The Dynamics of Tsunami Affected Soil Properties in Aceh, Indonesia

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Abstract

Understanding the dynamics of tsunami-affected soil properties is a key for reconstructing the local agriculture after tsunami events. We conducted a series of soil research after the 26 December 2004 Indian Ocean tsunami in the coastal areas of Nanggroe Aceh Darussalam (NAD) Province, Indonesia. The objectives of the study were to evaluate (i) the extent and types of soil damages, (ii) soil profiles of the affected area, (iii) changes in soil properties over time, and (iv) crop response. Survey of the extent and severity of soil damages was conducted from January 2005 to the end of 2007. Four soil profiles were evaluated in May 2005 and August 2007 in Aceh Besar District. Changes in soil salinity were evaluated at several monitoring sites using the electric conductivity (EC) meter based on soil samples and in the field using an electromagnetic induction soil conductivity instrument (EM38) from mid 2005 to the end of 2007. The tsunami waves affected the coastal areas up to 5 km inland. The damages ranged from permanent inundation, tsunami mud/sand deposition, surface crusting and soil salinity. Salinity level of up to 84 dS m^{-1} was measured a few weeks after the tsunami, but it decreased to <4 dS m^{-1} by October 2007 except in areas where lateral/vertical drainage is restricted. Soil pH, organic carbon content, exchangeable cations and total phosphorus were higher in the tsunami formed 'O' horizon than in the underlying layers. Yields of rice and dryland crops were lower in the first few seasons after the tsunami and empty pods of peanut and unfilled grain of rice were commonly observed. This could be attributed to either or combination of salinity, sodicity, cation imbalance and low micro nutrient availability. The tsunami effects were very variable and therefore management needs to be site-specific to be effective. In general, reconstruction of irrigation and drainage systems and application of organic matter speeded up the soil recovery.

Introduction

The earthquake of 9.1-9.3 of Richter scale that occurred southwest of Banda Aceh on Sunday 26 December 2004 was the third largest since 1900. It generated a large tsunami that killed 230,000 people on Indian Ocean coastlines, making it the worst tsunami in history in terms of lives lost. It devastated crops, buildings and infrastructure in low lying coastal areas around the Indian Ocean.

The forces of the waves and the mud brought by the waves changed the soil profile and nutrient balance in the upper soil layer. The affected land underwent either one or combination of the following problems: deposition of mud, silt, sand or coarser materials; increase in soil and water salinity; and desurfacing and compaction of topsoil (Hulugalle et al. 2009; Rachman et al., 2008a; McLeod et al. 2010; Slavich et al., 2008). The waves were up to 14.1 m height and devastated buildings, especially the simple constructed ones (Leone et al., 2011). Shofiyati et al., (2005), based on their estimation using Landsat ETM images, reported that the total area in Aceh flooded by the seawater was 120.295 ha.

The waves was higher on the west coast, facing the Indian Ocean epicenter and swept several kilometres inland, reducing the population of some villages by up to 80%. On the east coast of Aceh the wave heights varied from 2-6 m, population losses were generally lower (15-20%) and infrastructure damage was less. The erosive forces of the tsunami opened estuaries, transferred beach sands and coastal acid sulphate soils inland and reshaped wetlands. The tsunami also deposited sediments from the sea floor on the land. These transported terrestrial and marine deposits blocked drainage and irrigation systems. The impacts were most severe in low lands closest to the sea where landscape changes were greatest (Slavich et al., 2008).

Farming, one of the most important livelihoods of the people in the affected areas was practically stopped due to the failures of all enabling conditions. For several months to more than a year the local people's food supplies depended on food aids from other provinces as well as from national and international, government and non-government donations. In order to assist the local people in restarting agriculture, a series of soil related survey and research were conducted with the aim of (i) understanding the extent and level of damage on the soil, ii) evaluating soil profile of the affected area, (iii) understanding the temporal changes of soil properties, and (iv) evaluating crop responses to the problems.

