

Exploring the edge of a natural disaster

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Received 4 September 2012; revised 16 October 2012; accepted 24 October 2012

ABSTRACT

Natural geological, chronic and acute release of volcanic gases can have a dramatic impact on vegetative ecosystems and potential impact on regional agriculture and human health. This research incorporates a series of observations using leaf level gas exchange, chlorophyll fluorescence and remotely sensed reflectance measurements of vegetation experiencing chronic exposure to volcanic gas emissions; to develop techniques for monitoring the relative health of vegetation along the edge of an acute vegetative kill zone of a natural disaster and potential pre-eruption vegetation physiology. Experiments were conducted along an elevation gradient that corresponds to the SO₂ gradient on vegetation along the south flank of Volcán Turrialba, Costa Rica. This study site is a natural environment with high volcanic degassing activity with significant SO₂ emissions (n/d - 0.281 ppm). Corresponding to an SO₂ gradient, a substantial increase in CO₂ concentration of (430 - 517 ppm) was identified. We further show the physiological interactions of SO₂ and CO₂ have on vegetation along the kill zone of this natural disaster can be assessed by examining the SO₂/CO₂ ratios. The physiological indices tested and relationships among measurements emphasized in this research will add to the assessment of the impact atmospheric volcanic gas emissions have on the physiology of surrounding vegetation as well as advance the capability of remotely sensed environmental stress in natural settings.

Keywords: Carbon Dioxide; Chlorophyll Fluorescence; Leaf Level Gas Exchange; Natural Disaster; Remote Sensing; Sulphur Dioxide; Volcanic Gas Emissions

1. INTRODUCTION

On January 4th, 2010 Volcán Turrialba entered a new phase of activity, marked by an increased number of volcanic low-frequency signal B type earthquakes and large and high gas plumes [1]. On January 5th, two minor eruptive events occurred at 2:29 pm and 2:45 pm, which emitted ash over local farming areas of La Central and La Silvia, Capellades town, finer ash at Tierra Blanca, Llano Grande and Tres Rios, and volcanic dust in eastern San Jose [1]. Two new small craters opened, which later joined and formed a fracture-like structure where gases were expelled at temperatures greater than 350°C [1]. Residents from nearby farms around the volcano were evacuated. On January 8th the seismic activity and ash emission decreased, but after almost 144 years of inactivity, Volcán Turrialba had renewed its eruptive activity.

It is well known that tropical forests across the globe are disappearing [2-8]. It is widely recognized that tropical forest species are being adversely affected by exploitation, land-use changes, climate change and natural geological disturbances [7,9,10]. Along with the importance of tropical plants for their well recognized ecological goods and services of habitat creation and global carbon balance, these ecosystems have significant implications on water and soil quality in these regions. This study is an initial examination of a natural gradient of impact established by the recent volcanic gas releases on native vegetation, but has added implications for the agricultural zone and food supply within the same vicinity and potential impact on human health.

Sulphur dioxide (SO₂) and carbon dioxide (CO₂) are among the atmospheric contaminants and phytotoxic by-products emitted during recent volcanic activity at Turrialba. This investigation attempts to characterize the pre-symptomatic effects of these naturally emitted air pollutants on the physiological performance of native plants and their potential influence on the composition and stability of the ecosystems in which the plants live.

Leaf level gas exchange, chlorophyll fluorescence and spectral reflectance are important tools for evaluating stress and physiological impacts of air pollutants on plants [11,12]. The scope of this initial work was to study the effects of the recent volcanic emissions on photosynthetic activity, chlorophyll fluorescence and reflectance of plants under stress from chronic exposure to concentrations of elevated SO₂ and CO₂ under otherwise natural conditions.

Stress is characterized as any disturbing influence that results in physiological consequences [13]. However, by the time plants display visible symptoms of stress, they can already be adversely affected [14]. Photosynthetic reduction, increase in chlorophyll fluorescence and shifts in spectral reflectance in the absence of, or prior to, visible symptom expression could indicate suppression of growth or reduced vigor in an otherwise apparently healthy plant [15].

SO₂ is a well known stress inducing agent which can cause toxicity, reduced growth, cell death, plant organ death and whole plant death; and on a larger scale can influence biological systems, environments and whole eco-regions [16]. Environmental conditions, concentrations of SO₂, duration of exposure, sulphur status of soil and genetic attributes of plants determine the degree of stress and physiological impact due to the phytotoxicity of SO₂ [17].

To investigate the interactive physiological effects of elevated SO₂ and CO₂ under naturally occurring conditions, experiments were conducted along an elevation gradient between 1939 and 3280 meters along the south flank of Volcán Turrialba, Costa Rica. Measurements were conducted along an access road, which starts in Pastora de Santa Cruz, and leads to the entrance to Parque Nacional Volcán Turrialba, and the peak of the edifice of the volcano. Volcán Turrialba is a composite stratovolcano located 25 kilometers north east of Cartago on the eastern end of the Central Volcanic Range (Cordillera Volcanica Central) and approximately 40 kilometers east of San Jose, Costa Rica (Lat. 100 020 North, Long. 830 450 West) [18]. The peak of Volcán Turrialba is 3328 meters above sea level and is completely covered by vegetation except in the caldera [19]. Volcán Turrialba is the easternmost, and one of Costa Rica's largest active volcanoes.

