# CHEMICAL AND MINERALOGICAL CHARACTERIZATION OF AGRICULTURAL SOILS INUNDATED BY THE DECEMBER 26, 2004 TSUNAMI AFTER INTRINSIC BIOREMEDIATION IN BANDA ACEH, SUMATRA ISLAND, INDONESIA[1]

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**Abstract:** Almost 1.5 years and 3.5 years after the December 26, 2004 tsunami disaster, soil samples (10-20 cm) were taken from two adjacent sites located in the agricultural area of Banda Aceh, Aceh Province, Sumatra Island, Indonesia in order to investigate the impact of seawater flooding. The tsunami disaster deposited sediments containing extremely high concentrations of salts and heavy metals. The salt contents (detected as B, Na, Ca, Mg, and Cl), as well as the salinity levels (detected by electrical conductivity, EC) in tsunami-impacted soils still remained significantly increased compared to non-impacted soils, even after 1.5 and 3.5 years of intrinsic bioremediation. Heavy metals such as Pb, Cd, Zn, Cu, Ni, Co, Fe and Cr were significantly higher in impacted soils than in non-impacted soils in 2006, and they remained relatively increased in 2008, except for Cd and Pb which were significantly reduced. Furthermore, the tsunami disaster has led to an increase in macronutrients, such as N, P, K, and S, as well as to an increase in soil organic C content and C/N ratio. The tsunami-impacted soils, as assessed by Fourier transform infrared (FTIR) analysis, contained greater amounts of hydrophilic than hydrophobic organic compounds. The mean pH of soils in tsunami-impacted soils was 7.4 (in 2006) and 7.1 (in 2008), while in non-impacted soils the pH was 5.1 (in 2006) and 5.5 (in 2008). The soil mineral composition, as assessed by XRD analysis, revealed that the tsunami-impacted soils contained the major minerals (quartz, plagioclase and goethite), minor minerals (hornblende and lepidocrocite) and clay minerals (kaolinite, smectite and illite). Non-impacted soils contained major minerals (quartz, plagioclase, goethite and hornblende), minor minerals (lepidocrocite and cristobalite) and clay minerals (kaolinite and smectite). Thus, the tsunami disaster had potentially negative impacts, such as salt and heavy metal pollution, as well as potentially positive impacts, such as increases in major macronutrient contents and clay mineral composition, on agricultural soils.

**Additional Key Words**: Heavy metals, Salts, Soil organics, Soil minerals, FTIR, XRD.

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## Introduction

The earthquake of December 26, 2004 and the subsequent tsunami waves hitting Indonesia (Aceh, North Sumatra and Nias Island) and other countries in South Asia (Thailand, Malaysia, Myanmar, India, Sri Lanka) and Africa caused suffering and misery to people, damage to infrastructure, and large-scale environmental problems. Vast areas of agricultural and silvicultural sites were deluged, damaged by seawater (soil erosion, salinization) and contaminated with inorganic and/or organic pollutants of diverse origin. In some regions of Aceh, the zone of approximate tsunami damage represents total areas under 20 meters in elevation within 5 km of nearest coastline (the Food and Agriculture Organization of the United Nations (FAO), 2005a). Concerning the December 26, 2004 tsunami disaster, one may expect that most of the salts will be, or have already been, washed away by abundant rainfall. An FAO survey has found that high residual contents of salt are still present in the clay and silt fraction (FAO 2005b), which continue to be the major problem now. Another study reported on the effect of tsunami seawater flooding on arable sites and crop production in Aceh, Sumatra Island, Indonesia (Iskandar et al., 2006). Additionally, geochemists detected translocation of marine sediments and distribution of considerable amounts of pollutants across the tsunami-impacted coastal zones in Aceh (Moore et al., 2006; Monecke et al., 2008), Thailand (Szczucinski et al., 2005; Szczucinski et al., 2006; Szczucinski et al., 2007) and India (Chaudhary et al., 2006). Recent studies reported the impact of the earthquake and tsunami on groundwater and coastal areas, their water qualities, their environmental changes, and green reconstruction of the tsunami-affected areas using the integrated coastal zone management concept in India (Mascarenhas and Jayakumar, 2008; Chandrasekharan et al., 2008; Jayakumar et al., 2008; Sonak et al., 2008; Pari et al., 2008; Singh, 2008).

