Phytoremediation in Subtropical Hawaii—A Review of Over 100 Plant Species

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Phytoremediation is an emerging remediation technology that utilizes plants and microbes to clean up contaminated air, soil, and water. Tropical and subtropical environments have an advantage in that long plant-growing seasons and increased soil temperature can accelerate phytoremediation processes. Various contaminated sites in Hawaii have been addressed using this technology. In this article, work progress and advances of phytoremediation are briefly reviewed and exemplified with seven chemically contaminated sites in Hawaii. The investigations were performed for one or more of the following remediation needs: explosive residues, hydrocarbons, pesticide residues, soil stabilization, and slaughterhouse wastewater. In this unique article, studies of testing of over 100 plant species for remediation are reviewed and documented. The general trend leads one to consider that salt- and/or drought-tolerant plants can bear other potential stress-inducing conditions. © 2004 Wiley Periodicals, Inc.

INTRODUCTION

Phytoremediation is an emerging multidisciplinary field of science and technology. It uses plants and associated microbes to cleanse chemically contaminated air, soil, and water. Research activities to advance the science and technology have been carried out in the past decade. Several of its applications are phytoaccumulation, phytovolatilization, phytotransformation, rhizosphere filtration, and phytostabilization. The technology is a permanent treatment option, has low capital and energy costs, and is aesthetically pleasing (U.S. Environmental Protection Agency [USEPA], 2000). It is, however, often incapable of dealing with high chemical concentrations, and is slower than and requires greater land area than alternative treatment methods. A generally accepted hypothesis is that phytoremediation is suitable in warm climates. This encourages research, demonstration, and application of phytoremediation in tropical and subtropical areas. The use of native plants for phytoremediation in Hawaii has a particular appeal, as they are compatible with the island ecosystems. Their use is feasible and alleviates concerns due to a possible introduction of invasive species into fragile ecosystems.

In general, advances of phytoremediation were reviewed recently with an emphasis on various aspects. For example, Campanella et al. (2002) reviewed fate and dissipation mechanisms specifically for polychlorodibenzo-p-dioxins and -furans (PCDDs/Fs) and polychlorinated biphenyls (PCBs). Collins et al. (2002) surveyed the work done with benzene, toluene, ethylbenzenes, and xylenes (collectively known as BTEXs), and trichloroethlene (TCE). Hannick et al. (2002) reviewed explosive phytoremediation. Chaudhry et al. (2002) listed prospects and limitations of

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phytoremediation for removal of persistent pesticides. Coleman et al. (2002) described the roles of plants for phytoremediation of persistent herbicides. Singh et al. (2003) and Pulford and Watson (2003) reviewed recent progress of heavy metal remediation, the latter specifically addressing the use of trees. Susarla et al. (2002) appraised the treatability of organic contaminants using phytoremediation. Glass (1999) estimated that the U.S. phytoremediation market for 1999 would be between $30–$49 million. Estimated 1999 world phytoremediation markets were $34–$58 million. The focus of this article is recent progresses and advances of phytoremediation in Hawaii, particularly those conducted at the University of Hawaii. The data summarized can serve as a useful database for future investigations on phytoremediation.

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There are many unseen risks in the Hawaiian Islands. Heavily contaminated areas include several notable Superfund sites such as Pearl Harbor. Further, many thousands of hectares of agricultural land have received large numbers of pesticide applications. A former pesticide mixing and loading site on Oahu contains dioxins (CERCLIS HISFN0905536). A historical military use of the islands has resulted in live-fire areas with explosive residues. Everyday activities also result in pollution, which may be ameliorated through phytoremediation. Wastewaters from various sources often prove to be a challenge to individuals, industries, and municipalities. Trade winds, Hawaii's natural "air conditioner," can scour landscapes, preventing revegetation on previously cleared lands, and the volcanic soils of the islands historically have metal concentrations that often exceed regulated maximum contamination levels.

Bench-, pilot-, and field-scale phytoremediation studies have been conducted for several sites and contaminants in Hawaii. Recently, a record of decision for a Superfund site on Oahu (CERCLIS HID980637631) included the use of phytoremediation. This article presents the results of several notable phytoremediation investigations in Hawaii.