This initial research had three main objectives: 1) to establish relationships between leaf-level gas exchange and elevated atmospheric concentrations of SO₂ and CO₂ related to increased volcanic emissions, 2) to identify physiological correlations between leaf-level gas exchange and chlorophyll fluorescence measurements of plants under long term stress induced by volcanically emitted SO₂, and 3) to provide evidence that remotely sensed reflectance-derived fluorescence ratio indices can

be used to monitor plant stress and photosynthetic functioning.

2. STUDY PLANT

Gunnera insignis, common name poor man's umbrella or sombrilla de pobre, was chosen as the experimental plant for this experiment (**Figure 1**). *G. insignis* is located at the peak of Volcán Turrialba and continuously at all elevations, to approximately 500 meters. *G. insignis* is a giant herb ranging throughout Panama, Costa Rica and Nicaragua at elevations from 500 meters to 3400 meters [20]. *G. insignis* inhabits moist, nutrient poor, acidic soils and is capable of establishing a symbiotic relation with a nitrogen fixing cyanobacterium (*Nostoc* sp.). The plant has a solitary, thick, semi-erect stem, which holds a terminal set of rounded extremely large (can reach greater than 2 square meters) lobed leaves [20], providing a large surface for gas exchange with prevailing atmospheric conditions. Plants found at the lowest elevations at which *G. insignis* was identified on the south flank of Turrialba (1939 meters and 2454 meters), were designated as control plants, due to minimal levels of detectable atmospheric SO₂ concentration and used to run A-C_i, net CO₂ assimilation rate, A, versus calculated substomatal CO₂ concentration, C_i response curves and light response curves.

Under natural conditions, multiple environmental stressors co-occur and can result in a wide range of physiological effects. Analysis of the A/C_i curve and the light response curve showed sample plants in this study were neither light or CO₂ stressed. The leaf temperature/air temperature ratio shows that physiological shifts toward increasing heat production, was limited, indicating minimal stress of control plants (**Table 1**).

3. GAS EXCHANGE

Simultaneous measurements of leaf level gas-exchange including CO₂ assimilation rate (A), stomatal conductance (g_s), intercellular CO₂ (C_i) and chlorophyll fluorescence parameters of steady state fluorescence (F_s), quantum yield of PSII calculated from (F_mⁱ - F_sⁱ / F_mⁱ) and maximum quantum yield of PSII calculated from (F_vⁱ / F_mⁱ) as well as CO₂ response and light response curves were taken using infrared gas analyzers and a Leaf Chamber Fluorometer (LCF) [21].

Leaf level gas exchange on *G. insignis* and atmospheric SO₂ and CO₂ concentrations were measured at elevations ranging between 1939 meters and 3280 meters (**Table 1** and **Figure 1**). A steady rise in atmospheric SO₂ and CO₂ concentrations with a corresponding rise in elevation was detected during a 24-hour sampling period (**Table 1**). A few anomalies were observed; at 2773 m, SO₂ measurements were lower than the previous lower