Concerning agricultural soil properties, many studies have focused on the impact of salinity, flooding, or waterlogging on plant growth (Barrett-Lennard, 2003; Saqib et al., 2004a; Saqib et al., 2004b; Aragues et al., 2004; Willis and Hester, 2004). However, the results from these studies cannot be transferred to the problems encountered after tsunami floodings. Until now, the impacts of disastrous tsunami seawater flooding on agricultural soil chemical and mineralogical properties have not been studied.

The main objective of our study was to reveal impacts of seawater flooding caused by the 26th December 2004 tsunami on the chemical and mineralogical properties of agricultural soils after almost 1.5-years and 3.5-years of intrinsic bioremediation. The results of this study may provide a scientific basis to the development or application of bioremediation strategies, as well as contribute to the re-establishment and continued plants and crop production in the affected area.

## Materials and Methods

### Study sites and soil sampling

The study areas were located in Aceh Besar Regency, Banda Aceh, Aceh Province, Sumatra Island, Indonesia. The areas studied included tsunami-impacted areas (located in Lampisang village, Peukan Bada Subdistrict, Aceh Besar Regency), and tsunami-unimpacted areas (located in two villages: Garut Village and Pasheu Beutong Village, Darul Imarah Subdistrict, Aceh Besar Regency). The area severely impacted by the December 26 Tsunami are under intrinsic bioremediation. Topsoil layers (approximately 0-20 cm in depth) of three selected tsunami-impacted sites and three adjacent, un-impacted sites were sampled on May 21, 2006 after almost 1.5-years of intrinsic bioremediation (four composite, mixed samples per site from which five soil cores were randomly collected) and on June 15, 2008 after almost 3.5-years of intrinsic bioremediation (one composite, mixed sample per site from which five soil cores were randomly collected). The soil samples were sieved and stored at $4^{o}$C and $-80^{o}$C until analysis, and finally transferred to Georgia, USA and Muncheberg, Germany for analyses.

### Soil chemical characterization

Soil pH was measured by a potentiometer in a 0.01 M $CaCl_2$ suspension (1:2.5 w/v) according to DIN ISO 10390 (DIN ISO 1997). Total soil carbon content, total soil nitrogen content and total soil sulphur content were analyzed after dry combustion using a LECO CNS 2000 analyzer, according to DIN ISO 10694 and 13878 (DIN ISO 1996, 1998). Organic carbon was calculated after subtracting the amount of carbonate C. Extractable contents of elements were analyzed according to DIN ISO 38414-S (DIN ISO 1983).

### X-ray diffraction analysis

Mineralogical investigations of soil samples were performed by powder X-ray diffraction (XRD). A Ringaku Rinto 1200 X-ray diffractometer (CuKα radiation) operating at 40kV and 30 mA, and a scanning speed of 1-20 s per $0.02^{o}2\theta$ was used. For mineral analysis, soil samples were ground to fine powder, and the powdered samples were mounted on the square concavity of a glass slide for the XRD scan. For clay mineral analysis, soil samples were prepared by spreading 2 mg of the suspended clays over a 2.5-cm$^2$ area of a glass slide. The slides were air-dried, placed in a desiccator containing silica gel desiccant to prevent rehydration, and observed using CuKα generated at 40 kV and 30 mA by using the 2θ/θ method and a scan speed 2°/min (Rigaku Rinto 1200 X-ray diffractometer). For smectite clays, soil samples were treated with ethylene glycol and then dried at room temperature before being analyzed by XRD (Chaerun et al., 2005).

### Fourier transform infrared (FTIR) spectroscopic analysis

The functional characterization of soil organic matter was analysed using FTIR with a BioRad® FTS 135. The KBr-technique (Capriel et al., 1995; Celi et al., 1997; Kaiser and Ellerbrock, 2005) was applied to obtain absorption spectra of soil organic matter in a range of wave numbers between 3900 and 400 cm$^{-1}$. To obtain these spectra, 0.5 mg of the freeze-dried soil was mixed with 80 mg KBr and finely ground in an agate mortar. The resulting mixture was dried for 12 h over silica gel in an exsiccator to standardize the water content. Varying water contents would affect the interpretation of the spectra because the intensity of the O-H band is proportional to the water content. All spectra were recorded under same conditions: sample-KBr mixture as described above, resolution (1 cm-1) and 16 scans (=16 repetitions of a single spectra; Ellerbrock et al., 1999).

### Statistical analysis

The data are presented as the arithmetic mean ± standard error of the mean. The significance of differences between the soil samples of the study sites was estimated by the one-way ANOVA at significance levels of $P < 0.05$, using the software SigmaStat version 2.03 (SPPS Inc., Chicago, Illinois).