PHYTOREMEDIATION CASES IN HAWAII

Hickam Air Force Base Tank Farm on Oahu (Tang et al., 2003)

A former petroleum tank farm on Hickam Air Force Base (AFB) was investigated to clean up petroleum hydrocarbons using plants. The site is located at sea level and presented a variety of challenges to phytoremediation such as salinity and high levels of petroleum hydrocarbons in highly calcareous soil. The nature and conditions of the contaminated site provided clues to define criteria of plant selection, including deep rooting, low maintenance, salt tolerance, and remediation potential for multiple contaminants.

Island of Kaho'olawe (Kaho'olawe Island Reserve Commission, 2002)

The U.S. military used the island of Kaho′olawe as a training area at the start of World War II, primarily as a bombing target. In 1981, it was placed on the National Register of Historic Places. In 1993, Congress passed a law, among others, directing the U.S. Navy to conduct an unexploded ordnance cleanup and environmental restoration of the island in consultation with the state of Hawaii. The restoration of Kaho′olawe required a strategy to recharge the water table, control erosion (phytostabilization), re-establish vegetation, and gradually replace alien plants with native species. Candidate plant species were selected from extensive bench-, pilot-, and full-scale experiments.

Industrial Hemp Site on Oahu (Campbell et al., 2002)

The U.S. Drug Enforcement Agency (DEA)-approved facility was built on Oahu, Hawaii. The controlled access site provided a unique opportunity for a phytoremediation study using industrial hemp. Soil from the facility site was contaminated with chrysene and benzo[a]pyrene (B[a]P) in the laboratory. The soil was then planted with industrial hemp. Several experiments of this type were conducted at the fenced facility. The use of hemp for phytoremediation is, however, dependent on its controlled status.

Kunia Pesticide Spill Site on Oahu (Doty et al., 2003; USEPA, 2003)

The accidental release of ethylene dibromide (EDB) and 1,2-dichloropropane (DCP) in the 1970s resulted in soil and groundwater contamination. Soil was placed in a lined treatment unit, planted with koa haole trees, and irrigated with contaminated groundwater.

Makua Live-Fire Range on Oahu (Campbell et al., 2003; Ogoshi et al., 2003)

Makua Valley is the only location on Oahu where the Army can conduct company-level, live-fire training. A bench-scale experiment was carried out to identify native plant species that could remediate explosive residues–laden soils from Makua Valley. Native and non-native plant species were grown in pots containing explosives-contaminated soil for three months. Chemicals investigated were 1,3,5-trinitro-1,3,5-triazine (RDX), cyclotetramethylenetetranitramine (HMX), and dinitrotoluene (DNT).

Oahu Slaughterhouse Wastewater (Farmers Livestock Cooperative, 2001; Ocean Arks International, 2003)

The slaughterhouse pilot demonstration was the first "living machine" system operated in Hawaii. The pilot living machine system treated 8–20 m3/d of slaughterhouse wastewater. Five-day biological oxygen demand (CBOD5), chemical demand (COD), total suspended solids (TSS), fecal coliform, and ammonia mass removal were monitored, among others.

Pearl Harbor on Oahu (Hue et al., 2002; Paquin et al., 2002)

High salinity in marine sediments is one of the challenges to phytoremediation. Pearl Harbor–dredged sediment contained high levels of polycyclic aromatic hydrocarbons (PAHs) and heavy metals. Several means were compared for reducing sediment salinity, which were soil dilution, washing with gypsum solution or water, and mixing with several soil amendments.

High salinity in marine sediments is one of the challenges to phytoremediation.

PLAN SPECIES TESTED FOR PHYTOREMEDIATION

Exhibits 1–3 show the tested grasses, forbs and herbs, and trees, respectively. Scientific names, group type, duration, and some drought-tolerance data are from the USDA Web site (USDA, 2003) and the Web site of Carr (2003). As shown in the exhibits, one "plus" (+) indicates little, if any tolerance. If a species has either two or three pluses (++ or +++), it is considered drought-tolerant. Drought-tolerance ability is considered to be excellent if three pluses are indicated.

Grasses

There were 29 grasses reported, all being monocots. Four were annuals, and eleven were considered native (indigenous or endemic) to Hawaii. Nine perennials of the twenty-nine grasses were considered drought-tolerant, three of which were natives. Seven of the nine (78 percent) were very drought-tolerant.

