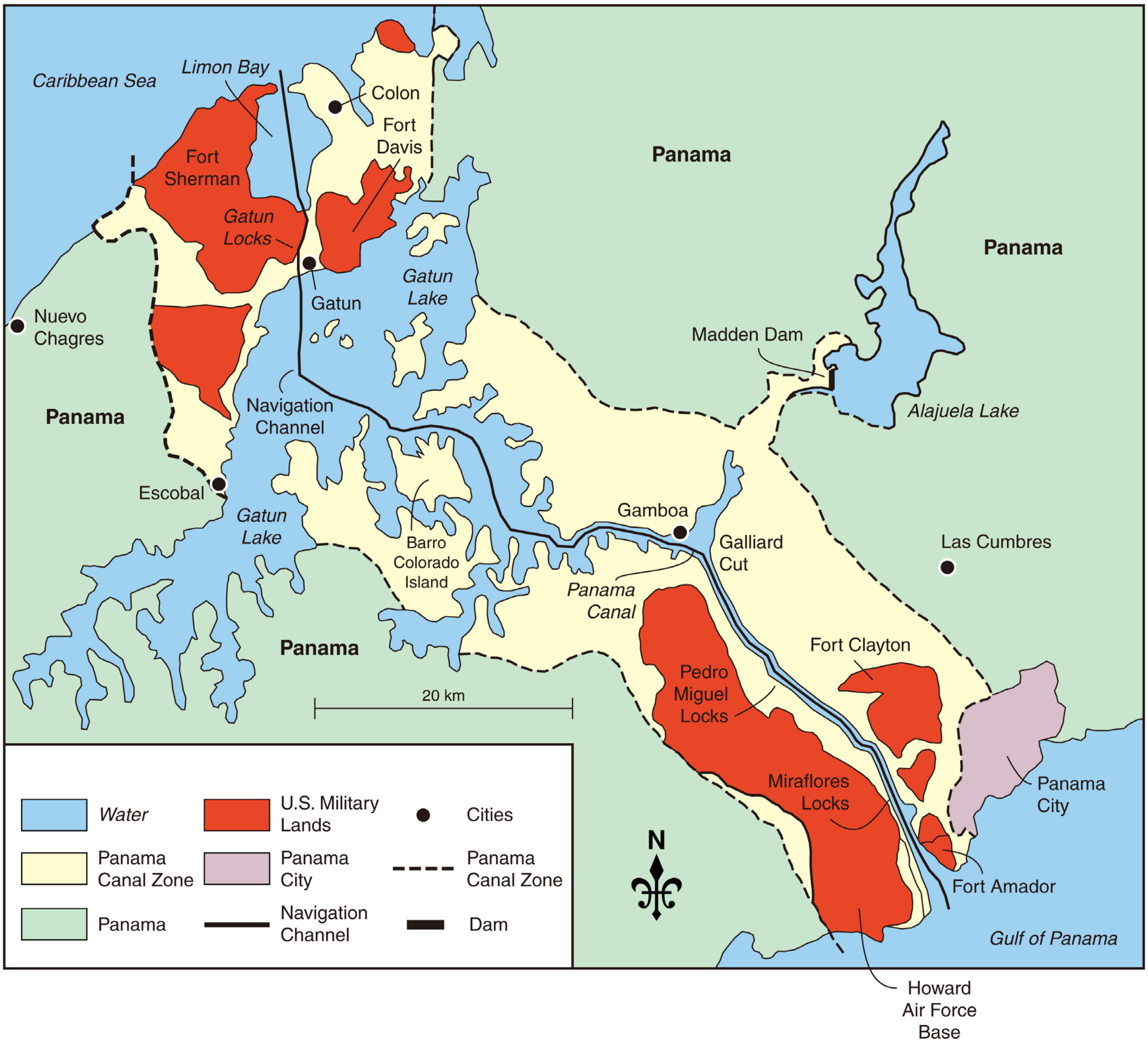

Figure 51. Panama Canal Zone map showing the Panama Canal, Lake Gatun, military bases and Panama City [13]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Figure 52. Perimeter fence at Davis-Monthan Air Force base in Arizona where the U.S. military planes go to die [21]. Published with the copyright permission from Editor of Open Journal of Soil Science.