## Results and Discussion

### Salt content and salinity of soils

Salt contents of B, Na, Mg, Cl and Ca in impacted sites were statistically greater by a factor of 2 to 54 than those in un-impacted sites ($P < 0.05$) (Table 1). Levels of B (34 ppm) and Mg (7249 ppm) in impacted soils were two times higher than un-impacted soils (17 ppm and 3598 ppm, respectively). Ca levels in impacted soils (13581 ppm) were three times higher than those in un-impacted soils (4639 ppm) in 2006, although its levels in the impacted soils were slightly reduced in 2008 (11196 ppm). The influence of seawater on Na content was more pronounced in that Na levels in tsunami-impacted soils (1225 ppm) were seven times higher than those in un-impacted soils (176 ppm). The concentration of Na in impacted soils decreased slightly in 2008 (1073 ppm).

Tsunami-impacted soils had remarkably high Cl concentrations that were 54 times (in 2006) and 23 times (in 2008), respectively, higher than un-impacted soils. These extractable salts represented salinity levels contained in the soils that could be measured by EC (electrical conductivity) values. Salinity was positively correlated with EC, which increased with increasing salt content (Table 1). Soil EC values drastically decreased along a salinity gradient from tsunami-impacted to un-impacted sites (0.5 to 0.6 dS $m^{-1}$ and 0.04 to 0.05 dS $m^{-1}$, respectively). Even after almost 1.5 years and 3.5 years of intrinsic bioremediation, tsunami-impacted soils continued to have EC levels 15 and 10 times, respectively, higher than un-impacted soils (Table 1). The high salinity of tsunami-impacted soils apparently arose from seawater of which major constituents included Cl (79.94 wt%), Na (8.27 wt%), Ca (3.57 wt%), K (2.99 wt%), S (2.94 wt%), Mg (1.49 wt%), Br (0.42 wt%), Si (0.26 wt%), Sr (0.06 wt%), and Co (0.05 wt%) (Chaerun et al., 2004). The high salinity and salt concentrations of Indonesian tsunami-impacted sites are similar to those published earlier by Chaudhary et al. (2006) and Szczucinski et al. (2005, 2006, 2007) that were conducted in India and Thailand.

### Heavy metal and nutrient content of soils

The aftermath of the tsunami disaster involved both high nutrient and heavy metal concentrations in tsunami-impacted soils. They were severely contaminated with several heavy metals such as Cr (73 ppm), Fe (38679 ppm), Co (18 ppm), Ni (88 ppm), Cu (49 ppm), Zn (131 ppm), Cd (0.4 ppm) and Pb (20.4 ppm) (Table 1). Even after almost 1.5-years of intrinsic bioremediation, the concentrations of these eight heavy metals in tsunami-impacted soils remained high compared to those in un-impacted soils (Cr: 60 ppm, Fe: 32487 ppm, Co: 15 ppm, Ni: 49 ppm, Cu: 35 ppm, Zn: 61 ppm, Cd: 0.06 ppm and Pb: 11.8 ppm) by a factor of 1.2 – 6.8. Of these eight heavy metals, Cd experienced the highest increase in concentration (6.8). This is presumably because Cd is one of the most active elements in processes that occur during mixing along a salinity gradient (Garnier and Guieu, 2003). Fe was most abundantly contained in soils (Table 1) because of its low bioavailability in aerobic environments at a neutral pH (Brantley et al., 2001), which is typical of tropical soil (oxisol).

Table 1. Chemical characteristics of agricultural soils 1.5-year and 3.5-year after the December 26, 2004 tsunami disaster in Banda Aceh, Aceh Province, Sumatra Island, Indonesia.