Common Name	Scientific Name	Group*	Duration	Drought** Tolerance
Barnyard grass	*Echinochloa crus-galli*	monocot	perennial	+
Bermuda grass	*Cynodon dactylon*	monocot	perennial	+++
Bryan's flatsedge ('ahu'awa)	*Cyperus pennatiformis ssp. Bryanii*	monocot, n	perennial	+
Buffelgrass	*Pennisetum ciliare*	monocot	perennial	+++
Bulrush	*Schoenoplectus lacustris*	monocot	perennial	+
Common waterweed	*Egeria densa*	monocot	perennial	+
Cosmopolitan bulrush (makai)	*Schoenoplectus (scirpus) maritimus*	monocot	perennial	+
Emoloa	*Eragrostis variabilis*	monocot, n	perennial	+++
Great bulrush (aka'akai)	*Schoenoplectus lacustris ssp. Validus*	monocot, n	perennial	+
Guinea grass	*Urochloa maxima*	monocot	perennial	+++
Japanese mat rush	*Juncus effusus*	monocot	perennial	++
Javanese flatsedge (ahu'awa)	*Cyperus javanicus*	monocot, n	perennial	+
Job's tears (pu'ohe'ohe)	*Coix lacryma-jobi*	monocot	perennial	+
Lemon grass	*Cymbopogon citratus*	monocot	perennial	++
Many spike flatsedge (kiolohia)	*Cyperus polystachyos*	monocot, n	perennial	+
Oat	*Avena sativa*	monocot	annual	+
Papyrus	*Cyperus papyrus*	monocot	perennial	+
Rice	*Oryza sativa*	monocot	annual	+
Seashore drop seed, seashore rushgrass (aki aki)	*Sporobolis virginicus*	monocot, n	perennial	+++
Seashore paspalum	*Paspalum vaginatum*	monocot	perennial	+
Smooth flatsedge (makaloa)	*Cyperus laevigatus*	monocot, n	perennial	+
Spikesedge (kohekohe)	*Eleocharis geniculata*	monocot	annual	+
Sticky flatsedge (pu'uka'a)	*Cyperus trachysanthos*	monocot, n	perennial	+
Sugar cane (ku)	*Saccharum officinarium*	monocot	perennial	+
Tanglehead (pili)	*Heteropogon contortus*	monocot, n	perennial	+++
Tropical twigrush (uki)	*Machaerina*	monocot, n	perennial	+
Umbrella sedge (ahu'awa haole)	*Cyperus involucatus*	monocot, n	perennial	+
Vetiver, Louisiana Sunshine	*Vetiveria zizanioides*	monocot	perennial	+++
Whitehead spikesedge (kalohe)	*Kyllinga nemoralis*	monocot	perennial	+

* n stands for native species

** The more pluses, the higher the drought tolerance.

Exhibit 1. Grass Species Tested and Their Drought Tolerance for Phytoremediation

Common Name	Scientific Name	Group*	Duration	Drought** Tolerance
Ama'u (amaumau)	*Sadleria cyatheoides*	fern	perennial, n	+
Beach pea (notched cowpea)	*Vigna marina*	dicot	perennial	+++
Canna, Indian shot (li'ipoe)	*Canna indica*	monocot	perennial	+
Carolina fanwort	*Cabomba caroliniana*	dicot	perennial	+
Cocklebur (kikania-haole)	*Xanthium strumarium* var. *canadense*	dicot	annual	+
Cowpea	*Vigna unguiculata*	dicot	annual	++
Cucumber	*Cucumis sativus*	dicot	annual	+
Dayflower, climbing (honohono)	*Commelina diffusa*	monocot	perennial	+
False daisy	*Eclipta prostrata*	dicot	annual, perennial	++
Ferny azolla, Pacific mosquito fern	*Azolla filiculoidus*	fern	annual	+
Fishgrass	*Cabomba caroliniana*	dicot	perennial	+
Ginger (awapuhi)	unidentified species	monocot	perennial	+
Ginger, shampoo ginger ('opuhi)	*Zingiber zerumbet*	monocot	perennial	+
Greenleaf ticktrefoil	*Desmodium intortum*	dicot	annual, perennial	++
Hawaii arrowhead	*Sagittaria sagittifolia*	monocot	unknown	+
Heliconia	*Heliconia*	monocot	perennial	+
Iris	*Iris sp.*	monocot	perennial	++
Industrial hemp	*Cannabis sativa*	dicot	annual	+
Ko'oko'olau	*Bidens torta*	dicot, n	perennial	+
Lesser duckweed	*Lemna aequinoctialis*	monocot	perennial	+
Mears silverhead	*Carax*	dicot, n	perennial	+
Perennial peanut	*Arachis pintoi*	dicot	perennial	+
Seaside morning glory (puhuehue)	*Ipomoea pes-caprae* var. *emarginata*	dicot, n	perennial	++
Shoreline seapurslane ('akulikuli)	*Sesuvium portulacastrum*	dicot, n	perennial	+++
Sunn hemp	*Crotalaria juncea*	dicot	annual	+
Swamp cabbage, swamp morning-glory	*Ipomoea aquatica*	dicot	perennial	+
Sweet basil (ki'a'ala)	*Ocimum basilicurn*	dicot	annual, perennial	+
Swordfern	*Nephrolepis cordifolia*	fern	perennial	+
Taro, coco yam (kalo)	*Colocasia esculenta*	monocot	perennial	+
Tropical whiteweed (maile hohono)	*Ageratum conyzoides*	dicot	annual, perennial	++
'Uki'uki	*Dianella sandwicensis*	monocot, n	perennial	++
Villous waterclover ('ihi'ihi'lau akea)	*Marsilea villosa*	fern, n	perennial	+++
Water hyacinth	*Eichhornia crassipes*	monocot	perennial	+
Water hyssop ('ae'ae)	*Bacopa monnieri*	dicot, n	perennial	+
Water moss	*Salvinia*	fern	annual	+
Watercress, swinecress	*Coronopus*	dicot	annual, biennial	+

