



Volcanic Emissions Injury to Plant Foliage

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Hawai'i's Kīlauea volcano has been active for many tens of thousands of years. It is currently the most active volcano on Earth and has been erupting continually since 1983, emitting SO₂ (sulfur dioxide), HCl (hydrogen chloride), and other gases into the atmosphere. Such materials are emitted from fumaroles on the volcano even during periods when lava is not erupting. These acid-precursor gases can adversely affect plants directly or can acidify rainfall, which also can have a severe effect on soils and vegetation, especially near or downwind from the volcano. In addition to emissions of gases, the volcano emits volcanic ash, which is deposited on everything near the volcano, including plants.

The northern and eastern slopes of Kīlauea volcano have lush vegetation, whereas the summit area and a triangular area leading southwest to the ocean are desert-like and not lushly vegetated. This is due partly to the trade winds, which sweep the gases and acid rain from the summit in a southwest direction.

Since late December 2007, SO₂ emissions from Kīlauea volcano at Halema'uma'u have been increasing. On March 12, 2008, emissions increased significantly from the new vent. In early April, the Hawai'i Volcanoes National Park on Hawai'i was closed because the high SO₂ levels were deemed a threat to human health.

Agricultural crops and other plants are subject to injury by exposure to the pollutants that emerge from Kīlauea, especially when they are present in high concentrations. Farmers and gardeners in the path of the pollutants (SO₂ and acid rain) have reported significant damage to plants caused by the northeasterly and southeasterly winds bringing SO₂ fumes from Pu'u 'Ō'ō and Halema'uma'u to downwind areas, such as those immediately surrounding Kīlauea, Pāhala, and Hawaiian Ocean View Estates.



At Halema'uma'u in Hawai'i Volcanoes National Park, beginning on March 12, 2008, volcanic emissions emerged from a new vent and contained high concentrations of sulfur dioxide, some other gases, and volcanic ash.
(Photo: K. Sewake)

This publication discusses the effects of the increased volcanic output on foliar injury to plants in Hawai'i, what can be done to moderate it, and what the state and federal agencies have done or are planning to do to help minimize damage to Hawai'i's forests and agriculture.

The disease

When plants are adversely affected, this disease is called by various names, depending on the type of action producing symptoms: air pollution injury, vog damage, sulfur dioxide injury, acid rain injury, or ash fall injury. While most plant pathogens are living organisms, this disease's causal agents (pollutants such as sulfur dioxide, acid rain, and ash) are abiotic (nonliving).

*Note: Preliminary versions of this publication were circulated before it was finalized, on August 29, 2008. Versions not bearing this notification contain some inaccuracies and should be discarded.

Vog

“Vog,” coined from “volcanic smog,” is a term used in Hawai‘i to describe hazy conditions caused by gaseous emissions from Kīlauea volcano. The SO₂ gas in vog is greater near the sources (Halema‘uma‘u and Pu‘u ‘Ō‘ō vents). SO₂ levels are lessened further away or upwind from the vents. The haze caused by vog may be heavy in West Hawai‘i, but the SO₂ levels are typically lower due to the geographic distance from the sources. One cannot judge the amount of SO₂ in the air or its danger to humans and plants by how heavy the vog appears—SO₂ levels can be high with only light vog.

SO₂ concentration in the air

The SO₂ gas content of unpolluted air is less than 0.05 parts per million (ppm). According to the *Toxicological Profile for Sulfur Dioxide* (U.S. DHHS 1998), the typical outdoor concentration of SO₂ in the air in the United States may range from 0 to 1 ppm. Occupational exposures to SO₂ may lawfully range from 0 to 5 ppm as enforced by various state Occupational Safety and Health Administrations. Effects on human health vary with type and length of exposure to SO₂, the human physiological system (e.g., respiratory, reproductive, etc.), human age and health condition, and other coincident pollutants in the air at time of exposure. Sulfur dioxide is usually present as a gas and therefore usually enters humans through the respiratory system. It enters plants through their leaves’ stomata, natural openings in leaf surfaces that regulate gas exchange. Plants generally do not display symptoms of SO₂ injury until the standards affecting human health are met or exceeded. Generally, the lower range of toxicity to sensitive plants is about 0.3 to 0.5 ppm SO₂. As evident from Table 1, the recent SO₂ output on the island of Hawai‘i is variable yet high enough to damage plants in regions proximal to and downwind from Kīlauea (refer to Table 2 and the photos for some plant species affected by vog during 2008 in this geographical area).

