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Long-Term Fate of Agent Orange and Dioxin TCDD Contaminated Soils and Sediments in Vietnam Hotspots

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Abstract

The soils, tropical climate, and network of canals and rivers of southern Vietnam have created one of the most diverse tropical jungles and intensely cultivated landscapes of Southeast Asia. This paradise has a long history of numerous wars, foreign occupations, and most recently the Second Indochina War (aka the Vietnam War 1965-1972) which defoliated rain forests and ancient wetland mangroves and left behind contaminated soil and sediment hotspots. During this war, the United States (US) military sprayed 80 million liters of Agent Orange contaminated with the dioxin TCDD in a guerrilla war against communist insurgents. Agent Orange was a synthetic plant growth regulator comprised of equal amounts of two herbicides 2,4-dichloro phenoxyacetic 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, the dioxin, 2,3,7,8-tetrachlorodibenzodioxin ($C_{12}H_4Cl_4O_2$) was an unintended byproduct of the accelerated combustion process used in the manufacture of herbicides containing 2,4,5-T. Agent Orange has frequently been blamed for soil and sediment contamination and long-term human health problems; however, the true source of harm is the dioxin TCDD. Agent Orange has a short half-life of days and weeks after application to vegetation, and has not been found to persist, after 50 years, in the water or soils of southern Vietnam. However, the half-life of dioxin TCDD depends on where it is deposited and varies from 1 to 3 years on soil surfaces that have been fully exposed to sunlight, to as long as 20 to 50 years or more when buried in tropical subsoils, and more than 100 years in river and sea sediments. Dioxin TCDD was heavily concentrated in the US Air Force bases in Vietnam where the herbicides were stored, loaded on planes and helicopters for aerial spraying, and used extensively around military base perimeter fences as a security measure to prevent surprise attacks. Bien Hoa Air Force base, 40 km northeast of Ho Chi Minh City, continues to be one of the mega-hotspots where after 48 years the dioxin TCDD levels in fish and shrimp are still high and fishing is banned in ponds and lakes adjacent to the airbase. Although expensive, one of the most effective remediation to dioxin TCDD contaminated soils is incineration which is the recommended method of dioxin TCDD disposal.

Keywords

Soils of Vietnam, Agent Orange, Dioxin, TCDD, Herbicides, Soil Contaminant, Sediment Contaminant, Half-Life, Hotspots, Operation Ranch Hand, US Airbases in Vietnam, Vietnam War, Cu Chi Soil Tunnels, Guerilla Warfare, Incineration

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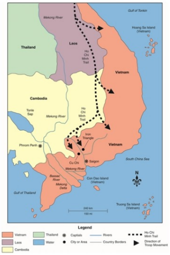
Vietnam Hotspots. *Open Journal of Soil Science*, **9**, 1-34. doi: 10.4236/ojss.2019.91001.

1. Introduction

The United States (US) fought the Second Indochina War aka the Vietnam War (1965 to 1972) in the jungles of the Republic of Vietnam (South Vietnam) (Figure 1). Guerilla warfare in the unfamiliar Mekong River delta wetlands, grasslands, and upland tropical forests of the Annamite Range was deadly to US soldiers and the military bases they established. Two herbicides, 2,4-dichloro phenoxyacetic acid $C_8H_6Cl_2O_3$(2,4-D) and 2,4,5-trichlorophenoxyacetic acid $C_8H_5Cl_3O_3$(2,4,5-T), and the dioxin, 2,3,7,8-tetrachlorodibenzodioxin $C_{12}H_4Cl_4O_2$(TCDD), a byproduct of the accelerated combustion process used in the manufacture of 2,4,5-T, were sprayed on jungle forests, along river banks, and on selected agricultural crops. The defoliation of the South Vietnamese landscape (Figure 2) was intended to destroy the jungle vegetation to reveal enemy hiding places, protect perimeter approaches to military bases (Figure 3), and destroy the food supply of opposing troops [1] [2]. The strategy had intended and unintended consequences on South Vietnam soils and sediments, agricultural and forested landscapes, civilian populations, and US, South, and North Vietnamese military personnel.

There were short-term, immediate-term and in some cases persistent long-term impacts of these herbicides and contaminates on Vietnam's soil, water, and sediment resources, dioxin bioaccumulation and magnification within the food chain, and human health consequences. Systematic investments in medical and environmental research on these impacts are beginning to increase understanding of effects to the Vietnamese landscape. More than fifty years later a number of natural resource questions linger: do any of these chemicals continue to persist in the Vietnam soils, waters and sediments, and do they pose a modern day threat? To what extent have the forested landscapes of the steep Ho Chi Minh mountain trail, the Cu Chi and Iron Triangle soil tunnels, and former military bases recovered? Some defoliated forests such as the U Minh mangrove forests of the Ca Mau peninsula are long-lived when healthy but fragile. They have been slow to regenerate as increased settlement, agriculture, and coastal climate change pressures compound their already compromised vulnerability. The dioxin



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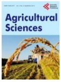

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Figure 1. The Ho Chi Minh Trail through the mountains and jungles of Vietnam, Laos and Cambodia was a system of trails and paths controlled by the Democratic Republic of Vietnam (1959-1975) used for transporting food, military equipment and North Vietnamese soldiers into southern Vietnam during the Vietnam War. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2017, 7:34-51.

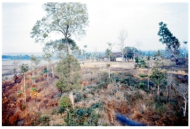

Figure 2. Agent Orange and other color-coded herbicides were sprayed by low flying planes over the Vietnam jungle and rural landscapes. Most these herbicides had short-half lives of hours, days and a few weeks; and vegetation regrowth required additional applications. Picture taken by US Army Flight Operations Specialist 4 John Crivello in 1969.

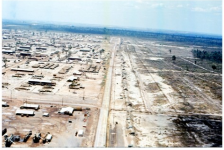

Figure 3. US military bases used herbicides to defoliate the base perimeter as a security measure to protect against surprise attacks. Picture taken by US Army Flight Operations Specialist 4 John Crivello in 1969.

TCDD, known to have a longer half-life than the herbicides it contaminated, accumulates in the fat of animals and humans, becoming a dozen times more concentrated (biomagnification) as it moves up the food chain [1]. Where are the dioxin TCDD hotspots, that is, places where large amounts of TCDD continue to be concentrated in southern Vietnam's soils, water sediments and wetland plants and bioaccumulate in fish, the main staple of Vietnamese diets (Figure 4)? And what are the alternatives to remediation of airbase mega hotspots?