* n stands for native species

** The more pluses, the higher the drought tolerance.

Exhibit 2. Forb and Herb Species Tested and Their Drought Tolerance for Phytoremediation

Common Name	Scientific Name	Group*	Duration	Drought** Tolerance
Aa'ali'i	*Dodonaea viscosa*	dicot, n	perennial	+++
Areca Palm, yellow butterfly palm	*Dypsis lutescens*	monocot	perennial	++
Banana (mai'a)	*Musa xpapdisiaca*	monocot, n	perennial	+
Beach sandmat (akoko)	*Chamaesyce degeneri*	dicot, n	perennial	+++
Bougainvillea	*Bougainvillea*	dicot	perennial	++
Candlenuttree, Indian walnut (kukui)	*Aleurites moluccana*	dicot	perennial	++
False ohelo (akia)	*Wikstroemia uva-ursi*	dicot, n	perennial	++
False sandlewood (naio)	*Myoporum sandwicense*	dicot, n	perennial	++
Firecracker hibiscus, mazapan	*Malvaviscus penduliflorus*	dicot	perennial	++
Goosefoot ('aheahea, 'aweoweo)	*Chenopodium oahuense*	dicot	perennial	+++
Hau (dwarf)	*Hibiscus tiliaceus*	dicot	perennial	+++
Hau (variegated)	*Hibiscus tiliaceus*	dicot	perennial	+++
Hau, sea hibiscus	*Hibiscus tilaceus*	dicot, n	perennial	+++
Hawaii rockwort (kulu'i)	*Nototrichium sandwicense*	dicot	perennial	+++
Hawaiian cotton (ma'o)	*Gossypium tomentosum*	dicot, n	perennial	+++
Heartleaf cyrtandra (ha'iwale)	*Cyrtandra cordifolia*	dicot, n	perennial	+
Hibiscus (koki'o, ke'oke'o)	*Hibiscus arnottianus* var. *punaluuensis*	dicot, n	perennial	+++
Hibiscus, (koli'o)	*Hibiscus kokio*	dicot, n	perennial	+++
Iliee	*Plumbago zeylanica*	dicot, n	perennial	+++
Ironwood, (beach sheoak)	*Casuarina equestifolia*	dicot	perennial	+++
Kava kava (awa)	*Piper methysticum*	dicot	perennial	+
Kiawe, mesquite	*Prosopis pallida*	dicot	perennial	+++
Koa	*Acacia koa*	dicot, n	perennial	+
Kona loulu	*Prichardia affinis*	monocot, n	perennial	+++
Kou	*Cordia subcordata*	dicot	perennial	+++
Lavender	*Lavandula sp.*	dicot	perennial	+
Mangrove	*Avicennia germinans*	dicot	perennial	+
Maui chaff flower	*Achyranthes splendens*	dicot, n	perennial	+++
Naupaka	*Scaevola sericea*	dicot, n	perennial	+++
Oahu schiedea (ma'oli'oli)	*Schiedea kaalae*	dicot, n	perennial	+
Oleander	*Nerium oleander*	dicot	perennial	+++
Papaya	*Carica papaya*	dicot	perennial	+
Pink lady	*Hibiscus rosa-sinensis*	dicot	perennial	+++
Portia (milo)	*Thespesia populnea*	dicot, n	perennial	+++
Primrose willow (pukamole)	*Ludwigia octovalvis*	dicot	perennial	+
Roundleaf chastetree (pohinahina)	*Vitex ovata*	dicot	perennial	+++
Screwpine (hala)	*Pandanus*	monocot	perennial	++
Starviolet (manono)	*Hedyotis (Gouldia??)*	dicot, n	perennial	+
Sweet marjoram	*Origanum majorana*	dicot	perennial	+
Ti (ki)	*Cordyline fruticosa*	monocot	perennial	++
Tiger's claw, tropic coral	*Erythrina variegata*	dicot	perennial	+
Tree fern, Cooper's Cyathea (haupu'u i'i)	*Cyathea cooperi*	fern, n	perennial	+
Waianae Range papala (papala)	*Charpentiera, tomentosa* var. *maakuaensis*	dicot, n	perennial	++
White leadtree (koa haole)	*Leucaena leucocephala*	dicot	perennial	+++
Wili wili	*Erythrina sandwicensis*	dicot, n	perennial	+++
Yellow ilima (ilima papa)	*Sida fallax*	dicot, n	perennial	+++