Agent Blue, the arsenic-based herbicide, was not burned do concerns related to its high concentrations of arsenic [21]. If incineration at sea, arsenic can become arsine, a toxic gas, especially under reducing conditions. Thus, arsenic was not a good candidate for disposal at sea by incineration. The Agent Blue stored in Vietnam and at Johnston Island (**Figure 35**) were shipped to Davis-Monthan Air Force Base (**Figure 52**), where obsolete military planes are permanently stored. The grounds crew routinely sprayed Agent Blue along the perimeter fence and around the decommissioned airplanes to keep the weeds down and to dispose of the remaining Agent Blue stockpiles.

3.3.8. Disposal of Chemical Weapons Including Agent Blue at Kelly Air Force Base

A General Accounting Office (GAO) review of DOD and VA documents [28] identified multiple examples of incomplete and inaccurate information on the DOD's list of tactical herbicide test and storage sites such as Kelly Air Force Base in Texas. GAO obtained command histories and original DOD reports that provided operational details about the procurement, distribution, use, and disposition of Agent Orange [25] and its components, 2,4-D and 2,4,5-T containing unknown amount of dioxin TCDD [58] [59] [60] [61]. GAO concluded that there was extensive documentation on the herbicide management program at Kelly Air Force Base during the American Vietnam War and more specifically years 1966-1973. According to an Air Force Logistics Command's Office of History monograph, the command directly responsible for managing Agent Orange was the Directorate of Aerospace Fuels at the San Antonio Air Material Area located at Kelly Air Force base [28].

During the Vietnam War, Kelly Air Force base was also a subcomponent of the U.S. Air Force Logistics Command. GAO documentation shows that quantities of the two components of the tactical herbicide Agent Orange were stored at Kelly Air Force base in Texas in 1972. There were 38,940 gallons of 2,4,5-T containing and unknown amounts of TCDD and 106,260 gallons of 2,4-D stored on the base [28]. The uneven quantities of these two herbicides suggest that not all the tactical herbicides in storage were pre-mixed (50% 2,4-D: 50% 2,4,5-T) to form Agent Orange.

Was Agent Blue destroyed in Kelly Air Force base burn pits [28]? If so, the smoke coming from the burn pits could become an environmental problem since the particulate and ash would have contained toxic arsenic contaminants and aerosols. The military base personnel could have been exposed to and inhaled arsenic laden smoke. Was it buried in the soils at Kelly Air Force base? If so, the water soluble As would eventually leak from the barrels in the last 50 years and into the groundwater. If so, the military base personnel could have been exposed to arsenic and some Kelly Air Force Base Vietnam Era Veterans [51] have already filed VA claims for benefits because of exposure to either dioxin TCDD or arsenic [50]. The fourth option would have been to transport the Agent Blue to Davis-Monthan Air Force Base in Tucson, Arizona for weed control around the aircraft and perimeter fence. Agent Blue barrels were shipped from southern Vietnam directly and from Johnston Island indirectly [21] between 1972 and 1977. So how did the DOD use up or destroy all of the arsenic-based Agent Blue left over from the American Vietnam War, including the storage stockpile at Kelly Air Force base in Texas, after DOD stopped the spraying of all tactical herbicides in 1971?