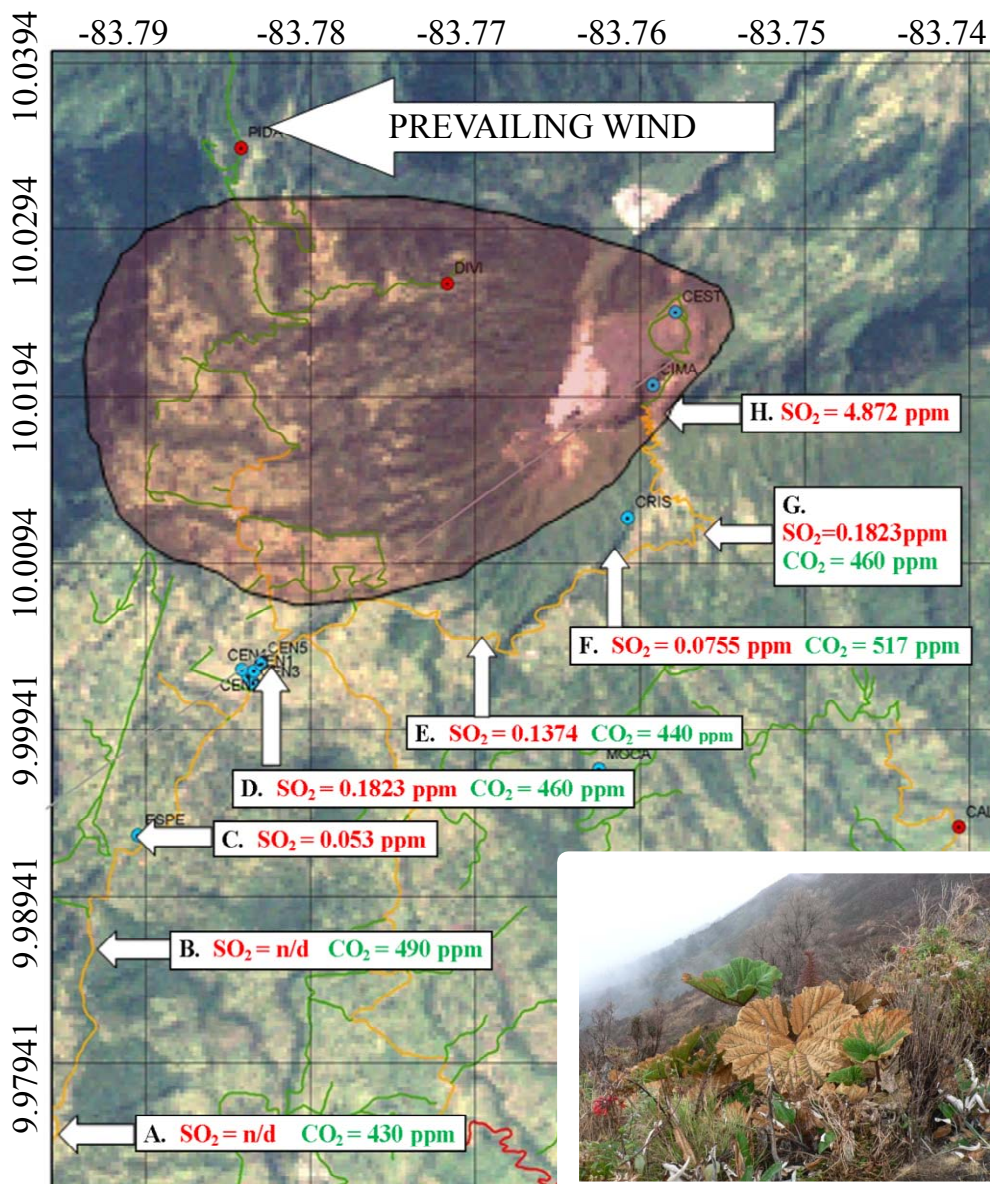


Figure 1. Map of Volcán Turrialba, access road (orange) with white arrows identifying sampling sites with elevations A = 1939 m, B = 2454 m, C = 2594 m, D = 2673 m, E = 2789 m, F = 2950 m, and G = 3280 meters used for SO₂, CO₂ and physiological measurements. The highlighted area is the kill zone. Image in bottom right is the study plant *G. insignis*.

elevation, and at 2789 meters there was much lower SO₂ measured. These anomalies are attributed to microclimatic variations in the data collection sites. *G. insignis* measured at 2789 meters elevation displayed the maximum A of $16.7 \mu\text{mol CO}_2 \text{ m}^{-2} \cdot \text{s}^{-1}$ and the maximum g_s of $0.329 \text{ mol CO}_2 \text{ m}^{-2} \cdot \text{s}^{-1}$, the highest rates observed during the study.

The first objective of this research was to establish relationships between leaf-level gas exchange and elevated atmospheric concentrations of SO₂ and CO₂ due to geologic emissions. Due to a limitation on the time available to conduct this research it is difficult to make statistically

valid comparisons. However, results may be seen as a way to gain a better understanding of the interactive impacts of naturally elevated SO₂ and CO₂ on the species studied under these ecologically shifting conditions bordering the edge of a natural disaster.

During this study period, volcanic gas concentrations along an elevation gradient ranged from 0.2805 ppm to non-detectable for SO₂ and from 517 to 430 ppm for CO₂. SO₂ concentrations of 4.872 ppm were identified at the edifice of Volcán Turrialba at an elevation of 3280 meters (Table 1). However, the measurements recorded at these sites are not included in the experiments described below

Table 1. Gas exchange parameters measured on *Gunnera insignis* at different elevations with corresponding SO₂ and CO₂ concentrations.

Elevation (meters)	SO ₂ (ppm)	CO ₂ (ppm)	Photo (A) ($\mu\text{mol CO}_2 \text{ m}^{-2} \cdot \text{s}^{-1}$)	C _i ($\mu\text{mol CO}_2 \text{ mol}^{-1} \cdot \text{air}^{-1}$)	Conductance (g _s) ($\text{mol CO}_2 \text{ m}^{-2} \cdot \text{s}^{-1}$)	LeafTemp/AirTemp (°C)
1939	n/d	430	14.9	278	0.275	1.03
2454	n/d	490	12.3	312	0.286	0.75
2594	0.053	-	10.75	306	0.236	0.74
2673	0.182	460	13.55	279.5	0.211	0.84
2773	0.137	440	12.65	303	0.258	0.68
2789	0.076	517	16.7	294	0.329	0.97
2950	0.281	430	15.17	247.7	0.184	0.99

due to extreme foliar damage and all related physiological processes. A measurements reported in this study demonstrate a weak correlation with SO₂ concentrations ($r^2 = 0.0575$). Previous studies reveal that photosynthetic response to SO₂ exposure depends on pollutant dose and genotype, and can either inhibit, stimulate or have no effect on photosynthesis [16]. Overall, minimal variation of carbon assimilation rates are observed among plants tested along this SO₂ gradient (**Table 1**). Moreover, carbon assimilation rates were not correlated with other measurements in this study due to over saturating levels of CO₂ as identified by the *A/C_i* curve (not shown).

g_s and SO₂ concentrations are moderately correlated ($r^2 = 0.552$). Reports on effects of SO₂ on g_s are highly variable, and depend strongly on environmental and exposure conditions and SO₂ concentrations [22]. Stomatal conductance has been reported as increasing at low SO₂ concentrations in some species, while partial stomatal closure is induced due to high concentrations of SO₂ [16]. In this study *A* measurements are weakly correlated with g_s ($r^2 = 0.073$). Differences in SO₂ uptake due to different g_s may partially explain the differences in SO₂ sensitivity [23], albeit not universally.