* n stands for native species

** The more pluses, the higher the drought tolerance.

Exhibit 3. Tree Species Tested and Their Drought Tolerance for Phytoremediation

Forbs and Herbs

Thirty-six forbs and herbs were examined for their potential for phytoremediation. Eleven were monocots; five were ferns, and the balance, dicots. Seven species are true annuals, and four are considered both annual and perennial. There were 23 perennials and one of unknown duration (Hawaii arrowhead); seven were native to Hawaii. Ten of the 36 forbs and herbs were considered drought-tolerant, 40 percent of which were native. Three of the ten drought-tolerant varieties were considered very tolerant.

Trees

Forty-six trees were used in phytoremediation studies, five of which were monocots, one fern, and 40 dicots. Forty-five percent of the trees (all perennial) were considered native to the islands. Seventy two percent were drought-tolerant, 16 of which are natives. Twenty-four varieties can suffer drought extremely well.

PHYTOREMEDIATION RESULTS BY CHEMICAL CLASSES

Phytoremediation activities are presented, generally grouped according to contaminants. Exhibits 4–6 show the phytoremediation results for explosives, hydrocarbons, and "others," which include EDB, DCP, phytostabilization, and slaughterhouse wastewater (WW), respectively. A subjective ranking of species tolerance or potential for remediation is presented using "plus" signs. One plus sign means no effect or that the species is sensitive to the condition. A plant with two plus marks is considered tolerant of the growing circumstance and/or capable of reducing chemical levels. Remediation capability is highly viable if three plus marks are indicated. A column lists a relative rank for each species's salt tolerance. The salt-tolerance ranking is similar to that used in Exhibits 1–3 for drought tolerance.

Explosives (Exhibit 4)

Twelve species were tested on the Makua soil contaminated with the explosives. Eight trees, three grasses, and one forb were used, five of which were natives. Ten were perennials and two were annuals. Three monocots and nine dicots were tested. Eight of 12 were salt-tolerant, four being very salt-tolerant. Ten of the 12 were considered very drought-tolerant. No species were found to have significant use for DNT remediation. Ten of the 12 species were tolerant to RDX, four of which were natives. Both pili grass and white leadtree (koa haole) were intolerant, or little to no reduction of RDX was noted. Dicots comprised eight of the 10 RDX-tolerant species, and four were native. The two RDX-degrading monocots were guinea grass and oat. In addition to oat and guinea grass, cucumber, goosefoot, and roundleaf chastetree showed exceptional promise as phytoremediation candidates for RDX. The annuals oat and cucumber are not tolerant of drought conditions. Hawaii rockwort, hibiscus, cucumber, and oat are not salt-tolerant. Guinea grass reduced RDX more than the other species.

Twelve species were tested on the Makua soil contaminated with the explosives. Eight trees, three grasses, and one forb were used, five of which were natives.