Sulfur dioxide (SO₂) injury

Sulfur dioxide must enter leaf mesophyll tissue, through stomata, to cause plant injury. The opening and closing of stomata are controlled by various environmental factors. If the stomata are not open, due perhaps to water stress or other causes, plants may escape severe injury. However, once SO₂ enters the moist mesophyll tissue, it combines with water and is converted to sulfuric acid which burns

Table 1. Sulfur dioxide air concentrations near the source at Kīlauea volcano (selected dates).

Date	Approximate sulfur dioxide emissions (tonnes* per day)
Normal (background)	150–200
December 2007	300 (approx. 1 ppm, Crater Rim Dr)
February 2008	600–1000
March 12, 2008**	1500
March 13, 2008	1800–2000 (approx. 40 ppm, Crater Rim Dr)
May 24, 2008	1540
May 25, 2008	990

*A tonne is a metric unit equivalent to 1000 kilograms (2204.6 pounds)

**A prominent new gas vent broke through the lower east wall of Halema‘uma‘u.

Source: http://hvo.wr.usgs.gov/pressreselases/pr03_14_08.html

plant tissue. Plant or tissue age may affect sensitivity to SO₂ for some species. Sulfur dioxide is also produced by human activities such as burning coal and oil, smelting ore, manufacturing steel, and refining petroleum.

SO₂-sensitive vs. SO₂-resistant plants

Sensitive plants show injury at SO₂ levels from 0.05 to 0.5 ppm for 8 hours, or about 1 to 4 ppm for 30 minutes. More resistant plants require dosages of 2 ppm SO₂ for 8 hours, or about 10 ppm for 30 minutes. Plants observed to be sensitive to SO₂ in Florida include bean (*Phaseolus* sp., *P. vulgaris*), clover (*Trifolium* sp.), soybean, (*Glycine max*), violet, (*Viola* sp.), broccoli (*Brassica oleracea*), clover (*Trifolium* sp.), brussel sprouts (*Brassica oleracea*), endive (*Cichorium endivia*), sweet clover (*Melilotus* sp.), lettuce (*Lactuca sativa*), okra (*Hibiscus esculentus*), pea (*Pisum sativum*), violet (*Viola* sp.), Swiss chard (*Beta vulgaris*), zinnia (*Zinnia elegans*), and turnip (*Brassica rapa*). Plants damaged on the island of Hawai‘i are presented in Table 2. More resistant crop plants include asparagus (*Asparagus officinalis*), cabbage (*Brassica oleracea*), celery (*Apium graveolens*), coffee (*Coffea arabica*), corn (*Zea mays*), onion (*Allium cepa*), and potato (*Solanum tuberosum*). A resistant plant native to Hawai‘i is *Metrosideros polymorpha* (‘ōhi‘a lehua).

Table 2. The following plants and crops were observed and reported to be damaged by aerial volcanic emissions between March 12 and July 10, 2008. The emissions derived from Halema'uma'u at Kīlauea Volcano on the island of Hawai'i. The extent of damage varied by location, plant, cultivar, and date of heavy vog emissions. Reports were from commercial farms, homeowners, and state and federal employees.