| Chemical composition | Study Sites | | | |
|---|---|---|---|---|
| | Tsunami-impacted soils | | Tsunami-un-impacted soils | |
| | May 2006 | June 2008 | May 2006 | June 2008 |
| Total C (%) | 3.2 (0.31)a | 2.6 (0.15)a | 1.2 (0.09)b | 1.2 (0.08)b |
| Organic C (%) | 3.1 (0.28)a | 2.5 (0.15)a | 1.2 (0.09)b | 1.2 (0.08)b |
| Carbonate C (%) | 0.14 (0.03)a | 0.08 (0.01)a | 0.00 (0.00)b | 0.02 (0.00)a |
| Total N (%) | 0.3 (0.02)a | 0.2 (0.01)a | 0.1 (0.01)b | 0.1 (0.01)b |
| Total S (%) | 0.04 (0.01)a | 0.06 (0.00)a | 0.01 (0.00)b | 0.05 (0.03)a |
| C:N ratio | 11.7 (0.29)a | 12.4 (0.58)a | 10.5 (0.51)b | 11.1 (0.27)a |
| pH | 7.4 (0.13)a | 7.1 (0.06)a | 5.1 (0.71)b | 5.5 (0.07)b |
| EC (dS m$^{-1}$) | 0.6 (0.08)a | 0.5 (0.02)a | 0.04 (0.003)b | 0.05 (0.004)b |
| Li (ppm) | 17 (1)a | NM | 12 (1.6)b | NM |
| B (ppm) | 34 (1.1)a | NM | 17 (2.5)b | NM |
| Na (ppm) | 1225 (78)a | 1073 (84)a | 176 (15)b | 243 (49)b |
| Mg (ppm) | 7249 (130)a | 6262 (55)a | 3598 (487)b | 3562 (1047)a |
| Al (ppm) | 56976 (1764)a | 44260 (913)a | 50869 (3223)a | 35904 (8499)a |
| Si (ppm) | NM | 2813 (16)a | NM | 2465 (242)a |
| P (ppm) | 369 (29)a | 354 (16)a | 139 (18)b | 151 (16)b |
| Cl (ppm) | 595 (61)a | 782 (145)a | 11 (1.5)b | 34 (6)b |
| K (ppm) | 2124 (38)a | 2968 (62)a | 1166 (159)b | 2440 (142)b |
| Ca (ppm) | 13581 (1280)a | 11196 (405)a | 4639 (355)b | 4439 (938) b |
| Cr (ppm) | 73 (2)a | 82 (1)a | 60 (4)b | 71 (10)a |
| Mn (ppm) | 436 (36)a | 386 (8)a | 442 (73)a | 404 (58)a |
| Fe (ppm) | 38679 (938)a | 41837 (209)a | 32487 (1933)b | 35851 (4110)a |
| Co (ppm) | 18 (0.4)a | 16 (0.2)a | 15 (1)b | 14 (2)a |
| Ni (ppm) | 88 (3)a | 83 (1)a | 49 (6)b | 51 (15)a |
| Cu (ppm) | 49 (1)a | 54 (1)a | 35 (4)b | 34 (7)a |
| Zn (ppm) | 131 (13)a | 120 (3)a | 61 (5)b | 63 (10)b |
| As (ppm) | 2.5 (0.6)a | <5 a | 2.4 (0.9)a | <5 a |
| Se (ppm) | <2 a | NM | <2 a | NM |
| Sr (ppm) | 55 (5)a | NM | 200 (29)b | NM |
| Mo (ppm) | <2 a | NM | <2 a | NM |
| Cd (ppm) | 0.4 (0.07)a | 0.1 (0.05)a | 0.06 (0.03)b | 0.09 (0.01)a |
| Pb (ppm) | 20.4 (1)a | 17.3 (0.4)a | 11.8 (1)b | 15.5 (1)a |

Values were calculated as means of all soil samples (n=12 for 2006 samples and n=3 for 2008 samples of which each sample was a composite sample consisting of 5 samples) with standard error in parentheses. Statistical differences are indicated by different letters ($P = 0.05$) for each year, comparing between tsunami-impacted and un-impacted soils. "NM" not measured.

The levels of Se and Mo were less than the detection limit (2 ppm) for all sites. Very low concentration of Mo is common in acid soils that are high in hydrous Fe and Al oxides typical of oxisols, while Se usually occurs in very small amounts in nearly all materials of the earth's crust, averaging only 0.09 ppm in rock and found mainly in sedimentary minerals (Tisdale et al., 1993). In contrast, the level of Sr in tsunami-impacted soils (55 ppm) was four times less than in the un-impacted soil (200 ppm). Furthermore, no significant differences were observed in concentrations of Li (12 – 19 ppm), Al (50869 – 60721 ppm), Mn (249 – 442 ppm) and As (2.4 – 2.9 ppm) between the two sites (Table 1).