Ten of 12 species tested were HMX-tolerant. Four tree species (hibiscus, naupaka, yellow ilima, and roundleaf chastetree) showed great promise for HMX remediation, among which the latter is not native. Tanglehead and Hawaiian cotton offered little reduction of HMX. Dicots comprised eight of the ten winning species, and three were

Common Name	DNT*	RDX*	HMX*	Salt Tolerance*
Cucumber	+	+++	++	+
Goosefoot	+	+++	++	+++
Guinea grass	+	+++	++	+++
Hawaii rockwort	+	++	++	+
Hawaiian cotton	+	++	+	+++
Hibiscus	+	++	+++	+
Naupaka	+	++	+++	+++
Oat	+	+++	++	+
Roundleaf chastetree	+	+++	+++	++
Tanglehead	+	+	+	++
White leadtree	+	+	++	+++
Yellow ilima	+	++	+++	+++

All data are from bench-scale experiments (Ogoshi et al., 2003).

* The more pluses, the higher the tolerance to salt and toxic chemicals, and remediation potential.

Exhibit 4. Remediation Efficiency and Salt Tolerance of Plant Species for Explosives

native. Guinea grass and oat (monocots) showed some promise for HMX remediation, but not as much for RDX.

Hydrocarbons (Exhibit 5)

Thirty-two species (7 monocots and 25 dicots) were tested on hydrocarbon-laden soils and marine harbor sediments in three of the seven cases surveyed for this review. Six grasses, six forbs, and 20 trees were screened, 41 percent of which were native. Only three were annuals, one considered both annual and perennial, and the rest were true perennials. Twenty of the 32 were salt-tolerant, and 13 of the 20 were very salt-tolerant. Twenty-six of the 32 were considered drought-tolerant, and 21 of the 26 were very drought-tolerant. At Hickam AFB site, results indicated that tropical tree species could be established at a highly calcareous and hydrocarbon-contaminated tank farm. Several tropical species significantly decreased hydrocarbon concentrations. Industrial hemp grew faster in spiked soil than in control soil, and PAH levels were significantly reduced in both control and treated pots. After 45 days of plant growth, the BaP concentration was decreased from an initial spiking level of 200 mg/g to 133 mg/g (Campbell et al., 2002). Industrial hemp would appear to be a prime candidate for remediation of PAH-laden tropical soils. Eleven of the 25 species evaluated were tolerant of aromatic hydrocarbons. Seashore paspalum, white leadtree, and the two natives, naupaka and portia, were very active in PAH reduction. Naupaka and portia were very salt- and drought-tolerant. Paspalum and white leadtree were considered to be moderately salt-tolerant. Paspalum did not bear drought situations; however, white leadtree endures drought. Dwarf hau and vetiver were tolerant of PAHs and very drought-tolerant, but sensitive to saline conditions.

Nine of the 20 species were tolerant of B[a]P-tainted soils and marine harbor sediments, of which naupaka and portia were natives. Six were dicots, and seven of the nine

Common Name	Scale/ Reference	PAH*	B[a]P*	Diesel*	Salt Tolerance*
Beach pea	Bench/Hue	++			++
Beach sandmat	Bench/Paquin	+	+		++
Bermuda grass	Bench/Hue	++	++		+++
Bougainvillea	Bench/Paquin	+	+		+
Buffelgrass	Bench, field/Tang			+	+
Cowpea	Bench/Hue	++	++		+++
False ohelo	Bench/Paquin	+	+		+
False sandlewood	Bench/Tang			+++	+
Greenleaf ticktrefoil	Bench/Hue	++			++
Hau (dwarf)	Bench/Paquin	++	+++		+
Hau (variegated)	Bench/Paquin	+	+		+
Hau (sea hibiscus)	Bench/Paquin	+	+		+++
Hibiscus	Bench/Paquin	+	+		
Iliee	Bench/Paquin	+	+		+++
Industrial hemp	Bench/Campbell	++	++		+
Ironwood	Bench, field/Tang			+++	+++
Kiawe, mesquite	Bench, field/Tang			++	++
Kona loulu	Bench/Paquin	+	+		+++
Kou	Bench, field/Tang			+++	+++
Mangrove	Bench/Paquin	+	+		+++
Naupaka	Bench/Tang, Paquin	+++	+++	+++	+++
Oleander	Bench/Tang			++	++
Perennial peanut	Bench/Hue	+			+
Portia	Bench/Tang, Paquin, field/Tang	+++	+++	+++	+++
Seashore drop seed	Bench/Paquin	+	+		+++
Seashore paspalum	Bench/Hue, Paquin	+++	+++		++
Sunn hemp	Bench/Paquin	+			+
Tanglehead	Bench/Paquin	+	+		++
Tiger's claw	Bench, field/Tang			+	+
Vetiver	Bench/Paquin	++	++		+
White leadtree	Bench/Paquin	+++	+++		+++
Wili wili	Bench/Paquin	+	+		+++

* The more pluses, the higher the tolerance to salt and toxic chemicals, and remediation potential.