Intercellular carbon dioxide (C_i) and SO₂ concentrations are also moderately correlated ($r^2 = 0.514$). *A/C_i* curves developed from control plants, demonstrated as C_i increases so does *A*. However, the correlation between *A* and C_i along the study site transect is moderate ($r^2 = 0.331$). In order to identify and quantify the effects of SO₂ on C_i , measurements of mesophyll conductance (g_m) should be included, but unfortunately these measurements were not made. However, the potential impacts of SO₂ effects on mesophyll resistance should not be discarded. SO₂ effects on photosynthesis are more likely the result of increases in mesophyll resistance (e.g. internal cellular damage), as opposed to decreases in stomatal conductance. This conclusion is consistent with results

from Barton *et al.* (1980) [24] and Karenlampi and Houppis, (1986) [25].

4. CHLOROPHYLL FLUORESCENCE

The chlorophyll fluorescence parameters of steady-state fluorescence (F_s), quantum yield ($F_m' - F_s / F_m'$) and max quantum yield (F_v' / F_m') were measured on *G. insignis* at elevations of 2673, 2773, 2789 and 2950 meters (**Table 2**). Electron transport rate (ETR) was calculated, using the LI-COR algorithm, in simultaneous measurements. Measurements of chlorophyll fluorescence parameters were utilized to evaluate the stress effects imposed on PSII photochemistry and the physiological correlations between leaf-level gas exchange and chlorophyll fluorescence of plants under stress from elevated SO₂ and CO₂ concentrations, identified as the second main objective of this study. Results reveal steady-state-fluorescence (F_s) and interaction between SO₂ and CO₂ concentrations are moderately correlated and F_s and *A* are weakly correlated with ($r^2 = 0.450, 0.113$), respectively.

The relationship between steady state chlorophyll fluorescence, quantum yield and maximum quantum yield and gas exchange measurements of *A*, g_s and C_i is complex and influenced by environmental factors, as well as physiological adaptations. Dobrowski *et al.*, (2005) [26] emphasized that the relationship between F_s and *A* is mediated through competing de-excitation pathways of photochemical quenching and non-photochemical quenching. This relationship shows a direct and inverse relationship depending on the intensity of the stress and the status of the alternate de-excitation pathways.

Chlorophyll fluorescence parameters; $F_m' - F_s / F_m'$ and ETR are strongly correlated with atmospheric SO₂ concentrations ($r^2 = 0.801$ and 0.799), respectively. However, ETR and *A*, and $F_m' - F_s / F_m'$ and *A* show weak

Table 2. Chlorophyll fluorescence parameters measured on *Gunnera insignis* at different elevations with corresponding SO₂ concentrations.

Elevation (meters)	SO ₂ (ppm)	Steady-State Fluorescence (F_s)	Quantum Yield ($(F'_m - F_s)/F'_m$)	Max Quantum Yield (F'_v/F'_m)	Electron Transport Rate (ETR)
2673	0.182	843.8	0.189	0.611	96.669
2773	0.137	1040.2	0.198	0.664	101.158
2789	0.076	1074.4	0.207	0.715	105.588
2950	0.281	927.7	0.189	0.741	96.38

correlations ($r^2 = 0.217$ and $r^2 = 0.231$), respectively, suggesting the induction of a non-photosynthetically productive metabolic pathway which could potentially provide a target mechanism for a remotely sensed measure of overall plant health. Previous studies have identified potentially large alternative electron sinks that contribute to photo-protection which are particularly important in plants growing for extended periods under of stressful conditions [27-30]. Alternative-acceptor-dependent photo-protection via O₂, the water-water cycle, nitrate, sulphate, light-stimulated synthesis of fatty acids, and oxaloacetate reduction are among a list of suggested mechanisms which may enable the progression of ETR under stress conditions to maintain rates similar to those of non-stressed leaves [30].

Zarco-Tejada *et al.*, (2003) [31] state, "In general, steady-state chlorophyll fluorescence is low when photosynthesis is high. However, chlorophyll fluorescence can also decline when photosynthesis is low, because of an intensified protective quenching action on chlorophyll fluorescence production. Under increasing stress, plant tissues shift toward increasing heat production to dissipate excess energy, and this tends to have the effect of reducing chlorophyll fluorescence production, at least in the initial and intermediate stages of stress". These observations suggest that under these environmental conditions it is not possible to estimate A directly from F_s , which is consistent with previous findings [26,32,33].

5. REMOTELY SENSED REFLECTANCE

A standard reflective index used in remote sensing work is the normalized difference vegetation index (NDVI), which is an index of chlorophyll content calculated from $(R750 - 675)/(R750 + R675)$ [34]. A revised version of the NDVI, which is based on a strong correlation and sensitivity to a range of chlorophyll concentrations and shifts in the Red-Edge is defined as chl NDI or mNDVI $(R750 - 705)/(R750 + R705)$ [12,35, 36]. The photochemical reflective index (PRI), which is based on reflectance at 531 nm and calculated as $(R531 - 570)/(R531 + 570)$ provides a strong estimate of photosynthetic efficiency for most species [37]

To most accurately track subtle changes in F_{ss} , the double-peak optical index (DPi) was utilized, calculated from $(D688 \times D710)/D697^2$ [31]. Due to the complexity of different study methods and field conditions, such as instruments used, analytical methods, characteristics of the species tested and changing environmental conditions, no one method has been universally adopted as satisfactory under all growth and environmental conditions [38].