In this paper, Vietnam's climate, vegetation, soils, river deltas and wetlands, and upland topography are first discussed to frame the context in which the jungle war was fought with defoliants and bombs. Then the characteristics, use, and longevity of the color-coded herbicides, including Agent Orange with the contaminant, dioxin TCDD used by the US military are presented. The results section elaborates the application and fate of these herbicides in the soils and wetland sediments, the unintended consequences of TCDD, short-term and geographic persistence in the soil, and remediation alternatives. Some Air Force bases in Thailand and Vietnam continue to be dioxin contaminated soil and sediment hotspots. As a result of water and wind action, runoff, soil erosion, transport and deposition, these hotspots are spreading beyond airbase perimeter fences and into adjacent lakes, rivers and ponds. Local Vietnamese living in nearby cities breathe the contaminated dust, cultivate dioxin contaminated soil which can be adsorbed by their skin, and still eat bottom feeding fish and mollusk harvested from lakes adjacent to the hotspots. The Vietnamese Government retains, after 48 years, a fishing ban in lakes adjacent to the remaining airbase hotspots. However, the contaminant dioxin continues to be found in the local food supply. Incineration of contaminated soils and sediments appears to be expensive, but is the most effective alternative remediation treatment for removing dioxin TCDD from the Vietnam landscape.

Figure 4. Fish (pisces) is a main source of protein and income for SE Asia families. Fish and aquatic animals feeding on dioxin-contaminated sediments in rivers and lakes near former military airbases have been found to have trace amounts of the dioxin TCDD 48 years later.

2. Vietnam's Landscape: Climate, Vegetation, Soils, and Rivers

Vietnam is a small country in Southeast (SE) Asia located in "one of those coveted parts of the world where the 'great powers' repeatedly collide" ([2], p. 1). An elongated "S" shaped country with nearly 1400 km of coastland along the South China Sea and 260 km on the Gulf of Thailand (Figure 1), it has spawned ancient civilizations, drawn competing warships seeking power and been a coveted gateway to trade with the Indian Ocean and beyond. Its 1100 km long and narrow (less than 210 km wide) topography extends from the Annamite Mountains over 1500 m high shared with the country of Laos to steep foothills, plateaus and valleys to alluvial plains that drop to barely meters above sea level at the coast [3] [4]. A rudimentary understanding of Vietnam's climate, vegetation, soils, rivers and sediment flows helps to grasp why the US military identified the SE Asia jungle as a "problem" and created a defoliation "solution" that impacted Vietnam's soils, sediments, natural resource base, and people.

2.1. Climate

Like much of SE Asia, southern Vietnam has a tropical monsoon climate. Prevailing winds pick up moisture from the Indian Ocean and drop heavy rains on the Mekong River Delta and upriver tributaries as they encounter the uplands of Vietnam and Laos during the summer monsoon season (May-August). The dry season begins in November and runs through March. The average temperature along the Ca Mau Peninsula and inland lowland plains ranges from 24˚C to 30˚C with high humidity during the summer wet-season. The southwest monsoon brings an average annual rainfall of 1 m to 3 m. The plateaus and mountain foothills are cooler and heavy rainfall in excess of 4 m results in a high soil erosion index. The winter monsoon (October-January) from the northeast impacts northern Vietnam and Hanoi. The monsoonal winds and typhoons produce large waves and powerful currents that erode and redistribute sediments and Vietnam coastal lands.

2.2. Vegetation

Vietnam's tropical climate produces diverse ecological systems that support a mosaic of vegetation-wild and cultivated, reflecting the Mekong and Red rivers' sediment-rich deltas, salt marshes and wetlands, coastal plains, uplands and plateaus of the Annamite Mountain Range. Guerrilla warfare was fought in the jungles of southern Vietnam, primarily south of the 17th Parallel demarcation line separating the Republic of Vietnam in the south from the Hanoi-based

Democratic Republic of Vietnam in the north. Wild vegetation consists of four distinct types influenced by geographic variations in soils, hydrology, micro-climates and topography [1] [4]. The tropical rain forest has a triple canopy of more than 500 plant species per hectare and the vegetation creates a density that sunlight doesn't easily penetrate (Figure 5). A second type of vegetation is the seasonal forest that contains hardwood trees that naturally lose their leaves in the winter dry season and has fewer types of understory vegetation making it less dense than the tropical rain forest. Mangroves, ancient wetland forests that grow along shorelines and marshes with unique wetland plants understory are a third type of vegetation. Lastly, tropical scrub vegetation consists of short woody shrubs, grasses, vines, bamboo and other plants that grow in poor soils (Figure 6 and Figure 7).

Figure 5. The dense tropical forests of the Annamite Mountains created ideal conditions for surprise attacks by North Vietnam guerrilla soldiers.

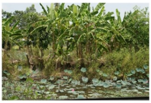

Figure 6. In the Mekong Delta the roots of banana and other exotic fruit trees on river banks slow bank erosion and grow a meter or two above water lilies, hyacinths, cresses and other wetland vegetation.

Figure 7. Bamboo (Bambuseae Poaceae), classified as a perennial evergreen grass, is fast growing and abundant throughout the warm, moist tropical climate and alluvial soils of SE Asia.

Rice and fish, sources of food and economic security, are the dominate food crops of Vietnam. The cultivation of rice, a type of grass (Figure 8), spread to Vietnam's Red and Mekong river deltas and plains from northern China about 3000 BCE [2]. With the development of dikes and canals, intensive rice production (Figure 9) expanded to support an increasing population and was (and still is) a primary source of export revenue [4] [5]. Along with rice, the central delta area and lands along fresh water rivers produce a wide variety of exotic tropical fruits and vegetables (Figure 10). Coffee, tea, and rubber trees have been grown for centuries in the highlands and mountain slopes and are important economic exports.