On the other hand, tsunami-impacted soils contained higher levels (Table 1) of essential macronutrients for plant growth such as P (369 ppm in 2006 and 354 ppm in 2008), K (2124 ppm in 2006 and 2968 ppm in 2008), Ca (13581 ppm in 2006 and 11196 ppm in 2008) and Mg (7249 ppm in 2006 and 6262 ppm in 2008), than did un-impacted soils (P: 139 – 151 ppm, K: 1166 – 2440 ppm, Ca: 4439 – 4639 ppm, and Mg: 3562 – 3598 ppm). These macronutrient levels in tsunami-impacted soils were greater than those in un-impacted soils for both 2006 and 2008 by a factor of 1.2 – 3, which presumably arose from nutrient-rich marine sediments. The high nutrient content and heavy metals in tsunami-impacted soils of Indonesia are similar to those published earlier by Chaudhary et al. (2006) and Szczucinski et al. (2005, 2006, 2007) that were conducted in India and Thailand except for arsenic, which was lacking from tsunami-impacted soils in Aceh, Indonesia. The differences may be due to different sampling sites (coastal areas vs. agricultural fields) and different sampling years.

### Soil carbonate, organic carbon, nitrogen and sulphur contents

Sites of tsunami-impacted and un-impacted soils differed statistically in contents of carbonate C, total C, organic C, total N, and total S (Table 1). Soils of both sites in 2006 contained carbonate (0.14%, 0.00%, respectively), total C (3.2%, 1.2%, respectively), organic C (3.1%, 1.2%, respectively), total N (0.3%, 0.1%, respectively), and total S (0.04%, 0.01%, respectively). In 2008, contents were slightly reduced in tsunami-impacted soils with the exception of carbonate C and total S, which were drastically reduced after 3.5-years of intrinsic bioremediation. Seawater flooding caused by the tsunami disaster may bring nutrients up from deep sediment at sea floor to the surface, where they accumulate into terrestrial zones such as agricultural soils. Tsunami-affected seawater contained essential organic and inorganic substances (e.g., nitrate, phosphate), thereby eliciting higher macronutrient contents in tsunami-impacted soils than other sites. Tsunami-affected seawater flooding may also carry marine sediments that harbor huge amounts of organic C (Gelinas et al., 2001), thus macronutrient (C, N, and S) accumulations at tsunami-impacted sites are predominantly marine-derived. A high concentration of organic C in tsunami-impacted soils is also believed to alleviate the adverse effects of salinity increases (Yadvinder-Singh et al., 2005).

The C/N ratio of tsunami-impacted soils in 2006 and 2008 (11.7 and 12.4, respectively) was slightly higher than that of un-impacted soils (10.5 and 11.1, respectively) and was statistically different ($P < 0.05$) in 2006 but not in 2008 ($P > 0.05$) (Table 1). The C/N ratios of soils generally range between 10 and 15, depending upon climate and management condition (Guggenberger and Haider, 2002). Soils of tsunami-impacted sites had circumneutral pH (7.1 - 7.4), while those of un-impacted sites had pH values of 5.1 - 5.5 (Table 1). Acidity is a common feature of soils in many of the tropical regions of the world, including Indonesia. The higher C/N ratio in tsunami-impacted soils indicates a less decomposed state of soil organic matter in tsunami-impacted soils than in tsunami-unimpacted soils (Guggenberger and Haider, 2002).

### Mineralogical characterization

Mineralogical composition of both tsunami-impacted and un-impacted soils analyzed by XRD is summarized in Table 2. The tsunami-impacted soils contained the major minerals (quartz, plagioclase and goethite), minor minerals (hornblende and lepidocrocite) and clay minerals (kaolinite, smectite and illite). Un-impacted soils contained major minerals (quartz, plagioclase, goethite and hornblende), minor minerals (lepidocrocite and cristobalite) and clay minerals (kaolinite and smectite). Tsunami-impacted soils appeared to have less minor mineralogical composition (a lack of cristobalite) than un-impacted soils, but an increase in clay mineralogical composition (i.e., illite).

The increase of illite clay in tsunami-impacted soils could be attributed to the higher K and Mg levels in tsunami-impacted soils, which are components and alteration products of clay and other minerals (Igwe et al., 2005). Mizota and Chapelle (1988) reported that high organic C concentrations were found to inhibit the formation of amorphous constituents by forming strong bonds with Al and Si released from the weathering of volcanic glass. The distribution of minerals in tsunami-impacted soils may be an indicator of mineral deposition and continual synthesis of new minerals, such as illite, due to seawater flooding. Thus, mineralogical composition of tsunami-impacted soils may be useful for understanding the relationships between the mineralogical composition as well as the nutrient capacity of the soils and thus aid in development of bioremediation strategies.