Flowers and ornamentals

African lily (*Agapanthus* spp.)
Alstroemeria spp.
 Asiatic lily and Oriental lily (*Lilium* spp.)
 chrysanthemum (*Chrysanthemum* spp.)
 cymbidium (*Cymbidium pendulum*)
 cypress (*Cupressus* spp.)
 Dutch iris (*Iris hollandica*)
 eucalyptus (*Eucalyptus* spp.)
 eugenia (*Eugenia* spp.)
 freesia (*Freesia* spp.)
 gerbera (*Gerbera* spp.)
 ginger (*Zingiber* spp.)
 hydrangea (*Hydrangea* spp.)
 juniper (*Juniperus* spp.)
 heavenly bamboo (*Nandina domestica*)
 orchid plantlets
 Arabian jasmine, pikake (*Jasminum sambac*)
 pine (*Pinus* spp.)
 podocarpus (*Podocarpus gracilor*)
 protea (various genera)
 rose (*Rosa* spp.)
 snapdragon (*Antirrhinum majus*)
 statice (*Statice* spp.)
 sunflower (*Helianthus annuus*)
 tuberose (*Polianthes tuberosa*)

Fruit and nut crops

young *Macadamia integrifolia* plants

Native plants

'a'ali'i (*Dodonaea viscosa*)
 'ākala (*Rubus hawaiiensis*)
 blackberry (*Rubus argutus*)
 ferns, laukahi (*Dryopteris wallichiana*)
 koa (*Acacia koa*)
 kōlea (*Myrsine lanaiensis*)
 naio (*Myoporum sandwicense*)
 pilo (*Coprosma foliosa*)
 'uki (*Machaerina angustifolia*)

Vegetable crops

broccoli (*Brassica oleracea*)
 cauliflower (*Brassica oleracea*)
 Chinese cabbage (*Brassica rapa*)
 daikon (*Raphanus sativus* var. *longipinnatus*)
 green onion (*Allium* spp.)
 lettuce (*Lactuca sativa*)
 Swiss chard (*Beta vulgaris*)
 tomato (*Lycopersicon esculentum*)
 watercress (*Nasturtium* sp.)

Rangeland grasses

guineagrass (*Panicum maximum*)
 kikuyugrass (*Pennisetum clandestinum*)
 pangolagrass (*Digitaria decumbens*)
 other grasses (unidentified)

Others

glycine (*Neonotonia wightii*)
 honohono grass (*Commelina diffusa*)
 a rush (unidentified)



Norfolk Island pine Photo: M. Nagao



Cymbidium orchid Photo: R. Anderson



Macadamia Photo: M. Nagao



Dutch iris Photos, this column: K. Sewake



Rose



Blackberry Photo: P. Scowcroft



Rose



Sunflower Photos, this page (unless noted otherwise): K. Sewake



Asiatic lily



Eucalyptus globulus Photo: S. Nelson



Eucalyptus



Statice



Protea



'Ākala Photos, p. 6–7 (unless noted otherwise): P. Scowcroft



Koa

Acute SO₂ injury

Absorption of high concentrations of SO₂ during a relatively short period of time can cause acute plant injury. Injury may appear rapidly, within hours or up to a few days after exposure. The symptoms may appear as lesions, visible on both sides of the leaves, that initially occur between leaf veins or along leaf edges. The color of the damaged area varies from light tan to near white to orange-red or brown and may depend on factors such as plant species and weather conditions.

Chronic SO₂ injury

Long-term absorption of SO₂ at sublethal concentrations is a chronic condition for plants. The symptoms are less severe than for acute injury and may appear as leaf yellowing or bronzing on the undersides of leaves.

Effects in Hawai'i

The concentration of sulfur dioxide since early March 2008 has been high enough to result in acute injury to

plants closest to and downwind from the source, and probably high enough to cause chronic injury to plants that are more geographically removed from the source.