MATERIALS AND METHODS

There were a few units of activities conducted in the West and East Coast of Aceh Province from 2005 to 2007, consisting of survey, evaluation of soil profile and construction of soil monolith, monitoring of soil salinity and evaluating crop responses.

Survey of extent and levels of damage

Initial measurement of soil salinity was conducted four weeks after the tsunami (January 2005) in Aceh Besar District. Soil salinity was measured using an Electric Conductivity (EC) meter using a 1:5 soil: water suspension at the soil laboratory of Indonesian Soil Research Institute in Bogor, Indonesia. EC 1:5 was then converted to effective EC (EC_e) using the conversion factor based on soil texture (Slavich and Peterson, 1990). The factor of 8.6 for soils with 30 –45% clay content was used as this represents the dominant soil in Aceh's lowland agriculture areas (McLeod et al., 2010; FAO, 2005).

A survey of the soil damage, covering the subject of inundation, salinity and mud accumulation was conducted in the districts of Banda Aceh, Aceh Besar, Aceh Jaya and Aceh Barat in the west coast of Nanggroe Aceh Darussalam (NAD) Province in May 2005. The damaged areas were assessed by comparing satellite images before and after the tsunami. Field survey was conducted on areas representing different levels of damages and different land use types as reflected by the satellite images, taking into account accessibility. The observations included thickness of mud and sand, the piling of debris, water table (including the level of inundation), soil texture, salinity (electric conductivity, EC), and soil pH. Classes of damage used the criteria as in Table 1.

Table 1. Class of damage of tsunami affected soil (Wahyunto dan Widagdo, 2005).

Class	Soil condition				Land condition	
	Decapping	Mud accumulation	Infiltration /texture*)	Salinity (EC) (ds/m)	Debris accumulation	Inundation
1. Light	*top soil* >10 cm	< 10 cm	Rapid, coarse	Low, < 2	Low <25%	None
2. Moderate	Top soil 5-10 cm	10 – 20 cm	Medium	Medium, 2 – < 4	Medium 25-50%	Drainable
3. Serious	Top soil <5 cm	>20 cm	Low, fine to very fine texture	High, 4 – 8 Very high >8	High >50	Seriously inundated
4. Inundated	Permanently inundated					

Soil profile properties

We described four soil profiles in May 2005 (five months after the tsunami) in Aceh Besar District, NAD Province. One of the pit (NAD 3) represented unaffected, while the other three (NAD 1, NAD 2, and NAD 4) represented the affected areas. In August 2007 (32 months after the tsunami) soil samples were taken with soil auger within 10 m distance from the initial profiles NAD 1, NAD 2, and NAD 4 using a soil auger at depth increments in accordance with the soil horizon depths. The site description of the four soil pits is provided in Agus et al. (2008). Soil properties evaluated included texture (pipette technique), pH (glass electrode), organic carbon (Walkley and Black), HCl 25% extractable phosphorous, exchangeable (and soluble) cations and cation exchange capacity (1M Ammonium acetate).

Dynamics of soil properties

Twenty permanent monitoring sites were established at selected areas to evaluate the changes in salinity and other soil properties. Soil samplings for laboratory analyses were collected in Sep. 2005, Nov. 2005, Jun. 2006, and Oct. 2007 from each site at 20 cm depth increment to 100 cm. The soil analyses included texture, pH (glass electrode), $EC_{1:5}$, organic C (Walkley and Black), and exchangeable cations and (1M Ammonium acetate). In line with the 20 plot monitoring using EC meter, twenty-three monitoring sites within 5 km of the east coast were selected across Aceh Besar, Banda Aceh, Pidie, and Bireuen districts for apparent EC_a measurement using electromagnetic induction soil conductivity instrument (EM38) (Slavich and Petterson, 1990). The ECa values were converted to EC_e using a linear relationship (McLeod et al., 2010). Most of the assessment sites were bunded lowland irrigated and rainfed rice fields (sawah), and some were more elevated and used for vegetables crops. In each site, 1–3 fixed transects of up to 100 m each were selected based on visual assessment of crop performance (poor, medium, and good) during the initial survey in August 2005 making a total of 38 transects across the 23 sites. The number of sites was reduced to 22 in January 2007 because one site was converted to housing. In December 2007 only 10 sites, where high salinity levels remained were measured.