2.3. Soils

The seven major soil areas (Figure 11) of Vietnam were formed in SE Asia's humid tropical climate under alternating wet and dry periods and high tropical temperatures [6]. Ultisols, formed by intense weathering and leaching processes dominate the humid Central Highlands. Consisting of quartz, kaolinite and iron oxides in a clay-enriched subsoil [7] these low fertility acidic soils are only a few centimeters thick. Inceptisols are found in Vietnam valleys and low-lying coastal regions including river deltas that flow into the Gulf of Thailand and the South China Sea. Derived from fluvial sediment deposits they exhibit very little accumulation of clay or iron and aluminum oxides. Entisols formed under extreme wet or dry conditions occur in Vietnam river flood plains, coastal dunes, and steep slopes where erosion and deposition rates are faster than the rate of soil development. Oxisols and Ultisols developed in former floodplain deposits when the South China Sea covered a portion of Vietnam millions of years ago; and Old Alluvium soils are at a 10 m higher elevation than the Mekong Delta [3]. These highly weathered, ferric soils provided the material for tunnel building (Figure 12) used for housing and guerilla warfare against colonial occupiers and more recently against the US during the Vietnam War [3].

Figure 8. Rice (Oryza), a grass grown for its grain, throughout Vietnam has a long history as a main food staple and key agricultural export. Agent Blue herbicide used to kill rice crops and grasses immediately had no TCDD contaminate and did not persist and contaminate the soil.

Figure 9. A major rice growing region, the Vinh Te Canal in 2016 runs along the Vietnam-Cambodia border. The mountains to the north were used by the National Liberation Front as military bases to conduct guerilla warfare.

Figure 10. Vietnam's soils and tropical climate are well suited to a vast array of exotic fruits and vegetables.

Figure 11. 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; Rome, 1964. Adapted from Moormann (1961). Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2017, 7:34-51.

Figure 12. The Cu Chi and Iron Triangle tunnels were constructed in Old Aluvium soils which had high concentrations of ferric oxides and clays. Reprinted with permission from Open Journal of Soil Science 2017, 7:34-51.

2.4. Rivers, Wetlands, Marshes and Coastal Landscapes

The Mekong River watershed is the major river system in southern Vietnam. The Mekong at 4350 km long flows from sources in the Chinese Tibetan plateau. The river discharges 475 km^3 of water annually from a 795,000 km^2 watershed and into the Mekong Delta region to the South China Sea. Hordoir et al. [8] estimated the coastal water flows of the Mekong Delta to produce an offshore plume to be 5 - 10 m deep based on a modified Princeton Ocean Model [9]. The width of the plume is estimated to be 37 to 93 km off the southernmost point of the delta with the freshwater influence extending far offshore from the mouth of the Mekong Delta.

Southwestern Vietnam is 40,000 km^2 of complex alluvial deltas formed by two mainstem rivers, the Bassac and Mekong and their tributaries that flow to the South China Sea [4]. Although roads are few in this wetland landscape of fresh and salt water rivers and canals, sand dunes, rice paddies, wild vegetation and settlements on leveed river channels, an extensive fluvial transportation system creates a vibrant river economy (Figure 13). The Chinese, French, Japanese, Russians, British, Americans and Vietnamese throughout Vietnam's history used longboats, barges and a variety of other vessels to move rice, animals, civilians and troops throughout the delta region [2]. The French in the 1930s improved existing dikes and polders to increase rice production; and constructed 4000 km of new canals to improve rice field irrigation and expand the transportation network deep within the delta and connect it to main stem rivers and the seas (Figure 14) [2]. Rice and rubber trade by the end of 1930s made Saigon-Cholon France's sixth most important port [2].

Figure 13. The Mekong River and its extensive tributaries throughout the Vietnam Delta are the primary "roads" for moving rice, agricultural and manufactured products in 2016; during the Vietnam War they were used to transport military troops and US Navy boats spraying herbicides to defoliate river banks.

Figure 14. 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. Reprinted with permission from Journal of Soil and Water Conservation 2018, 73:4:83A-89A.

The coastal region of the Ca Mau Peninsula and the Mekong and Bassac delta mouths are only a meter or two above sea level and subject to frequent flooding from monsoon rains, upland run-off, river bank overflows and salt water intrusions from coastal wave action [5]. During the dry season, coastal tidal forces control river flows and direction. Dense mangrove forests and peat swamps are found along the coastline (Figure 15). The U Minh Forest was one of the most famous refuges for Vietnamese nationalists fleeing the French secret police, a sanctuary for Communist Party cells, and the site of the Viet Minh's Ninth Military Region headquarters [10].

Figure 15. 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 Seas 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.

American military bases Cu Chi (Figure 16) and Bien Hoa were located in the upper delta on higher ground near Ho Chi Minh City (formerly Saigon) on the Saigon River. Nearby, the rugged, steep Annamite Mountains rise to the east by northeast and contact with the delta lowlands is marked by alluvial fans and isolated rock outcrops [11]. The southern slopes of this range are exposed to tropical cyclones as well as the seasonal heavy rains of the southwestern monsoon making the steep forested slopes highly vulnerable to erosion and landslides. Here, in 1959 the Vietnamese Workers Party began extending the network of overland paths known as the Ho Chi Minh Trail (Figure 1) through the mountains southward from Hanoi and eastern Laos, through the Central Highlands and eastern Cambodia in order to control Vietnam's western border with Lao [2]. This mountain trail below the 17th Parallel became the Communist supply line into southern Vietnam used to move troops, obtain intelligence, arm and feed their rice-consuming troops. The defoliation of the Ho Chi Minh Trail destroyed the jungle canopy and was intended to improve US detection and bomb targeting of mountainous paths [2].

3. Color-Coded Herbicides

Plant hormones regulate the growth and development of plant cells, influencing the characteristics of roots, shoots, leaves, flower and fruiting from seed to maturity and death. Herbicides mimic these botanical hormones by chemically messaging the plant to abnormally accelerate and grow itself to death [1] [12]. Herbicide hormones are synthesized in the stem and roots and transported throughout the plant resulting in root and stem swelling, leaf chlorosis and abnormal leaf forms, chloroplast destruction and membrane disruption followed by necrosis [13].

Figure 16. The heavily forested Cu Chi and Iron Triangle jungles were frequently sprayed by US military with herbicides to expose tunnel entrances and North Vietnamese guerillas. Map by Mic Greenberg. Reprinted with permission from Open Journal of Soil Science 2017, 7:34-51.