Disease symptoms on leaves from SO₂ exposure

Low SO₂ concentrations cause general chlorosis (yellowing) of plant foliage. Higher concentrations can cause bleaching or browning of tissues between leaf veins. The symptoms can mimic those produced by biotic stresses such as plant pathogens causing root rot or stem blight, drought, phytotoxicity, or damage from pesticides. SO₂ and hydrochloric acid fumes can cause similar symptoms:

- bleached white to tan to brown tissues between veins
- leaf spots or blights
- at lower doses of SO₂, there may be chlorosis (yellowing) of leaves
- pollutant dose (concentration of pollutant x duration of



A rush



'Uki



Naio Photo: S. Nelson



Naio



Kīlea



Pilo

exposure) determines the severity of damage; at high concentrations, leaves may die.

General effects of elevated SO₂ levels

The general effects of SO₂ exposure to plants may vary and depend upon plant species and the SO₂ dosage; these include

- reduced seed germination
- enhanced susceptibility to other diseases
- foliar necrosis (spots, blight)
- epicuticular wax erosion
- rupture of epidermis, plasmolysis
- reduced chlorophyll content
- increased membrane permeability of plant leaves
- decreased plant growth (root length, shoot length, leaf numbers)
- plant organ or entire plant death.

Acid rain

Where SO₂ combines with atmospheric moisture, damaging sulfuric acid precipitation known as acid rain can occur. It may also take the form of an acid fog, especially near the volcano. Acid rain forms where oxidized sulfur and/or nitrogen molecules that are suspended in the atmosphere combine with airborne moisture. This forms acidic compounds such as sulfuric acid that dissolve in the water and fall as acidified rain or move through crops as acidified fog. Acid rain can have geographically widespread consequences and can affect each component of an ecosystem. The pH of acid rain at areas downwind of the Kīlauea fumaroles can be 4.0 or less. The general effects of acid rain on soils and plants are

- increased soil acidity
- increased availability of toxic heavy metals in soils
- reduced soil fertility
- reduced plant growth and productivity
- foliar and flower damage.

To detect acid rain, look for plants that display necrosis or chlorosis, especially (and initially) between leaf veins. Disease symptoms may appear rapidly on plants in the vicinity of or downwind from the Kīlauea volcano. Some plants are more sensitive than others to lower concentrations of the air pollutants.

Volcanic ash

Ash does not damage plants directly if it is removed; otherwise it can block sunlight and thereby reduce pho-

tosynthesis. Combined with moisture on foliage, it can become acidic and cause foliar and flower damage. Ash can cause cosmetic damage, and it probably should not be eaten. It can and should be washed from plant foliage and fruits with water. Volcanic ash is composed of fine rock particles erupted from the volcano. As it falls, the ash cools, and therefore heat of the ash is not a hazard to plants. It appears as dust. Ash fall has recently been reported from the areas of Pāhala, Nā'ālehu, and the South Point communities of Ka'ū. As a precautionary measure, harvested crops affected by ash fall should be thoroughly washed before consumption.