Table 2. Mineralogical characteristics of agricultural soils 1.5-year after the December 26, 2004 tsunami disaster in Banda Aceh, Aceh Province, Sumatra Island, Indonesia.

| Mineralogical composition | Study Sites | |
|---|---|---|
| | Tsunami-impacted soils | Un-impacted soils |
| Major minerals | Quartz<br>Plagioclase<br>Goethite | Quartz<br>Plagioclase<br>Goethite |
| Minor minerals | Hornblende<br>Lepidocrocite | Hornblende<br>Cristobalite<br>Lepidocrocite |
| Major clay minerals | Smectite<br>Kaolinite<br>Illite | Smectite<br>Kaolinite |

Mineralogical analysis of all soil samples was carried out in replicates (n=4 for tsunami-impacted soils and n=3 for un-impacted soils).

Soil organic matter (SOM) characterization

Figure 1 represents FTIR spectra of agricultural soils collected from two study sites (tsunami-impacted and un-impacted sites) in May 21, 2006. The main peaks observed in the FTIR spectra of both sites were: a broad band at 3000-3600 cm$^{-1}$ (H-bonds, OH-groups); two peaks at 2860 and 2920 cm$^{-1}$ (asymmetric and symmetric C-H stretching vibrations of $CH_3$ and $CH_2$ groups); a band at 1698-1740 cm$^{-1}$ (C=O of COOH groups); a band at 1600-1640 cm$^{-1}$ (C=C double bonds conjugated with C=O and/or $COO^-$ bonds); a peak at 1400 cm$^{-1}$ (carboxylic and carbonylic groups); a sharp peak at 1081 cm$^{-1}$ (C-O vibration of C-O-C groups, e.g., cellulose); and bands at 400-800 cm$^{-1}$ and at 1100 cm$^{-1}$ (inorganic components such as minerals and clays, e.g., quartz and kaolinite, respectively). The intensity of O-H bands depends on the water content, which may vary between FTIR samples (Ellerbrock and Kaiser, 2005), and the intensity of the absorption bands depends on the amount of absorbing groups (Gunzler and Brock, 1990).

For characterizing soil organic matter (SOM) based on these FTIR spectra (Fig. 1), three absorption bands were used to determine the relative amount of hydrophobic groups (CH-groups) by calculating the C-H-to-C-O-C ratio (CH/COC), the relative amount of hydrophilic groups by calculating the C=O-to-C-O-C ratio (CO/COC), and the ratio between hydrophobic

(CH-groups) and hydrophilic (CO-groups) groups (CH/CO) in organic molecules for indicating wettability, as described by Ellerbrock et al. (1999, 2005), Ellerbrock and Gerke (2004) and Ellerbrock and Kaiser (2005). The CH-bands occurred at 2920 cm$^{-1}$ (asymmetric stretching) and 2860 cm$^{-1}$ (symmetric stretching); these were combined into a single band (3020-2800 cm$^{-1}$) and denoted as absorption band A. Hydrophilic C=O groups occurred at 1640-1620 cm$^{-1}$ and 1740-1710 cm$^{-1}$, and together were denoted as absorption band B. The band at ~ 1081 cm$^{-1}$, which indicated C-O stretching vibrations of C-O-C groups (e.g., in cellulose), was denoted as absorption band C. The spectra of both tsunami-impacted and un-impacted soils (Fig. 1) were used to calculate the A-to-C ratio, the B-to-C ratio, and the A-to-B ratio (Fig. 2).