3.1. Agent Orange and Other Color-Coded Herbicides

Scientists during World War II experimented with a variety of chemical compounds that had potential to destroy Japanese and German food crops by defoliation. Ultimately, none of the herbicides were used in combat and experimental findings were publicly released post-war including the formulations of 2,4-D and 2,4,5-T [1]. The agricultural chemical industry quickly realized their value in controlling weeds in agricultural fields and commercialized them. Today herbicides are labeled and widely used in modern agriculture from large-scale food crop production to turf and lawn management and small-scale gardening.

Herbicides used by the US military in the Vietnam War were sprayed full strength without dilution at more than double normal commercially labeled rates [1]. In fact, the 208 liter barrels that arrived at South Vietnam air bases were not labeled for use or with application rates but instead had color-coded strips designating the content of the chemical compound: Agent Purple, Agent Green, Agent Pink, Agent White, Agent Blue and Agent Orange [1]. Agents Purple, Pink, Green and Orange consisted in part of 2,4,5-T and various amounts of the contaminant dioxin TCDD from the herbicide manufacturing process. These defoliants were effective on broadleaf vegetation such as forest tree leaves, fruit trees, root crops, melons, soybeans, and cabbage. Agent Blue was used specifically on rice fields as it was a contact desiccant that killed rice and grasses within hours. It did not contain the dioxin TCDD contaminate. Agent White (aka the agricultural herbicide Tordon) persisted in the soil up to 19 months, five times as long as the herbicides with 2,4,5-T and was used sparingly. It was primarily used in forest and understory defoliation since it was too persistent in the soil and would suppress crop growth for several seasons [1].

Agent Purple was a patented mix of 50% butyl D and 50% butyl T with the T component including butyl and isobutyl esters. However, the most commonly used herbicide was Agent Orange, a synthetic growth regulator consisting of equal amounts of two herbicides 2,4-D (Dichlorophenoxyacetic acid) and 2,4,5-T (Trichlorophenoxyacetic acid). Although similar in formulation to Agent Purple, Agent Orange had no patent restrictions and was less expensive than the other color-coded herbicides. It was used extensively across the rural Vietnamese landscape on broadleaf trees, bamboo and shrubs as well as food crops such as peanuts, taro, manioc, yams and other root crops, fruit trees, cabbage and melons [1] [14]. About 39.4 million liters were sprayed over the course of the war. Agent Orange had a short half-life and quickly degraded, remaining toxic for only a short period, days or a few weeks at most. Thus, repeat applications were needed as tropical vegetation quickly regrew. Unfortunately, Agent Orange and the defoliants with 2,3,5-T in their formulations had an unanticipated by-product or contaminant in them, the dioxin 2,3,7,8-Tetrachlorodibenzodioxin (TCDD) which had a very long half-life and did not easily degrade.

3.2. Dioxin TCDD

The term dioxin represents a class of about 300 chemicals which are formed (usually unintentionally) when chlorine at very high temperatures binds to a molecule that contains carbon (C) such as in the bleaching of paper/pulp and chemical manufacturing processes [1]. As the US military demanded greater quantities of Agents purple and orange, the manufacturing processes were speeded up by raising the temperature. A 3% increase in temperature or about 5 degrees centigrade increased the byproduct dioxin 2,3,7,8-Tetrachlorodibenzodioxin (TCDD) in the waste stream about three thousand times (between 6 and 10 thousand ppm). The average concentration of dioxin in each batch of 2,3,5-T herbicide was about 2 - 3 ppm but the range ran from 0.05 ppm to almost 50 ppm [1]. Many batches of Agents purple, pink and green had more dioxin than Agent Orange.

TCDD is the most toxic of all the dioxins and dioxin-like compounds [15]. The US National Academy of Sciences estimated between 110 and 180 kilograms of TCDD were released into South Vietnam as part of the Vietnam War defoliation project [1] [2]. The International Agency for the Research on Cancer and the US National Toxicology Program (NTP) both listed dioxin and TCDD as known human carcinogens. Dioxins are endocrine disrupters and can cause certain cancers, chloracne, and reproductive and developmental effects [16]. Although TCDD is not absorbed by plants nor is it water soluble, it can adhere to leaf surfaces, fine soil particles, organic materials and sediments that can be carried by runoff into downstream waters and deposited in ponds, wetlands and lakes. In this way, TCDD bioaccumulates in aquatic species and can become biomagnified throughout the food chain via mollusks, fish and fowl eaten by other animals and humans.

4. Results and Discussion

In 1961, US President J. F. Kennedy approved a counter insurgency strategy for South Vietnam and the US Department of Defense initiated a program to develop military herbicides 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 US troops in southern 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 [3]. US planes and helicopters sprayed Agent Orange and other herbicides over the Ho Chi Minh Trail jungle canopy in search and destroy missions to expose and bomb enemy forces (Figure 1). After the 1968 Tet Offensive the Cu Chi and Iron Triangle agricultural and forested areas (Figure 16) were defoliated and became a free strike zone [3]. 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'" ([2], p. 326).

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 used on both sides of perimeter fences of US military bases to ensure visibility and alert base security of pending raids and sabotage (Figure 17). US military personnel were unintentionally exposed to some of the greatest concentration of herbicides and dioxin TCDD.

A third target, rice and other food crops were sprayed primarily with Agent Blue during the early growing season of rice. Agent Blue was intended to kill or eliminate the food supply for the communist soldiers fighting in southern Vietnam but led to high levels of food insecurity in the rural civilian population.

4.1. Herbicide Applications

The first batch of herbicides arrived in southern Vietnam on January 9, 1962 at Tan Son Nhut Air Base in 208 liter drums. The color-coded herbicides including Agent Orange were sprayed from low-flying C-123 Provider aircraft powered by turbojets and propeller engines. Helicopters were re-fitted with 3800 liters chemical tanks, sprayers, and MC-1 Hourglass pump systems [17]. To maximize the contact of herbicide with the forest and to minimize spray drift the spray sorties were restricted to calm days and only sprayed early in the morning. Trucks, US Navy boats and backpack sprayers were also used to spray herbicides.

The US 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 [18] [19]. From January 1962 (3 years before the official start of the Vietnam War) to January 1971, Operation Ranch Hand flew more than 19,000 combat sorties with jungle defoliation and crop destruction missions [20]. The amount of Agent Orange and other herbicides sprayed during these missions has been variously estimated at 105 - 119 kg [14] and 221 to 336 kg [21]. An unknown fraction of aerial spraying by the US Navy was over river transportation corridors and coastal regions. Herbicides contaminated with dioxin TCDD could enter water courses and sediments via bank spraying as well as surface runoff and soil erosion from sprayed areas [20].