Leaf level reflectance data from sample plants were gathered using a portable spectrometer (UniSpec, PP systems, Haverhill, MA), 1 meter above vegetation. Remotely sensed spectra for intact leaves of *G. insignis* were measured at elevations of 1939, 2594, 2673, 2789 and 2950 meters with SO₂ concentrations of n/d, 0.053, 0.1823, 0.0755 and 0.2805 ppm, respectively (**Table 3**).

The third main objective of this research was to provide evidence that remotely sensed reflectance-derived fluorescence ratio indices can be used to monitor plant stress and photosynthetic functioning. Leaf reflectance of SO₂ stressed plants show that in at least some cases, there were significant changes and shifts that could be detected remotely. When comparing the shifts and changes in reflectance across a wide range of wave-lengths there are general trends, but a few inconsistencies. These inconsistencies could have been caused by frequently changing environmental conditions, such as changing light conditions and precipitation causing differences in reflectance.

Reflectance spectra for *G. insignis* measured at elevations 2673 and 2950 meters with SO₂ concentrations of 0.1823 and 0.2805 ppm, respectively, show maximum shifts in the Red-Edge region and maximum reflected PAR (**Figure 2**). As expected and previously reported [39-42] the maximum of the first derivative (the inflection point of the red-edge, IPP) shifted toward shorter wavelengths, due to pigment degradation. Gates *et al.*, 1965 [43] provided observations that chlorosis caused by the loss of chlorophyll induces an increase in reflectance across the visible spectrum, which causes a blue shift of the IPP. In addition, Rock *et al.*, (1988) [41] displayed air pollution results in a blue shift of the IPP due to loss of

Table 3. Remotely sensed reflectance indices.

Elevation (meters)	SO ₂ (ppm)	Red-Edge mNDVI	Double Peak Optical Index Dpi	Photochemical Reflective Index PRI	Normalized Difference Vegetation Index NDVI	Modified Red-Edge mNDI	Reflective Water Index WI
1939	n/d	0.585422	0.891596	0.015323	0.86752	0.654559	1.156297
2594	0.053	0.475426	0.953824	-0.00723	0.73413	0.568996	1.105463
2673	0.182	0.505334	1.093702	-0.01248	0.78142	0.595786	1.041003
2789	0.076	0.626071	0.95177	0.047125	0.85928	0.724589	1.130384
2950	0.281	0.433832	1.147461	0.016208	0.65548	0.58324	1.054046

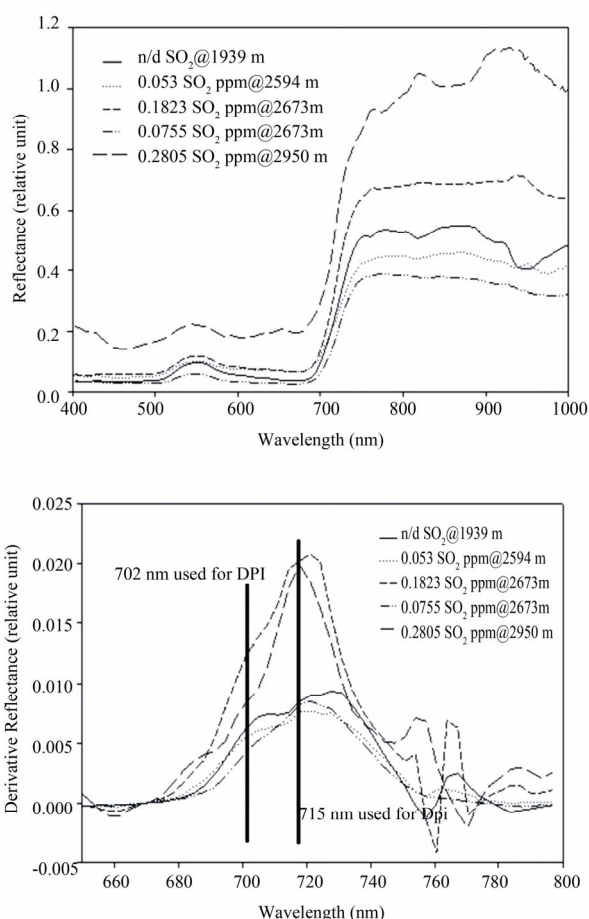


Figure 2. Remotely sensed reflectance and derivative spectrum on a single leaf of *Gunnera insignis* at different SO₂ concentrations, used to calculate Dpi index measured with Unispec-SC portable spectrometer (UniSpec, PP Systems, Haverhill, MA) in the 400 - 1000 and 640 - 820 nm spectral range, respectively.

chlorophyll b.

Reflectance spectra for *G. insignis* measured at elevations 1939, 2594 and 2789 meters with SO₂ concentrations of n/d, 0.053 and 0.0755 ppm, respectively, show minimal shifts in the Red-Edge region and the least reflected PAR (**Figure 2**). These results generally corre-

spond to the highest values of CO₂, the highest rates of conductance and the highest A rates. The SO₂ and CO₂ relationship will be discussed in a following section, but should be noted throughout these measurement results.