3.3.9. Human Health Consequences of Tactical Herbicides: Lawsuit Involving Vietnam Veterans versus Eleven Chemical Companies

1) Agent Orange Dioxin TCDD Human Health Consequences

By 1953, the chemical companies, including BASF, had also discovered the dioxin TCDD health effects on workers after an explosion [58] but were slow to inform the U.S. Government and Military of the extent and magnitude of the dioxin TCDD contaminant in Agent Orange after the combustion temperature was raised 5˚C (9˚F) [3] [7]. Dioxin TCDD by-product was also in other tactical herbicides with associated risks to the environment and human health [10] [60]. This delay in notifying the U.S. Government and Military may have increased the 11 chemical companies' past, current, and future legal exposure [7]. By the late 1950s, the U.S. Government and Military became fully aware of the environmental and health consequences of the contaminant dioxin TCDD [58]-[63]. On April 15, 1970 the DOD announced that the use of Agent Orange was suspended. Two brigades of the Americal Division continued to use Agent Orange for crop destruction in violation of the suspension. The military officers were later disciplined. The defoliation and crop destruction was fully stopped on June 30, 1971 [25]. The DOD ordered all tactical to be removed from southern Vietnam. What happened to the stockpiles of tactical herbicides in Thailand, Laos and Korea? Were they also shipped to Johnson Island?

2) Impact of Agent Blue (Arsenic) on Human Health

Drinking water and consuming rice are considered the two major pathways to potentially high daily levels of arsenic intake [62]. Vietnamese military, farmers and civilians were at risk of arsenic exposure from contaminated groundwater supplies, long-term diets of daily rice with trace amounts of arsenic, and rice and vegetable crops produced in soil with significant arsenic concentrations. Water and food supplies were critical to U.S. and South Vietnamese military and Vietnamese civilians during the Vietnam War.

Arsenic toxicity and health effects are complex and the impact of Agent Blue on human health was not well known for many years. Post-Vietnam War, arsenic-based industrial wood preservatives and herbicides with cacodylic acid were used throughout the U.S. in wood products, golf course management, cotton fields and drying out agricultural plants prior to harvesting [9]. Today, none of these herbicides is commercially available with the exception of the weed killer monosodium meta-arsonate (MSMA) for use on U.S. cotton [9]. The frequent use of manufactured arsenic products in industry and agriculture has resulted in human exposure by way of inhalation, contaminated drinking water, and food.

Epidemiological evidence and animal studies show excessive risks of lung and skin cancers as well as delayed health effects at relatively high exposure rates [21] [60].

The spraying of arsenic-based Agent Blue was field tested in United States, Puerto Rico, Canada and Thailand. Often, Agent Blue was used at full strength during the Vietnam War. The Cancer Assessment Group of EPA currently puts arsenic in the top category of cancer-causing chemicals. Arsenic, even at low doses has been found to be responsible for lung, bladder, and liver cancer, and arsenic is able to cross the placenta to create cancers in the fetus as well. Both birth defects and childhood cancers have been linked to arsenic. The effects of arsenic are delayed and can take decades to appear in humans [45]. Arsenic can cause damage to human DNA, which can adversely affect future offspring. Arsenical herbicides containing cacodylic acid as active ingredients are still used today as weed killers and crop desiccants. Less toxic formations of arsenical herbicides sold over the counter today can cause headaches, vomiting, dizziness, profuse and watery diarrhea, followed by dehydration, electrolyte imbalance, and gradual fall in blood pressure, convulsions, stupor, general paralysis, and possible death in 3 to 14 days [62] [63].

The New Jersey Department of Health and the EPA regard sodium cacodylate as a Special Health Hazard. The Agency for Toxic Substances and Disease Registry suggests, "Arsenic cannot be destroyed once added to the environment". Therefore, the arsenic amounts (1,232,400 kg of arsenic) U.S. and Republic of Vietnam militaries added when spraying Agent Blue during the Vietnam War, have increased the arsenic load in Mekong Delta and southern Vietnam environment. Arsenic caused additional health effects in humans and animals. Water-soluble arsenic can get into the surface water, soil, and groundwater from applications of Agent Blue on the rice paddies. After the Vietnam War vast amounts of arsenic laced groundwater was pumped to the surface for rice paddies, shrimp ponds and for the water needs of the 15 million people living on the Mekong Delta.