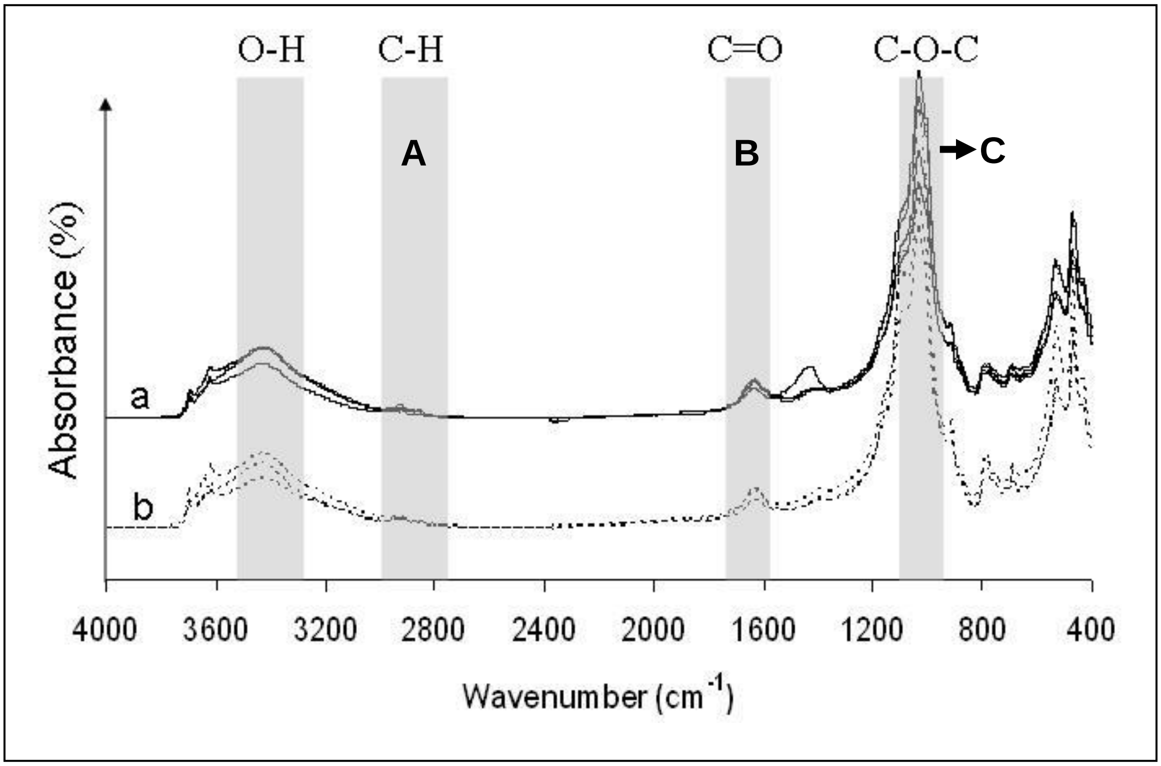

Figure 1. FTIR spectra of agricultural soils collected from tsunami-impacted area (a) and un-impacted area (b).

The intensity of the C=O absorption bands in the spectra of tsunami-impacted soils was slightly higher than that of un-impacted soils (Fig. 1), indicating that the content of CO groups in tsunami soils is higher than that in un-impacted soils. The tsunami-impacted soils also exhibited a greater intensity of the C-H absorption bands in the spectra than did un-impacted soils, indicating that the hydrophobic content in tsunami-impacted soils is greater than that in un-impacted soils. However, they were not statistically different based on the calculation of relative absorption given in Fig. 2 ($P > 0.05$). The CH/CO ratio (A/B ratio) of tsunami-impacted soils tended to be higher than that of un-impacted soil, but no statistically significant differences in A/B ratio were observed ($P > 0.05$). In addition, both tsunami-impacted and un-impacted soils contained significantly higher amounts of hydrophilic groups (B/C ratio of 0.171 ± 0.012 and 0.145 ± 0.014, respectively) than either hydrophobic groups (A/C ratio of 0.024 ± 0.005 and 0.016 ± 0.003, respectively) or wettability (A/B ratio of 0.136 ± 0.021 and 0.109 ± 0.011, respectively), but no significant differences were observed between their hydrophilic contents and hydrophobic/hydrophilic ratios ($P > 0.05$) (Fig. 2).