Figure 17. The defoliated perimeter of an airbase fence after being sprayed with Agent Orange in the 1960s. Picture taken by US Army Flight Operations Specialist 4 John Crivello in 1969.

US Air Force records document 6542 spraying missions covered 12% of the total area of South Vietnam by 1971. Between 1962 and 1971 more than 20% of South Vietnam forests were sprayed one or more times [3] and approximately 10 million ha of agricultural land was sprayed. 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 United States Department of Agriculture (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 US Environmental Protection Agency (EPA).

Vast areas of Vietnam were stripped bare of vegetation with the Ho Chi Minh Trail and US military bases receiving high concentrations of the dioxin contaminated Agent Orange herbicide. One of the most contaminated sites was the Cu Chi soil tunnels and agricultural and horticultural areas [3] located 40 km to the west of Ho Chi Minh City (formerly Saigon) (Figure 12 and Figure 16). Today, tourists can view and crawl through a portion of these Viet Cong tunnels network. The Vietnam Memorial Park shows a 40-year old black and white film of women picking fruit near Cu Chi in what was once known as the Garden. A variety of trees, jungle undergrowth (Figure 18), and bamboo (Figure 7) have grown up in the bomb craters of Cu Chi during the last 45 years and rubber tree plantations have been established nearby (Figure 19).

The targeting of food crops began in October of 1962 but the US public was not aware of this CIA action until 1964. More than 40% of all herbicide spraying targeted the destruction of food crops. Members of the US Congress in 1965 were told that crop destruction was the most important purpose of the herbicide campaign, but media reports primarily focused 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 South Vietnamese people malnourished or starving and contributed to widespread famine in rural southern Vietnam and movement of the Vietnamese population to Saigon.

4.2. Distribution of TCDD within Vietnam Landscape

During the time of the Vietnam War no studies on the persistence or distribution of dioxin TCDD in Vietnamese ecosystems have been identified. Without baseline data, projections are based in the theoretical understandings of dioxin TCDD distribution and transport in ecosystem processes. Studies in the 1980s found measurable dioxin TCDD levels in soil and sediment samples taken in Vietnam that were linked to the use of Agent Orange and the by-product dioxin TCDD in the Vietnam War. Low concentrations of dioxin TCDD were found to

Figure 18. Agent Orange was sprayed in 1970 over the Cu Chi tunnels area to help target bombing of the tunnels. In the last 45 years the vegetation has regenerated naturally but the trees are slow growing and will take many more years to reach a mature forest. Picture taken 2016 at Cu Chi Vietnam War Memorial Park.

Figure 19. Rubber tree plantations have been planted on the Old Alluvial terrace between Ho Chi Minh City and Cu Chi. Photo taken in 2016.

have accumulated in aquatic systems [22] and soils. These findings suggests soil erosion and water runoff transport from locations where herbicides were applied and/or substantial dioxin TCDD degradation occurred in places where Agent Orange and other dioxin carrying herbicides were sprayed. Sediment and soil samples taken in 1999 from Bien Hoa Air Base, Vietnam, had concentrations of 1,164,699 pg/g (ppt) dry matter in soil [23]. This mega-hotspot airbase was a staging site for Operation Ranch Hand aerial spraying and storage with apparently sizable spillage and leakage occurring [1]. Dioxin TCDD levels of 0.8 - 117 ng/kg (ppt) were found in Bien Hung Lake sediments adjacent but outside the airbase, and 0.8 - 1.5 ng/kg were measured in the Dong Nai River that flows to the South China Sea from the lake [24].

Soil and food samples collected from 1996-1999 and analyzed by Dwernychuk et al. [25] revealed heavily sprayed areas from the Aluoi Valley had higher concentrations of dioxin TCDD than locations where Agent Orange was less frequently applied. Soil and animal fat samples taken from a Vietnamese village near a US Army base where dioxin contaminated herbicides were stored during 1963 to 1966 showed some of the highest concentrations. Breast-milk and soil samples taken in 2002-2003 from heavily sprayed sites also showed higher dioxin TCDD concentrations than areas where Agent Orange had not been sprayed according to a study by Nhu et al. [26].

Dioxin TCDD concentrations in adipose tissues of some Vietnamese populations living in areas that were not heavily sprayed was hypothesized by Quinh et al. [27] to be caused by the transport of dioxin contaminated soils via runoff and erosion from heavily sprayed sites. High soil erosion of defoliated fields and stream banks during the heavy rains of the monsoon season would inevitably lead to contaminated soils in wetland rice fields and contaminated lake and river sediments leading to the biomagnification of dioxin as it moved up the food chain.

Red River sediments in North Vietnam have not been found to have any concentration of dioxin TCDD suggesting that contaminated Agent Orange and other color-coded herbicides were not used on Hanoi or within the Red River watershed. However, low concentrations of TCDD and several other dioxins and furans were found in some inland water sediments as well as lagoon sediments along the Vietnam coast according to research by Piazza et al. [28]. These findings led researchers to hypothesize that most degradation occurred within days or months after Agent Orange was applied.

4.3. Deposition of Agent Orange and TCDD onto Forest Canopy

Post-war, a detailed simulation of the deposition and long-term impact of dioxin TCDD contaminated Agent Orange on Vietnamese forests was conducted in Florida (US) at Elgin Air Force Base [14] [29]. Operation Ranch Hand pilots were quite skilled at "crop-dusting" and the Florida study estimated that the plane spray swath would have carried about 87% of the herbicide to the forest canopy within one minute. These calculations used a leaf area index (LAI) of 5, meaning the area of leaf canopy was 5 times greater than the forest understory below. Further, 99% of the sprayed Agent Orange could defoliate the entire forest when the estimate included sorption (surface absorption and adsorption) by tree branches, trunks and the jungle vegetation below. TCDD in contact with the leaf surface adheres to the waxy cuticle of leaves [30]. Some studies [31] show leaf contamination results in finger-like protrusions of the cuticle in leaf surfaces with transport potential of dioxin TCDD moving from the leaf to soil surfaces.