Rainfall distribution in the study area is bi-modal with the annual average for Aceh Besar, Pidie, and Bireuen districts of 1668, 1889 and 1613 mm, respectively. The cumulative rainfall from 2005 to 2007 for these districts was 5205, 7779 and 7214 mm, respectively (McLeod et al., 2010).

Crop Response Soil Remediation

Evaluation of crop response included unstructured interview with the local stakeholders, visual observation and review of reports in the affected areas.

Results and Discussion

Extent and kinds of damages

The thickness of the mud in January 2005 observed in Aceh Besar area varied from 1 to 25 cm (Table 2) and in some pockets it was a few times deeper. These materials had grey to light green color, had a high clay content (mostly >40%), medium to high organic carbon (3 – 4%, except for Tanjung site), high 25% HCl extractable (potential phosphate) (300 – 1420 mg kg^{-1}) and available (Olsen) phosphate (>27 mg P kg^{-1}), high 25% HCl extractable potassium (200 – 2560 mg/kg), and high exchangeable Ca, Mg, K, and Na. The EC_e ranged from 20 in Mire to 84 dS m^{-1} in Keneuneu, Aceh Besar District. These mud characteristics reflected a potential for nutrient enrichment into the soil, despite the extremely high salinity and sodicity. The high sodium concentration caused soil dispersion and enhanced surface sealing and crusting as well as clogging of soil pores as clay particles leached down the profile during rainfall (Emerson and Bakker, 1973). Surface sealing and crusting which could be visualized every where in the mud deposited areas can cause a wide range of problems, such as delayed crop emergence due to lack of oxygen and surface hardness, waterlogging, increased runoff, and reduced microbial activities.

Example of the map of Aceh Barat District, showing the level of damage, is in Fig. 1. Salinity problem extended to 4 km and in Aceh Besar District (not shown) to 6 km inland. This seems to be depended on the topography and presence of river channeling the water and the direction of the waves (Leone, 2011). Mud and sand accumulation was found along some parts of the coast and further inland in the flood plains. Thin, permanently inundated areas, stretched near the beaches.

Table 2. Characteristics of deposited mud measured in Aceh Besar District, January 2005.

Soil properties	Sites				
	Lamcot	Keneuneu	Lampineung	Tanjung	Mire
Thickness (cm)	10-20	15-25	15-25	2-5	2-5
Sand (%)	53	26	12	47	6
Clay (%)	8	43	42	25	42
ECe (dS m^{-1})	60.9	84.2	80.1	38.9	19.8
Salt (mg kg^{-1})	31,280	46,268	44,116	20,140	9,804
pH_{H2O}	7.4	7.8	7.7	7.7	8.1
Organic C (%)	2.9	4.1	2.3	1.0	2.8
$P_2O_{5(HCl\ 25\%)}$ (mg kg^{-1})	520	550	930	300	1420
$K_2O_{(HCl\ 25\%)}$ (mg kg^{-1})	300	1330	2560	730	2470
$P_2O_{5(Olsen)}$ (mg kg^{-1})	64	60	48	27	115
Ca (cmol(+)kg^{-1})	24.7	20.1	18.6	8.6	18.9
Mg (cmol(+)kg^{-1})	6.9	24.5	26.2	10.8	19.7
K (cmol (+) kg^{-1})	0.5	2.2	2.9	0.8	2.4
Na (cmol(+)kg^{-1})	13.6	59.7	56.9	18.9	13.8

Note: Exchangeable cations (Ca, Mg, K, Na) in this table are mixtures of soluble and exchangeable cations as there were no separation of soluble cations in the analysis.