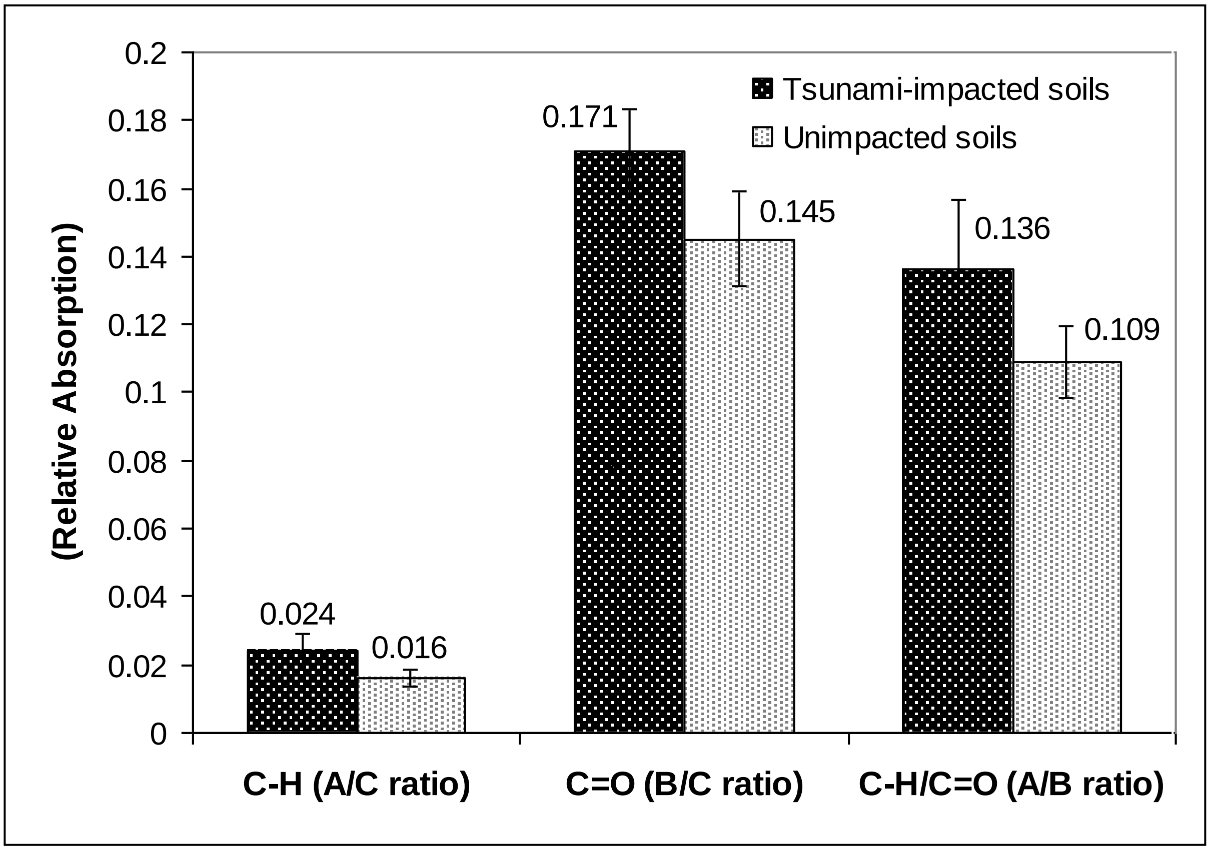

Figure 2. Absorption intensities of C-H and C=O bands in FTIR relative to C-O-C absorption band (A/C and B/C ratios, respectively) as well as CH/CO ratio (A/B ratio) obtained from FTIR spectra in Fig. 1.

Soil organic matter (SOM) is composed of the hydrophobic carbon backbone and functional groups, where the amount of hydrophilic C=O groups (i.e., O and N containing hydroxyl and carboxyl groups) relative to that of hydrophobic CH groups determines the hydrophobic character of SOM (Ellerbrock et al., 2005). Its conformation is also affected by pH, salt content, and ion composition of solution (Sposito, 1989; Stevenson, 1994). In this study, the FTIR spectra of SOM from tsunami-impacted soils tended to exhibit both C=O and C-H absorption bands higher than un-impacted soils, which were positively related to their higher organic C contents (Table 1). Thus, the tsunami disaster caused a higher organic C content and a higher content of both C=O and C-H groups within SOM fraction of tsunami-impacted soils. A higher C=O content than C-H content in tsunami-impacted soils indicates that they may contain a more highly decomposable organic compound. The higher hydrophilic and hydrophobic contents in tsunami-impacted soils also correspond with their higher levels of total C, organic C and total N (Table 1). Therefore, a high decomposability of organic C contained in tsunami-impacted soils (based on FTIR spectra) could eliminate the high salinity and heavy metal concentrations as negative impacts of the tsunami disaster. This is evidenced by decreases in the levels of salts, total salinity and some heavy metals in 2008 after 3.5-years of intrinsic bioremediation (Table 1).

## Conclusion

After almost 1.5-years and 3.5-years of exposure to seawater flooding caused by the December 26, 2004 tsunami disaster, agricultural soils in Banda Aceh (Aceh Province, Sumatra Island, Indonesia) still contain high salt levels and heavy metals. The tsunami disaster has caused not only negative impacts (salts and heavy metal pollution) but positive impacts. An increase in major macro- and micronutrient concentrations and clay mineral composition as well as a more highly decomposable organic C on agricultural soils is generally considered to be a positive impact. Macronutrient concentrations (i.e., organic C, N and S) in tsunami-impacted soils might be able to mitigate the effect of increased salinity and high levels of heavy metals, subsequently leading to a decrease in the concentrations in salts and heavy metals after 3.5-years of intrinsic bioremediation. This study has provided insights into major changes in the chemical and mineralogical properties of agricultural soils affected by the tsunami disaster.

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