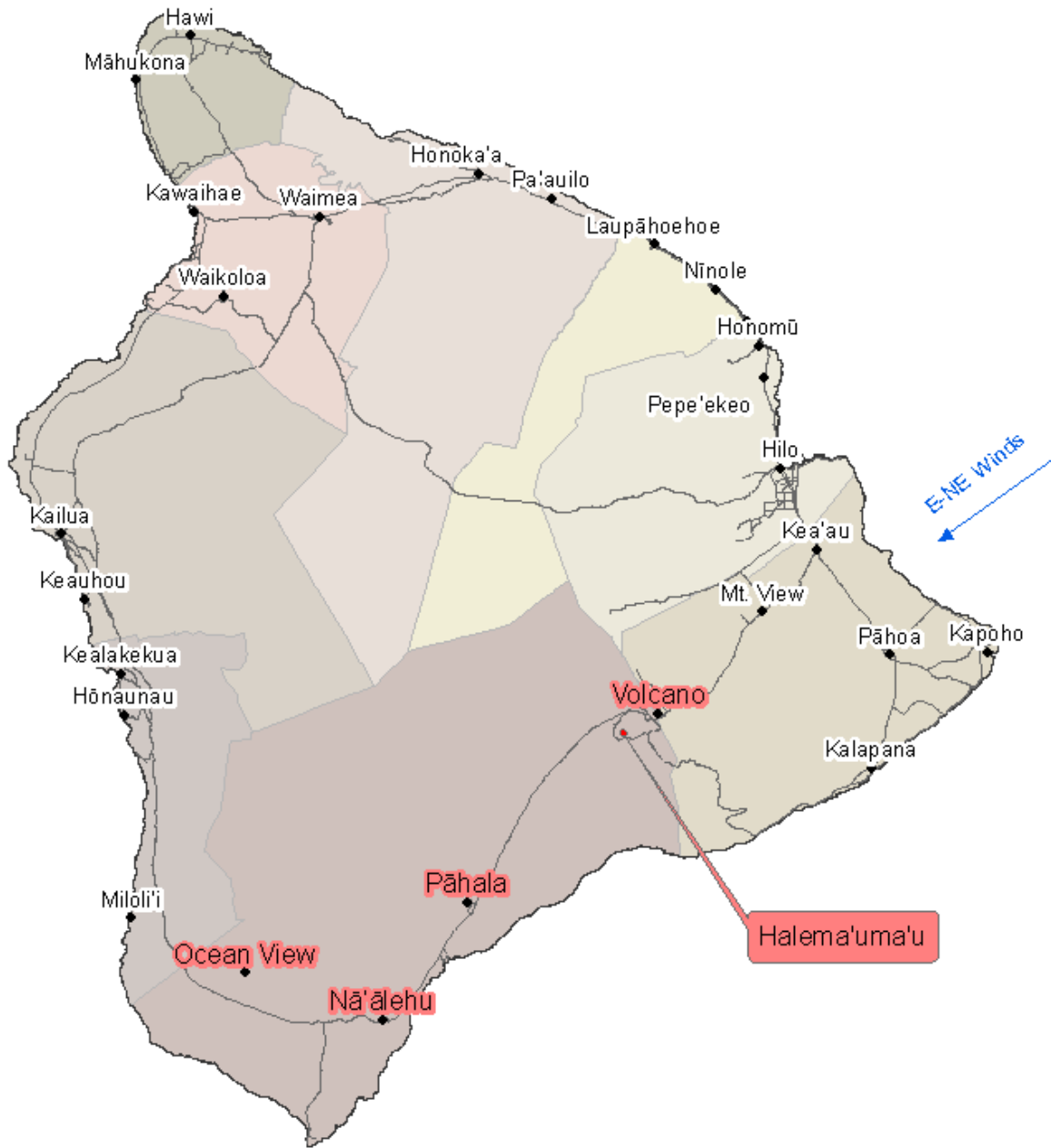
Integrated management of volcanic emission injury to plants

- Flush leaves and flowers with fresh water after their exposure to acid rain or ash.
- Treat acidified irrigation water to raise the pH.
- Grow plants under cover, in greenhouses where possible.
- Grow plants that are SO₂-resistant, if possible.
- Selectively and temporarily cover valuable plants with fabric or plastic.
- As a possible preventative measure, spray plants with anti-transpirant products to close their stomata or with bicarbonate solution to neutralize acidity (while preliminary field tests have shown some promise, these measures are still the subjects of current research proposed by the University of Hawai'i to scientifically validate their effects).

The symptoms of volcanic emission injury to plant foliage can be difficult to diagnose accurately with certainty. However, the symptoms usually develop relatively rapidly compared to many other plant diseases when the dosage of SO₂ is high or the exposure is prolonged. Symptoms on plants can appear within hours after severe exposure events. The symptoms can resemble other biotic plant diseases, such as foliar wilts caused by root rots or blights or spots caused by plant pathogenic bacteria or fungi. Economic impacts can be severe where dosage of SO₂ is high and/or prolonged or frequent and plants are sensitive.