The most useful reflective index incorporated in this study was that based on the double-peak (Dpi) feature in the 700 - 715 nm spectral region, as reported and demonstrated by Zarco-Tejada *et al.*, 2003 [31]. Strong correlations were calculated between Dpi and SO₂, $F'_m - F'_s / F'_m$, ETR and CO₂ with $r^2 = 0.975, 0.945, 0.942$ and 0.801 , respectively. Moreover, Dpi is at least moderately correlated with every physiological measurement in this study.

It has been previously reported that the double-peak indicator of fluorescence emission can be detected at times of higher fluorescence emission can disappear during times of lowest fluorescence emission [31], corroborating results were found in this study (**Figure 2**). However, Zarco-Tejada *et al.*, 2003 [31] observed this double-peak feature as diminishing with increasing stress induction. Confounding results from this study are seen in (**Figure 2** and **Table 3**), which show the greatest Dpi value of 1.148 and 1.094, corresponding to the highest level of SO₂ concentration of 0.2805 and 0.1823 ppm, respectively. The Dpi index in this study was developed as a modified optical index calculated using $D702 \times D715 / (D708)^2$. The above mentioned results suggest the Dpi using $D702 \times D715 / (D708)^2$ is capable of remotely tracking SO₂ induced stress under natural conditions.

In this study, ground based leaf-level reflectance measurements allowed the evaluation of SO₂ induced stress and showed that shifts in the IPP toward shorter wavelengths and greater maximum values corresponded with SO₂ stress. And thus the incorporated reflectance indices appear to be a valid tool for remote tracking of SO₂ induced stress.

6. SULPHUR DIOXIDE AND CARBON DIOXIDE RELATIONSHIP

Passive monitoring was conducted to determine atmospheric gas concentrations of SO₂ using Ogawa Pas-

sive Air Sampler's [44]. Lab analyses of $[\text{SO}_2]$ were conducted at Anatek Lab, in Moscow, Idaho. $[\text{CO}_2]$ measurements were taken using a Vaisala CARBOCAP Hand-Held Carbon Dioxide Meter GM70 with a GMP222 Carbon Dioxide Probe [45].

This study site is a natural environment with high gas emission activity with significant SO_2 emission. However, along with the increased SO_2 emission a substantial increase in CO_2 concentration was identified (**Table 1**). Previous studies have reported an increase in A due to CO_2 enrichment, which has been attributed to an increase in substrate availability for Rubisco [46]. The reduction in g_s due to high CO_2 concentrations is a well known phenomenon, however this reduction would be expected to reduce the SO_2 flux into the leaf interior, which would reduce the effective dose of SO_2 [47]. The role of CO_2 enrichment in protecting plants against harmful airborne pollutants has been reported in previous studies [48,49].

This SO_2 and CO_2 relationship is very apparent in the measurements and observations collected around the fault scarp at the 2789 meters sampling site (**Table 1** and **Figure 1**). The fault scarp likely facilitates CO_2 accumulation, either by virtue of CO_2 emissions along the fault plane and/or CO_2 not being blown away from the low area due to topography. Measurements collected within the fault scarp seem to be influenced from the sharp drop in SO_2 from 0.1374 to 0.0755 ppm and back up to 0.2805 ppm (**Table 1**) and a sharp rise in CO_2 from 440 ppm to 517 ppm and back down to 430 ppm (**Table 1**). Gas exchange measurements of A and g_s (**Table 1**), chlorophyll fluorescence parameters of F_s , ($F'_m - F_s/F'_m$) and ETR (**Table 2**) and remotely sensed reflectance indices of mNDVI, PRI and mNDI were all highest at this sample site (**Table 3**).

To emphasize the physiological interaction SO_2 and CO_2 concentrations have on vegetation, the capability of the interaction and induced effects to be remotely detected using the Dpi index a ratio of SO_2/CO_2 concentrations was developed and correlated with the Dpi index results. The SO_2/CO_2 ratio and Dpi index are strongly correlated ($r^2 = 0.927$). Previous studies have shown that physiological and physical measurements of plants exposed to elevated CO_2 and SO_2 were similar to those observed for CO_2 enrichment only [47]. The findings of this study lend further support to the observed relation of the phytotoxic effect of SO_2 is reduced by the positive physiological responses plant undertake when exposed to increase concentration of CO_2 [47].

Limitation of plant growth and/or quantification of SO_2 induced stress cannot be assigned to a single physiological process or measurement. The direction and magnitude of the physiological alteration is not completely clear, and plants' resistance to SO_2 varies depending on the plant species [50]. However, the results of

this study may be used to gain a better understanding of the impacts of volcanically emitted SO_2 on the species studied, different species, the ecosystem and different environments under elevated SO_2 loading.

From a general analysis of the data collected along the edge of this kill zone, it may be concluded that SO_2 affects *G. insignis* gas exchange, chlorophyll fluorescence and reflectance in a variety of ways, which were in some cases buffered by elevated CO_2 concentration. The results of this study show that elevated CO_2 mitigated the damaging effects of SO_2 in *G. insignis*. This study indicates that *G. insignis* growing in the volcanically emitted SO_2 toxic region of Volcán Turrialba has developed a physiological adaptive mechanism that enables the plant to survive. One point to consider is the easily observable chlorosis on mature leaves of *G. insignis*, as opposed to the non-visible effects on younger leaves, which suggests the plants resource partitioning mechanisms that allow young leaves to remain relatively healthy despite high SO_2 levels, but eventually the adaptive adjustments break down and leaves die. While adaptive responses may develop in certain species and genotypes, most will eventually succumb to elevated SO_2 .