Herbicides on the leaf could volatilize with an increase in air temperatures. Contaminated leaves that were not exposed to direct sunlight had photo degradation half-life of hours to days, or even weeks depending on the amount of TCDD in the herbicide. Residual herbicide and dioxin TCDD contamination could be degraded and eliminated by one or more processes: exposure to sunlight, volatilization into the atmosphere, wind or water transport (and subsequent exposure to sunlight), ultraviolet light and resulting in dechlorination, degradation by microbial action, or biomass removal [32] [33].

4.4. Transfer Pathway of Agent Orange and TCDD to Soil

Dioxin TCDD can transfer from plant and leaf applications to the soil via re-adsorption and/or atmospheric volatilization and deposition. When dioxin TCDD at the soil surface volatilizes it usually degrades as it enters the atmosphere by photolysis [34]. A similar degradation process occurs when TCDD contaminated soil is exposed to sunlight due to disturbance or tillage and degrades by photolysis [35]. However, forest soils are not normally tilled and sun exposure is limited by foliage density.

Other transfer pathways of TCDD to soil can occur when the soil is directly sprayed with contaminated herbicides under a variety of conditions: foliage overspray, missed foliage target, and weather or military situation required aborting the mission and dumping the load rather than spraying it on the target. Soils can be indirectly contaminated when the eroded leaf waxes where the dioxin and herbicide mixture deposited dry up and fall to the ground and by leaf wash-off during precipitation events falls onto the soil surface. Several researchers [36] [37] have found greater concentrations of dioxin TCDD in the soils of forest soils than in pasture soils. They posit that leaf accumulation of atmospheric dioxins occurs when temperature and humidity conditions are just right and the contamination is transferred from the tree canopy and deposited on the soil surface when the leaves dies and drop to the forest soil.

4.5. Fate of Agent Orange and Dioxin TCDD in Soil

TCDD can remain toxic in the subsoil for decades. Millions of hectares of food cropland and forest land remained degraded and unproductive many years later due to dioxin TCDD contamination. Agent Orange, when it reaches the soil surface has a very short half-life. However, the contaminant dioxin TCDD in herbicide 2,4,5-T, does not. In soils dioxin TCDD was found to slowly degrade by microbial activity, hydrolysis, or sunlight [38]. Defoliation could also increase photo degradation in soils because of increased exposure to sunlight. Although TCDD in contaminated dry soil volatizes somewhat, most of the TCDD is adsorbed by organic or clay soil particles. Adsorption occurs when TCDD molecules, either as a gas or dissolved solid, stick to or adhere and accumulate to soil particle surfaces. This differs from the absorption process, where herbicide molecules are systemically absorbed into the entire leaf, roots and plant.

Direct photo degradation has been found to occur in the upper soil profile about 0.2 mm or less [38], and likely represents a very small portion of total dioxin TCDD loss from soil. Microbial degradation can take decades or a century in temperate regions [39] where temperature and moisture conditions are much lower than the tropical Vietnamese climate. Karch et al. [40] observed that herbicides seemed to stimulate microbial activity and thus increase the degradation of dioxin TCDD.

Although TCDD can persist in soil for decades, rain and wind induced erosion [41] or leaching to underlying soil horizons [42] can lead to a small amount of TCDD being lost from the soil. However, very little of dioxin is likely to leach from the soil profile into shallow groundwater. TCDD attached to colloidal organic or humic soil materials was the most mobile and likely to leach. Colloids can transport hydrophobic contaminants such as TCDD especially during periods of high water runoff. However, colloid concentrations in the subsoil are low and aquifers are rather efficient at filtering out colloids. This makes it very unlikely that TCDD would be transported to river water via groundwater colloids.

Soil samples were analyzed from former American military bases in Thailand (Figure 20) and Vietnam (Figure 21) where Agent Orange and other herbicides were stored. Most of these soil samples tested for TCDD were below Government of Vietnam (GOV) threshold standards which are based on land use. The annual cropland threshold is 40 ppt (toxicity equivalent) dry weight; forest lands or tree crops are 100 ppt; rural residential lands are 120 ppt; urban residential is 300 ppt, recreational is 600 ppt, and commercial and industrial is 1200 ppt. Clearly cropland standards are the most restrictive in an attempt to protect the food supply from the contaminant TCDD.

Soils in three of the former US military bases in southern Vietnam had very high concentrations of TCDD. Most Vietnamese soils range between 1.8% and 5% organic matter content [43]. Because of TCDD's hydrophobicity, those soils were efficient sinks for TCDD and known to be highly persistent in subsoils [36]. Researchers found that very little TCDD over a 12 year period was lost from the subsoil below this depth. Further, the half-life of 2,3,7,8-TCDD directly applied to field soils was less than a year, or about 131 - 321 days according to Muir et al. [41].

Figure 20. There are 7 hotspot airbases in Thailand with dioxin-contaminated soils where the dioxin contaminated herbicides were stored and handled. Agent Orange was sealed in 208 liter barrels that were shipped to Vietnam airbases for use by C-123 aircraft during the Vietnam War. Map by Mic Greenberg.

4.6. Atmospheric Fate: Agent Orange and Dioxin TCDD Half-Life

About 13% of Agent Orange sprayed over jungle forests is estimated to have not made contact with the vegetation canopy and was likely lost to spray drift [14]. Direct aerial spraying over water could also have resulted in TCDD being lost to the atmosphere by volatilization. The gas-phase TCDD degrades in two ways, first when it reacts with hydroxyl radicals and second, via photo degradation from ultraviolet radiation [44]. Volatilization during degradation of soil particle-sorbed TCDD is negligible [45]. The gas-phase of TCDD was estimated to have a half-life of about 3 days by Atkinson et al. [44]. Other researchers calculated TCDD half-life by photo degradation to be in the range of 55.5 - 72.3 hr, or 2.3 - 3 days [46]. Although these half-life estimates represent the short-term persistence of TCDD in the atmosphere, it is important to not overlook the impact of spray drift and deposition in the air. Aerial spraying of dioxin contaminated herbicides during the Vietnam War had potential to contaminate the inland and coastal waters of Vietnam via atmospheric deposition.

Figure 21. There are 10 Agent Orange hotspot airbases in Vietnam with dioxin-contaminated soils and sediments. These US airbases handled most of the Agent Orange coming into Vietnam and were the collection sites for shipping of Agent Orange for at-sea incineration. Map by Mic Greenberg.