3) Human Health Consequences

On January 8, 1979 Victor J. Yannacone, filed a class action suit, re Agent Orange Product Liability Litigation (1979-1984) on behalf of all the Vietnam veterans that were exposed to Agent Orange containing dioxin and other tactical herbicides. By the end of the year, Yannacone and associates represented 8300 Vietnam veteran clients in a lawsuit against 11 chemical companies including: Dow Chemical, Thompson-Hayward, Diamond Shamrock, Hercules Inc., Monsanto, Ansul Company (the manufacturer of Agent Blue), Riverdale Chemical Company, Uniroyal, Occidental Petroleum, Hooker Chemical Company and N.A. Phillips [3].

The chemical companies argued in federal court that the U.S. government was responsible for the injuries claimed by the veterans and their families. In addition, the companies argued that the government controlled the manufacturing, distribution, and application of Agent Orange (and other tactical herbicides including Agent Blue), some of which included dioxin (TCDD) although military contracts were thought to protect the chemical companies. The U.S. Government having sovereign immunity was eventually dismissed from the case [21].

In May 1984, the Vietnam War Veterans and chemical manufactures settled out of court for $180 million. These chemical companies could then renounce liability even though they knew about the toxic effects of by-product dioxin (or TCDD) [16]. However, the effects of arsenic were not addressed or its affects were combined with dioxin TCDD. Raising the heating temperature during the manufacture of Agent Orange to accelerate chemical reactions during the manufacturing process increased the dioxin TCDD levels up to 3000 times of commercial production thereby magnifying the toxicity of Agent Orange [13].

Although the manufacturing process for Agent Blue was different, this did not affect the inherent toxicity of arsenic by itself. Many of the 52,000 Vietnam Veterans were dissatisfied with the amount of the settlement ($3800.00/veteran or the family). The judge ruled the out of court settlement was fair. The funds were dispensed by 1997. After the settlement, the U.S. Government established an Endocrine Disruptor Screening Program to test industrial and agricultural chemicals for endocrine effects prior to marketing and use. The goal was to prevent future unanticipated consequences of the use of a new chemical or herbicide [7].

The Agent Orange Product Liability Litigation (1979-1984) records retained by the New Jersey State Council, Vietnam Veterans of America, Inc. were transferred in 1000 legal boxes to the Vietnam Center and Archive (VNCA) at Texas Tech University (*personal communication from Executive Director Stephen Maxner*) and are of immense importance to furthering understanding of how tactical herbicides with dioxin (TCDD) and Agent Blue with arsenic were manufactured and deployed during the Vietnam War. This specific collection is unique as it represents the years of document and material collection in preparation for the landmark, "Agent Orange" legal action with regard to its contamination with dioxin and could include information and records about other tactical herbicides including Agent Blue.

The resulting out-of-court settlement was of crucial importance in providing countless Vietnam veterans, and their families, exposed to dioxin and perhaps arsenic with much needed financial support and restitution. The settlement also resulted in the temporary storage of nearly 1000 boxes of materials that provide detailed information regarding the eleven chemical manufacturers involved in tactical herbicide production and also included Ansul Chemical Company, which manufactured Agent Blue [21]. These documents are the most comprehensive collection of military and government historical documents detailing the use and storage of Agent Orange and other potentially dioxin contaminated tactical herbicide defoliants and/or arsenic based herbicide (Agent Blue) throughout the entire Vietnam War.

The Vietnam Center and Sam Johnson Archive submitted proposals in 2019 and 2020 (to National Academy of Humanities) to electronically scan the hundreds of thousands of documents. The collection will undoubtedly provide additional details pertinent to ongoing environmental and human health studies of tactical herbicide remediation programs in Vietnam, Thailand, Korea, and the United States including various storage facilities on wartime military bases as well as U.S. chemical manufacturing sites, such as Newark, New Jersey; Marinette, Wisconsin; and Menominee, Michigan.