It should not be overlooked that results and physiological responses of the study plants in this research could have been confounded by the presence of other volcanically emitted air pollutants and possibly a multitude of non-measured environmental perturbations. However, environmental conditions such as light, moisture and photoperiod remain fairly constant at these latitudes. Most field experiments have not been able to separate and distinguish between the physiological effects of individual pollutants when they occur in mixtures.

Relationships identified between SO_2 and the Dpi index developed using $D702 \times D715/(D708)^2$, Dpi and quantum yield and Dpi and electron transport rate ($r^2 = 0.975$, 0.945 and 0.942), respectively, along this SO_2 gradient further demonstrate the validity to the already well documented capability of the Dpi index to track chlorophyll fluorescence. Results of this study add to the increasing evidence that remote sensing and derivative reflectance analysis is capable of identifying plant stress under natural conditions. The capability and extent to which this study's findings can be extrapolated to larger scale detection of SO_2 induced stress using aerial and/or satellite imaging should be further explored. Validation of this study's results via similar experiments on vegetation surrounding other volcanoes with similar gas emissions would be of great value. With the above mentioned recent increased volcanic activity of Volcán Turrialba and the importance of the surrounding agricultural areas to the locals, the region and the country; particular invested research in both monitoring the volcanic activity and

Table 4. NDVI values from Landsat 5 TM and Landsat 7 ETM+ images and ground measurements.

Elevation	Dec.13	Dec.27	Jan.15	Apr.5	Ground Data
(m)	2000	2008	2010	2010	(May 2010)
1939	0.8157	0.809	0.7579	0.7654	0.8675
2594	0.8011	0.6445	0.696	0.7942	0.7341
2673	0.6789	0.7279	0.474	0.5524	0.7814
2789	0.7867	0.7692	0.7458	0.5958	0.8593
2950	0.7332	0.6895	0.5729	0.4377	0.6555