4.7. Fate of Dioxin TCDD in Rivers and Marine Coastal Waters

In addition to atmospheric TCDD deposition, the rivers and marine coastal waters of Vietnam were exposed to dioxin by direct stream bank and coastal vegetation herbicide applications as well as river deposition and re-suspension of dioxin contaminated sediments. The deposition of TCDD into water bodies occurred in several ways: fully dissolved in the water, adsorbed and absorbed into colloidal organic materials, and bound to particles in the water. There was a high probability that TCDD bound to particles and organic materials would attach to sediments within estuaries where coastal salt-waters mixed with fresh-water rivers [8]. Most TCDD that entered the South China Sea would be greatly diluted depending on the distance from shore.

TCDD is lost from the surface of coastal waters by photo degradation. The half-life of TCDD in the clear coastal waters of Vietnam is estimated to be much shorter than measured at 40˚N based on the higher intensity of ultraviolet radiation hitting Vietnamese waters. The largest fraction of TCDD in most waters binds to algae, detritus, mineral matter and organic materials. These particles do not remain in the water column but deposit as sediment. The rate of loss can be calculated by measuring particle concentration in the water and their rate of settling. Very little of TCDD is dissolved in water due to it hydrophobic nature.

TCDD in these sediment particles can be returned to the water when sediment is re-suspended [47]. Sediment re-suspension to the water column occurs especially in Vietnamese coastal waters which are shallow and easily churned by wave and wind action [8]. TCDD is ultimately lost from the aquatic system via microbial degradation within sediments or when TCDD particle-bound sediments are buried deeply in the river and coastal sea bottoms. Degradation by anaerobic microorganisms in sediments or continuously wet soils occurs over long time periods, 10, 20, 50 years to centuries [39].

The quality of fresh and salt water rivers is hugely affected by soil erosion and run-off from monsoon high rain events. In most cases it can be assumed that TCDD contaminated river sediments originated from terrestrial sources. TCDD tends to adsorb to suspended humic materials and particles rather than dissolve into river or coastal waters [15]. Thus, as the organic-rich waters of the Mekong River and tributaries flowed through the Delta and entered estuaries at its coastal mouths, flocculation and agglomeration processes bound TCDD contaminated colloids to each another and to other particles in the water. This binding action to soil and sediments as well as dioxins' low solubility in water explains why very little TCDD has been found in surface waters.

4.8. Modeling Fate and Transport of Dioxin TCDD to US Military Personnel

Parsing out the distribution, deposition and transport processes of the dioxin TCDD in Vietnam's ecological systems is useful in evaluating the presence and persistence of TCDD in the environment and the exposure of military personnel. The degradation processes, photochemical exposure, limited bioavailability and low levels of residual TCDD suggest that dioxin exposure levels were low for most of the troops who served in Vietnam. Direct skin contact with the liquid herbicide would be necessary for dioxin to be absorbed by animals and humans. Thus high levels of exposure to TCDD from Agent Orange and other color-coded herbicides was most likely occur to those pilots and ground troops that loaded and unloaded the 208 liter drums, filled the spray tanks, applied the herbicide to base perimeters and transported herbicide supplies within and between airbases [48]. Appreciable accumulation of TCDD in civilians and service personnel serving in Vietnam would have required repeated long-term direct skin contact. This repeated physical contact was experienced by USAF Operation Ranch Hand and US Army Chemical Corps who had direct contact with liquid herbicides as a result of handling, leaks and spills. This was not incidental exposure under field conditions where Agent Orange was sprayed but frequent, concentrated exposure.

In 1971 a team of scientists from National Academy of Sciences [18] collected and analyzed soil samples from an area where 3700 liters of Agent Orange were jettisoned in 1968. Neither 2,4,5-T nor significant amounts of the dioxin TCDD were detected. Where Agent Orange was jettisoned or where leaking or drum spills occurred the dioxin levels were as high as 62,000 mg/kg in the top 10 cm of soil. However, samples taken four years later showed only 2% persisted.

4.9. Soil Contamination by Dioxin TCDD at Vietnam Air Force Bases

The fate of TCDD in the environment can best be understood by studying the movement of dioxin at hotspots including Thailand (Figure 20) and Vietnam (Figure 21) Air Force bases and land beyond their perimeter fences. The most contaminated site in Vietnam appears to be Bien Hoa Air Force base 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.

Ten Air Force bases of Vietnam were the primary hotspots of dioxin contamination (Figure 21). A 2016 report, "Environmental Assessment of Dioxin Contamination at Bien Hoa Air Force Base" funded by USAID [47] extensively detailed TCDD contamination at Bien Hoa approximately 41 years after the Vietnam War ended and 43 years after the stock pile of Agent Orange barrels were removed from Vietnam and shipped to Johnston Island in south Pacific for eventual incineration in 1977 [24]. 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 [24] 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.

4.10. Mega Hotspot: Bien Hoa Air Force Base Dioxin Contamination

Bin Hoa Air Force base is well-known as a dioxin TCDD mega hotspot in Vietnam (Figure 21). Eleven studies characterizing the dioxin contamination at Bien Hoa Air Force Base were conducted between 1990 and 2015. In 2016, USAID [24] 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. Examination of the historical soil and sediment sampling data revealed that dioxin contaminated soil and sediments in the area continued to be contaminated with dioxin more than 45 years later [24]. This high concentration was the result of how Agent Orange and the other herbicides where disposed of, handled, and stored. The hydrophobic water insoluble dioxin compounds attached to the organic fractions of Air Force Base soils and sediments. Contaminated surface soils and sediments spread from sites within the military base by leaks 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.

Soil samples were collected from 76 different locations within Bien Hoa Air Base and surrounding areas 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. This was the largest dioxin TCDD sampling program ever undertaken in Vietnam [24]. 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 sediment (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 biomagnification 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 airbase continued to have high potential for dioxin contamination even after 45 years. All fish tested for dioxin were contaminated except for one. Although raising and selling fish for consumption have 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 [24]. 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.

4.11. Remediation of Dioxin Hotspot Sites

To address the Bien Hoa hotspot, between 347,800 m^3 and 414,400 m^3 of dioxin contaminated soil will need to be treated [24] [49]. The 2016 US Agency for International Development (USAID) assessment report suggests eight approaches to remediate the Bien Hoa Air Force Base site (Figure 21).

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.