Exhibit 5. Remediation Efficiency and Salt Tolerance of Plant Species for Hydrocarbons

were perennials. Seven of the nine were drought-resistant and six were salt-tolerant. Naupaka, portia, dwarf hau, seashore paspalum, and white leadtree were very active at B[a]P degradation. Four of the five—the exception being seashore paspalum—were very drought-tolerant. Naupaka and portia were very salt-tolerant.

Seven of the nine species tested were tolerant of diesel surroundings, all being perennials and dicots. False sandlewood, ironwood, kou, naupaka and portia were very effective in diesel degradation. Portia, naupaka and false sandlewood were natives. Ironwood, naupaka and portia were very salt-tolerant and very drought- tolerant.

Ethylene Dibromide (EDB) and 1,2-Dichloropropane (DCP) (Exhibit 6)

One species was used on the Kunia Superfund site. White leadtree is a perennial dicot and exhibits high drought and medium salt tolerance. The results showed that phytoremediation could be used effectively and safely at this site to clean up the contaminated soil and groundwater. Wellwater containing an average of 25 μg/L of EDB was used to irrigate the trees over a three-year period, with no visible phytotoxicity. White leadtree was proven to metabolize EDB (DCP results were inconclusive) and has been accepted for use in the final clean-up activities for the site.

Marine sediment from Pearl Harbor was successfully modified by different physical methods and remediation technologies

Phytostabilization (Exhibit 6)

Phytostabilization activities on the island of Kahoʻolawe were accomplished with aaʻaliʻi, emoloa, goosefoot, iliee, tanglehead, and Maui chaff flower. All except goosefoot were natives. All six species were perennials and were very drought-tolerant. All were very salt-tolerant, except tanglehead (somewhat salt-tolerant).

Slaughterhouse Wastewater (Exhibit 6)

Seventy-four plants were evaluated for use with the living machine technology. Most of these were "water plants." Twenty-seven received two or three pluses, indicating promising or good activity, and ten were rated very appropriate for slaughterhouse wastewater treatment. Twelve species were natives. Treated discharge met Hawaii Department of Health R-2 recycle wastewater standard (less than 2,000 counts/100 ml). It met or bettered design treatment performance for five-day biological oxygen demand (CBOD5), chemical oxygen demand (COD), total suspended solids (TSS), fecal coliform, and ammonia mass removal. The pilot study proved to be a cost-effective sustainable design for remediation of the wastes.

CONCLUSIONS

Marine sediment from Pearl Harbor was successfully modified by different physical methods and remediation technologies, so that terrestrial plants grew successfully in bench-scale studies with hydrocarbons. Those methods could be applied to solve similar saline problems. Portia and naupaka trees showed very active degradation of diesel, PAH, and B[a]P. They also had extremely high resistance to drought and salinity conditions. In one study, dwarf hau reduced B[a]P concentrations by 90 percent with respect to the no plant control. False sandlewood, ironwood, and kou were also effective for reclamation of diesel-contaminated media. For remediation of explosives, goosefoot, guinea grass, naupaka, roundleaf chastetree, and yellow ilima were promising species. A field pilot study demonstrated that white leadtree effectively dissipated EDB/DCP-contaminated soil and groundwater. Aaʻaliʻi, emoloa, goosefoot, iliee, Maui chaff flower, and tanglehead were selected for a large acreage soil stabilization on Kahoʻolawe Island. Ten of the 74 plant species proved to be very suitable for slaughterhouse wastewater treatment using the living