Extent of damage by vog to Hawai'i's protea crops in 2008

From June 9 to 30, 2008, one of the authors (K. Sewake), stationed in Hilo, conducted a protea crop damage and



Map of the island of Hawai'i identifying the outline of the island, major roadways, and town place names. Shaded areas within the map delineate the nine judicial districts of the island. The reddish-shaded box points to the new fumarole (Halema'uma'u) that erupted at Volcano in March, 2008. The typical E-NE trade winds send sulfur dioxide and other air pollutants downwind to affect agriculture in the vicinity of the reddish-shaded site names. Photographs and observations of vog-damaged plants in this publication are from Volcano, Pāhala (and nearby Wood Valley, not indicated on the map), Nā'ālehu, and Ocean View. Map courtesy of G. Bailado, Hawai'i County

loss-assessment survey of protea growers. The survey indicated that most of the damage to protea by vog seemed to be concentrated in the southern parts of the island of Hawai'i, namely Hawaiian Ocean View Estates, Pāhala, and Nā'ālehu. Dozens of cultivars of this plant are grown for flower production. The survey is ongoing, but based on the response of 14 farmers (representing 36 acres of protea), the economic damage and social effects by vog to protea farms is significant (Table 3). The vog has dampened farmers' willingness to remain in business and has caused farmers to consider relocation, to change to more vog-resistant protea cultivars, to diversify their farming operations by replacing protea with alternate crops, to lose significant income, and to consider stopping farming the crop altogether or evacuating the area. Some protea farms face or report the possibility of total crop loss for 2008. An average of 43% loss of total family income was reported by survey respondents. Protea farmers should note that there seems to be variation among cultivars for reaction to the vog, according to survey results. Vog-tolerant types (20% or less damage to the plants) are "Kings" and *Banksia* species. Vog-susceptible protea cultivars are the widely grown, productive types known as pincushion proteas (*Leucospermum* spp.).

Government agency response to the crisis created by vog injury

Since the Halema'uma'u emissions began on March 12, 2008, numerous early communications by farmers to legislators and later testimony provided by farmers, government officials, and University of Hawai'i at Mānoa personnel at the Hawai'i State Capitol at a Round Table Discussion of the House Special Committee on Vog (July 10, 2008, Honolulu) and at Governor Linda Lingle's Interagency Task Force Meeting on Vog Effects (July 18, 2008, Hilo) provided sufficient information via appropriate government channels for the United States Department of Agriculture (USDA) to act on an official request for a declaration of disaster. As a result, the USDA announced a Disaster Declaration due to vog on July 30, 2008. This declaration provides funding for relief of damages due to crop production losses. Farmers affected can also apply for funding due to revenue losses under a USDA Supplemental Agricultural Assistance Program. Farmers are encouraged to apply for disaster relief funding by contacting their local USDA-Farm Service Agency office for assistance.

The Hawai'i Department of Agriculture (HDOA) also

provides farm loans to farmers. Those farmers who have difficulty with their existing HDOA loan and those who need operating funds were encouraged to contact their local HDOA office for more help. Loan officers will work closely with farmers on an individual basis to provide assistance and information.

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Table 3. Survey results for vog damage to protea farmers in Hawaiian Ocean View Estates, conducted June 9–30, 2008).

Type of sale	Avg. annual yield	Avg. annual total sales value prior to vog damage (\$)	Anticipated loss in sales for this calendar year due to vog damage (\$)
Cut flowers	Total of 88,305 cut flowers (5 responses)	Total \$108,388 or \$15,484 average per farm (7 responses); range = \$4,000 to over \$50,000	Total = \$134,755 (7 responses)
Plants and cuttings	Total of 7,800 plants and cuttings (2 responses)	No data	Total = \$134,500 (3 responses)
Other	Wreaths, baskets, arrangements, gift boxes, foliage (3 responses)	Total = \$77,700 or \$25,900 average per farm (3 responses); range = \$700 to \$50,000	Total = \$75,500 (4 responses)
			\$364,755 (8 responses)

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