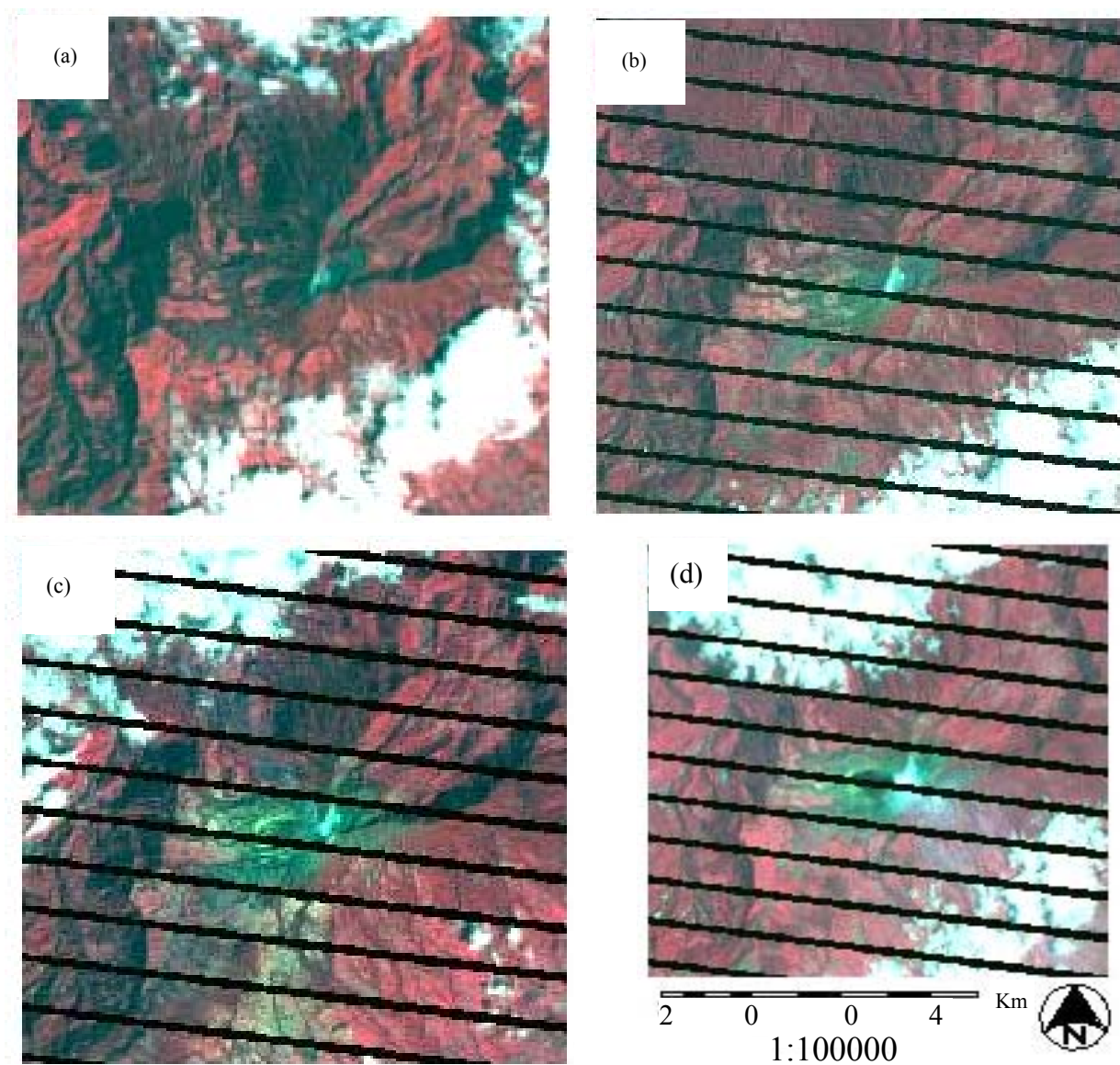


Figure 3. Landsat TM and ETM+ derived false color composites, near infra-red shown as red, red shown as green and green shown as blue (4, 3, 2) time series of images used to calculate vegetation indices along the elevation gradient sampled on site (**Table 4**). (a) Dec.13, 2000; (b) Dec. 27, 2008; (c) Jan. 15, 2010; and (d) April. 5, 2010. Horizontal white lines are due to the scan line corrector error present in Landsat ETM+ data following its failure in 2003.

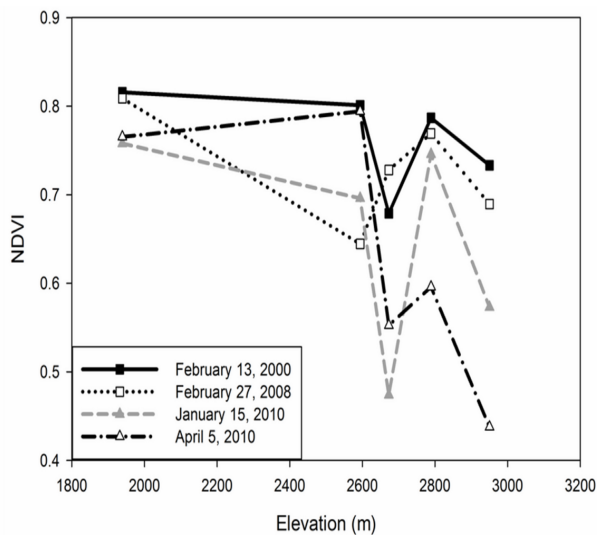


Figure 4. NDVI extracted from available Landsat 5 TM scene and three Landsat 7 ETM+ scenes over Costa Rica. Each point represents the NDVI of a 30 meter pixel along an elevation gradient following the edge of the natural disaster.

surrounding vegetative response is warranted.

7. PERSPECTIVE

This initial examination has highlighted potential physiological measurements to describe effects of volcanic emissions on *G. insignis* as an indicator species, but can be used to emphasize and focus future experiments; from direct leaf level physiological and reflective measurements on single individuals to ecosystem scale remote sensing with aerial and satellite imaging capabilities. As proof of this concept, NDVI values were determined from Landsat 5 TM and Landsat 7 ETM+ data using the USGS GLOVIS tool, for temporal periods predating and concurrent with the volcanic activity as well as a fourth scene acquired close to the dates of the field campaign: February 13, 2000, February 27, 2008, January 15, 2010 and April 5, 2010, respectively (**Table 4** and **Figure 3**). The raw Digital Number (DN) values were converted to top-of-atmosphere reflectance with dark object subtraction (TOA-DOS) to account for atmospheric effects [51]. We then processed the imagery through a Matlab script that calculated NDVI and queried pixels according to a list of GPS coordinates relating elevation to sampling location from the field campaign. **Figure 4** shows the results of the ETM+ analysis.

When NDVI values are plotted along the elevational gradient (**Figure 4**), a trend is easily identified. The first data point (elevation = 1939 m) plotted in **Figure 4** represents the control site with no detectable SO_2 , and highest NDVI values. The second data point (elevation = 2594 m) represents minimal SO_2 stress ($\text{SO}_2 = 0.053$

ppm) with NDVI values dropping from the previous site (**Table 4**). The third data point (elevation = 2673) represents extreme SO_2 induced stress ($\text{SO}_2 = 0.1823$ ppm) with moderate CO_2 buffering ($\text{CO}_2 = 460$ ppm) and dramatic drops in NDVI values. The next data point, we have referred to as “fault scarp” (elevation = 2789 m); this site displays the greatest CO_2 buffering ($\text{CO}_2 = 517$ ppm) from SO_2 induced stress ($\text{SO}_2 = 0.0755$ ppm), which is clearly demonstrated in the satellite derived NDVI values. The final data point in **Figure 4**, represents the most extreme SO_2 induced stress ($\text{SO}_2 = 0.2805$ ppm) and least CO_2 buffering potential ($\text{CO}_2 = 430$ ppm).

While the interactions between SO_2 and CO_2 are difficult to assess and whether the emissions are anthropogenic or natural, the ability to determine potential phytotoxic induced mortality can greatly limit the consequences and extent of damage. For a more effective assessment and possible control of the effects of atmospheric pollutants on tropical plants and forests, human health and the environment, it is necessary to further develop strategies, test hypotheses and build models for regional and ecosystem monitoring, that are economically viable, and can be used in remote areas.

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