Common Name	Scale/ Reference	EDB/ DCP*	Kaho'olawe*	WW*	Salt Tolerance*
Aa'ali'i	Field/KIRC		+++		+++
Amaumau fern	Pilot/FLC			+	+
Areca palm	Pilot/FLC			+	++
Banana	Pilot/FLC			++	+
Barnyard grass	Pilot/FLC			+	+
Bryan's flatsedge	Pilot/FLC			+	+
Bulrush	Pilot/FLC			++	+
Candlenuttree	Pilot/FLC			++	+
Canna, Indian shot	Pilot/FLC			++	+
Carolina fanwort	Pilot/FLC			+	+
Cocklebur	Pilot/FLC			+	+
Common waterweed	Pilot/FLC			+	+
Cosmopolitan bulrush	Pilot/FLC			+	+
Dayflower, climbing	Pilot/FLC			+	+
Emoloa	Field/KIRC		+++		+++
False daisy	Pilot/FLC			+	++
Ferny azolla	Pilot/FLC			++	+
Firecracker hibiscus	Pilot/FLC			+	++
Fishgrass	Pilot/FLC			+	+
Ginger	Pilot/FLC			+++	+
Ginger, shampoo	Pilot/FLC			+++	+
Goosefoot	Field/KIRC		+++		+++
Great bulrush	Pilot/FLC			+++	+
Hau, sea hibiscus	Pilot/FLC			+++	+++
Hawaii arrowhead	Pilot/FLC		+	+	
Heartleaf cyrtandra	Pilot/FLC			+	+
Heliconia	Pilot/FLC			++	+
Hibiscus	Pilot/FLC			+	+
Hibiscus, red	Pilot/FLC			+	+
Iliee	Field/KIRC		+++		+++
Iris	Pilot/FLC			+	+
Japanese mat rush	Pilot/FLC			++	++
Javanese, flatsedge	Pilot/FLC			+++	+
Job's tears	Pilot/FLC			+	+
Kava kava	Pilot/FLC			++	+
Koa	Pilot/FLC			+	+
Ko'oko'olau	Pilot/FLC			+	+
Lavender	Pilot/FLC			+	+
Lemon grass	Pilot/FLC			+	++
Lesser duckweed	Pilot/FLC			+	+
Many spike flatsedge	Pilot/FLC			++	+
Maui chaff flower	Field/KIRC			+++	+++
Mears silverhead	Pilot/FLC			+	+
Oahu schiedea	Pilot/LM			+	+
Papaya	Pilot/LM			+	+
Papyrus	Pilot/LM			+	+
Pink lady	Pilot/LM			+	++
Portia	Pilot/LM		+++		+++
Primrose willow	Pilot/LM			++	+
Rice	Pilot/LM			+	+
Screwpine	Pilot/LM			++	++
Seashore drop seed	Pilot/LM			++	+++
Seashore paspalum	Pilot/LM			+	+
Seaside morning glory	Pilot/LM			+	++
Shampoo ginger	Pilot/LM			+++	+
Shoreline Seapurslane	Pilot/LM			++	+++
Smooth flatsedge	Pilot/LM			+	+
Spikesedge	Pilot/LM			+	+
Starviolet	Pilot/LM			+	+
Sticky flatsedge	Pilot/LM			+	+
Sugar Cane	Pilot/LM			+++	+
Swamp cabbage	Pilot/LM			+	+
Sweet basil	Pilot/LM			+	+
Sweet marjoram	Pilot/LM			+	+
Swordfern	Pilot/LM			+	+
Tanglehead	Field/Kaho'olawe		+++		++
Taro, coco yam	Pilot/LM			++	+
Ti	Pilot/LM			+	++
Tree fern, Cooper's cyathea	Pilot/LM			+	+
Tropical twigrush	Pilot/LM			+	+
Tropical whiteweed	Pilot/LM			+	+
'Uki'uki	Pilot/LM			+++	+
Umbrella sedge	Pilot/LM			++	+
Villous waterclover	Pilot/LM			++	++
Waianae Range papala	Pilot/LM			+	++
Water hyacinth	Pilot/LM			+	+
Water hyssop	Pilot/LM			+++	+
Water moss	Pilot/LM			+	+
Watercress	Pilot/LM			++	+
Whitehead Spikesedge	Pilot/LM			+	+
White leadtree	Field/Doty	+++			++

* The more pluses, the higher the tolerance to salt and toxic chemicals, and remediation potential.

Exhibit 6. Remediation Efficiency and Salt Tolerance of Plant Species for Kunia EDB-and DCP-Contaminated Site, Kaho'olawe Phytostabilization, and Slaughterhouse Wastewater Treatment

machine. Reviews of the results of the seven cases and plant species naturally growing at the sites suggest that remediation plant species can be selected from those initially found at the site. This can be considered as an overlap area with phytoforensics. The range of plant species and their effectiveness thus far utilized indicate high potential of phytoremediation technology to clean up contaminated sites in Hawaii as well as other tropical and subtropical areas where long growing seasons and high temperature favor this technology.

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