Ansul and other chemical companies were named as defendants in a 2005 lawsuit alleging that the use of the tactical herbicides by the U.S. military led to serious birth defects for Vietnamese children (**Figure 53**) and (**Figure 54**) and perhaps the U.S. military Vietnam veterans' children. The United States District Court for the Eastern District of New York ruled that the eleven defending companies were manufacturing tactical herbicides under the direct order of three Presidents of the United States and could not be sued for the consequences of the use of their herbicide products [21]. The court also ruled that the British had previously used Agent Orange (with the by-product dioxin TCDD) during the 1950s Malayan Emergency and that they set the precedent for America's use in the Vietnam War.

Figure 53. Congenital heart failure in the offspring of a Vietnamese whose parents were exposed to dioxin. Credit line: Courtesy of the Virginia-Pilot, Pro Publica, Oct 26, 2016.

Figure 54. Four children or grandchildren of Vietnamese parents who were exposed to dioxin TCDD or arsenic during the Vietnam War. Photo credit: Picture taken by Ash Annand, Newsmado. Courtesy of the Courier Mail, Brisbane, Australia.

4. Summary and Conclusions

Dr. Ezra Kraus was the father of the development of agricultural herbicides as a military and environmental chemical weapon. Dr. Kraus a plant physiologist and Head of the Department of Botany at the University of Chicago suggested on the eve of WWII that weed killers had significant military value as chemical weapons. This gave him the notoriety of being first to recognize the modern military value of herbicides even before the U.S. military officers. Professor Dr. Arthur W. Galston (Yale), said in later interviews that few scientists who were engaged in biological and chemical warfare projects placed their moral qualms, if any, above the application of scientific knowledge towards destructive military ends in part because of their own sense of national duty to win the "good war". The only exception during WWII was when some nuclear scientists tried to prevent the nuclear attack on Japan. However, there is no known evidence available that suggests that civilian and military scientists working on a WWII top-secret herbicide weapons program had any such moral qualms.

Before the herbicide weapons program was ready to be deployed on Japan's food supply, rice, and their island forests (jungles), WWII ended abruptly after United States military use of two atomic bombs. However, after WWII the military scientists at Camp Detrick continued development of tactical herbicides including Agent Orange and Agent Blue. These tactical herbicides weapons were not used during the Korean War. However, they were used by the U.S. military during the Vietnam War from 1961 to 1971. By 1964, U.S. scientists, with moral and environmental concerns led by Dr. Galston (Yale, Cal Tech, and University of Illinois) tried to stop the U.S. Government and Military deploying the use of tactical herbicide (chemical) weapons in South Vietnam during the Vietnam War. The scientist movement and protest was one of many factors that merged and resulted in DOD ordering the military to stop the spraying of Agent Orange in 1970 and the other five tactical herbicides in 1971.

After the American-European War, the U.S. military considered tactical herbicides to be a strategic necessity as a deterrent in future conflicts and wanted to keep this chemical weapon in their arsenal. This issue was not settled until 1975 when President Ford renounced "first" use concept and said the United States would not be the first nation to use herbicides in war, effectively banning any United States use of chemical (herbicide) weapons in any future conflicts or wars.