4.12. Recommended Mitigation and Remediation Option of Dioxin Contaminated Soil and Sediment-Incineration

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 one of the most commonly used technologies [24] having been used to treat soils at more than 150 superfund sites, including on the Passaic River near Newark, New Jersey, and is a mature and tested technology.

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 [24] using 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 rather high 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 [24].

The excavated areas of the airbase can be re-filled 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 hr days). Two separate incineration units could reduce the time to 5 years. However, there would be start up 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 airbase dioxin concentrations and prevent continued off-base leaching and transport. Further, protected tourism, cultural and heritage resources would again be safe. Potential concerns during remediation are that the movement of contaminated soils and incineration could impact surface water quality from material handling and air quality as a result 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 resulting in a potential sea level rise and inundation or increased frequency and intensity of extreme weather if airbase drainage is managed.

4.13. Use of Agent Orange in Korean DMZ during the Vietnam War Time Period

A US National Academy of Science report declared that there was a "causal relationship between Agent Orange and the contaminant dioxin TCDD and various diseases including cancer" [50]. A class-action lawsuit was filed in 1979 against the herbicide manufacturers (Dow Chemical and Monsanto) and the suit was settled out of court in 1984. An Agent Orange Settlement Fund was created and distributed nearly $200 million to US Vietnam War veterans between 1988 and 1996.

Agent Orange was apparently used in Korea in addition to Vietnam in the late 1960s. US veterans who were able to prove their presence in Korea between April 1, 1968 and August 31, 1971 around the Demilitarized Zone (DMZ) and that they were presumptively exposed and developed medical problems on the list of presumptive diseases, may receive compensation from the US Veterans Administration. In 1978 it was alleged that the US Army had buried 250 barrels each containing 208 liters of Agent Orange in Camp Carroll, the US Army base in Gyeongsangbuk, Korea. Approximately 20,000 Koreans filed two law suits against the US companies, Dow Chemical and Monsanto, seeking $5 billion dollars in damages. In 2002 the Korean court ruled against the Koreans. It was appealed and in 2006 the South Korea Appeals court ordered Dow Chemical and Monsanto to pay $62 million in compensation to about 6800 soldiers and their families. The ruling acknowledged that the defendants failed to ensure safety of those exposed to the chemicals and that the defoliants had a higher level of dioxin than standard. The judge did not acknowledge the relationship between the chemical and peripheral neuropathy which is the most commonly reported disease.

5. Summary and Conclusions

Production and use of the 2,4,5-T herbicide in Agent Orange and the other herbicides were halted in the 1980s in most countries. However, 2,4-D is still produced by Dow Agro Science and is a common component of over 70 products, including Scott's Weed and Feed, Miracle-Grow Weed and Feed, Weed B Gone and many others.

Agent Orange and similar formulated herbicides have very short half-lives, and their direct effects on the Vietnam landscape are confined to the Vietnam War period while they are in use. However, indirect environmental effects of the 2,4,5-T manufacture with the by-product or contaminant dioxin TCDD in the defoliation herbicide persisted. TCDD was transported as a result of soil erosion, landslides and ecologically degraded landscapes throughout the hilly and mountainous areas of South Vietnam. The pre-war forests that existed took hundreds of years to reach an ecologically-balanced mixture of large numbers of species of flora and fauna. Natural regeneration after the spraying of Agent Orange and other defoliants with the contaminant dioxin TCDD will take centuries to reproduce those landscapes. In sprayed areas, runoff, soil erosion, transport and landslides occurred which sharply lowered soil nutrient levels and altered the topographical features of the landscape. These vegetative changes have opened forest canopies and grasslands to a few low value grasses and invasive trees. Active replanting with species of trees and shrubs which are ecologically viable and have economic value, such as rubber trees, will require substantial and sustained long-term investments. The U Minh mangrove forests of the Ca Mau Peninsula were especially sensitive to all herbicides. Large tracts of these ancient mangroves were killed and regeneration has been very difficult due to changes in agricultural uses, increased settlement in the region, salt water intrusions in coastal rivers, and changes in natural water levels [10].

The contaminant dioxin TCDD that was carried in the formulation of these defoliants continues to be an environmental and human health problem that needs to be addressed. Sediments and organic materials high in TCDD were transported by water and wind from Air Force bases into waterways creating hotspots. Fish, especially bottom feeders, in ponds and lakes adjacent to these hotspot areas resulted in dioxin entering the food chain via bioaccumulation and biomagnification processes even after more than 45 years. Fish is the primary protein in diets and a major source of income for rural Vietnamese [5] (Figure 22). Dioxin in the food chain affects both health and Vietnamese capacity to derive livelihoods from fish and other aquatic plants and animals. Most countries now have tight environmental restrictions on emissions of dioxin and dioxin-like compounds. However, dioxin does not degrade readily and is toxic over long periods of time, many decades. The half-life of dioxin varies depending on location: in surface soil that has been fully exposed to sunlight the half-life is between 1 and 3 years; in humans the half-life is between 11 and 15 years; estimated to be 20 to 50 years or more when buried in a tropical soil. In river and sea sediment the half-life can be more than 100 years [51]. It has only been 50 years since the Tet Offensive so approximately half of the dioxin potentially still exists in Air Force base hotspots and adjacent surrounding soils and water that are not remediated.

The production and application of Agent Orange and the other herbicides were halted in 1970. Approximately two hundred thousand 208-liter drums were sent to Vietnam with 65% used in Operation Ranch Hand and Chemical Corps Agent Orange stored at Bien Hoa Airbase and Chemical Corps Operations 1964-1972. The remaining 35% was re-drummed, removed and taken to Atoll Johnston, an Island 1000 km southeast of Hawaii, and destroyed in 1977 by sea incineration [14]. The stockpile of Agent Orange was stored at Naval Construction Battalion Center site at Gulfport, Mississippi with fifteen thousand 208-liter drums of Agent Orange and at the Naval Construction Battalion Center on Johnston Island with twenty five-thousand 208-liter barrels of Agent Orange. Ten years after removal the dioxin levels at these sites were 0.6 to 1.0 mg/kg.

Figure 22. With the loss of stream bank vegetation in 2016, bank erosion looks similar to the soil erosion that occurred in the 1960s after stream bank defoliation. Dioxin in contaminated river sediments can bioaccumulate in harvested fish and become magnified throughout the food chain and affect human health.

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Conflicts of Interest

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

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