How did agricultural herbicides become military and environmental chemical weapons? It was started in secret at the University of Chicago on the eve of WWII. The secrecy (the U.S. Government and Military were fully aware of the military and environmental chemical weapons program but the public was not) continued during WWII. The funding of research on synthetic herbicides was tightly controlled and research work required total secrecy or it would not be funded since it was conducted during the dark days of WWII. Even the scientific literature was monitored to prevent the disclosure of the secret herbicide weapons program information. This program secrecy was maintained even after WWII. Many scientists and the public are still not aware of this secret WWII chemical weapons program. During WWII, the Office of Strategic Services (OSS) field test site was an area later called Camp Detrick in Maryland. The research was expanded from insecticides to herbicides with experiments on the Beltsville Agricultural Experiment Station (USDA). Even the name of the site (apparently first used by the OSS for research and testing of chemicals) was not identified until 1952 and was later renamed Fort Detrick in 1957 as the program expanded. After WWII ended in 1946 the Camp Detrick military scientists did not stop their chemical weapons research. Research continued in secret. The public was not even aware of the biological weapons program until at least 1957.

The Camp Detrick tactical herbicides were ready for use during the Korea War but were not used since U.S. did not want to be the first country to use herbicide weapons. The "honor" went to British during the Malaysia Conflict. After that President Kennedy and staff, not wanting to be charged in the World Court with War crimes after the Vietnam War continued to label tactical herbicides as herbicide weapons even though the synthetic herbicides were clearly chemical weapons. During the Vietnam War the military and USDA maintained that herbicides only harmed plants and were harmless to animals and humans. This was never true but provided additional cover for the secret herbicide (chemical) weapons program. The United States was at war and wanted additional weapons in its arsenal as a deterrent. Clearly, the national security issues overrode any potential environmental or human health concerns of the Vietnamese or even our own Vietnam Era veterans. Since 1977 Veterans have been making benefit claims related to their symptoms believed to be from exposure to dioxin TCDD and arsenic.

GAO documentation shows that quantities of the two components of the tactical herbicide Agent Orange were stored at Kelly Air Force Base in Texas in

1972. There were 38,940 gallons of 2,4,5-T containing TCDD and 106,260 gallons of 2,4-D stored on the base. Apparently all of the Agent Orange and components, 2,4-D and 2,4,5-T with an unknown amount of dioxin TCDD was transferred in the early 1970s to the USDA, Forest Service to be sprayed on clear-cut public forest areas to kill broad leaf weeds and shrubs to increase the survival of recently planted trees in the Western United States forests. GAO records show that approximately 173,910 gallons of the tactical herbicide Agent Blue containing cacodylic Acid (arsenic) was also stored at Kelly Air Force base. The fate of this massive amount of Agent Blue, an arsenic based herbicide, is not publically known at this time. It mostly likely was transferred along with Agent Orange and components to the USDA, Forest Service for grass and narrow leaf weed control on recently clear-cut and re-planted public forests. Unfortunately, arsenic has no half-life and if used would still remains in the Western United States forested landscape. Was it sprayed along with Agent Orange and components by the USDA, Forest Service for grass and narrow leaf weed control on recently clear-cut and re-planted public forests? If Agent Blue, which has no half-life, was sprayed its arsenic residual would still remain in the Western United States forested landscape".

Most Vietnam Veteran lawsuits have been filed in the United States court system where the U.S. Government has been given immunity by the U.S. court system; and in some cases the chemical companies were sued instead. A settlement did occur with 52,000 Vietnam Era veterans or their families if deceased received an average of $3800.00. In a Korea lawsuit the international world court system has ruled against the United States Government and provided compensation, to 5800 Korean soldiers and their families, who served at the DMZ in South Korea were exposed to dioxin TCDD at the border fence during the Vietnam time period [3]. In 2020, a Vietnamese woman who had become a French citizen, filed a suit in a French Court against the United States Government and the international chemical companies including Bayer (Monsanto) a Germany company. She requested benefits for treatment of her health problems associated with past exposure to dioxin TCDD during the Vietnam War. The French court, in 2021, initially ruled in favor of Bayer (Monsanto) but the case is currently under appeal.

Many unanswered questions remain about the persistence of herbicides with dioxin TCDD and arsenic in soil, sediments and water environments and present-day human health and generational effects that are legacies of the herbicides previously used as military and environmental chemical weapons.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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