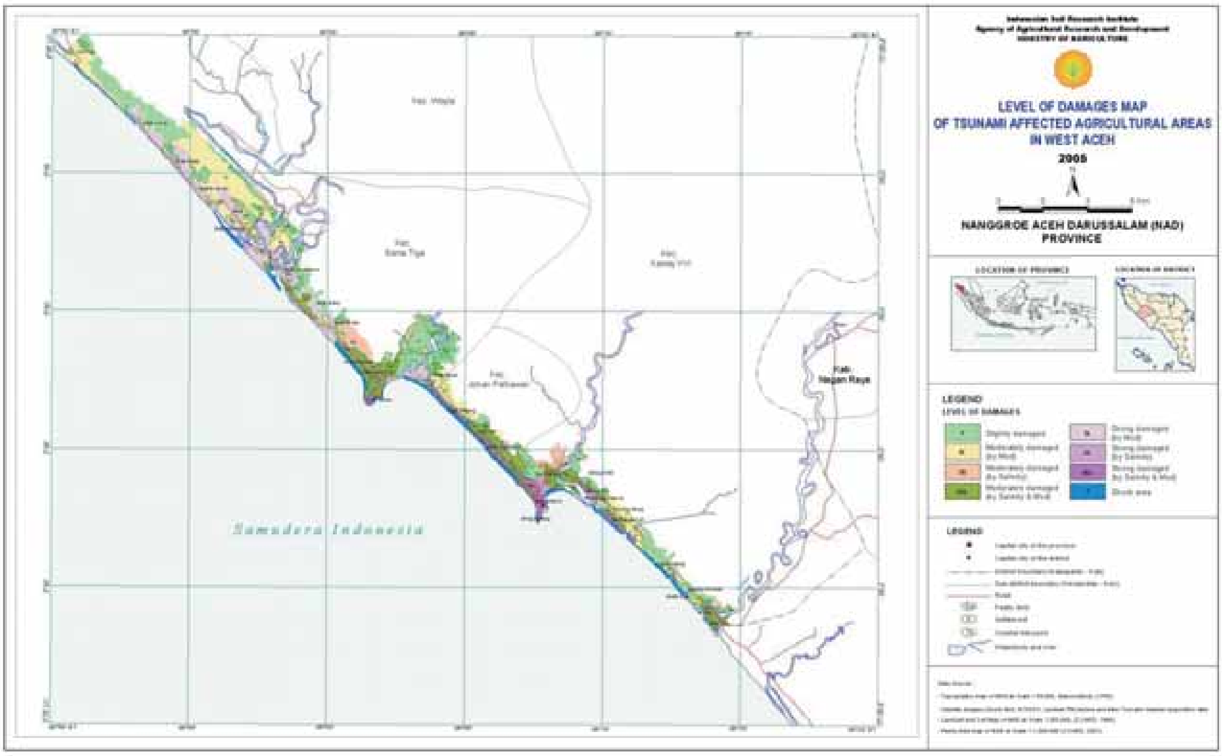

Fig. 1. Types and levels of damages of coastal area of West Aceh District, based on observation in May 2005, five months after the tsunami (Wahyunto and Widagdo, 2005).

Soil profile properties

The unaffected NAD 3 profile shows the typical characteristics of acid upland soils. Its organic matter, total nitrogen, phosphorus and exchangeable bases were only slightly higher in the Ap horizon compared with those in the lower horizons (Table 3). For the

Table 3. Selected soil profile properties, five and 32 months after tsunami.

Horizon	Depth (cm)	Texture		pH	Org	Total	Exchangeable cations (NH_4OAc 1N, pH 7)				
		Sand	Clay	H_2O	C	P	Ca	Mg	K	Na	CEC
		%			%	mg kg^{-1}	cmol(+) kg^{-1}				
NAD 3 (Beradeun village, 05˚30'09"N; 95˚16'28"E, Peneplain, 30 m asl; Unaffected soil, **May 2005**)											
Ap	0-16	47	20	5.2	1.3	90	4.0	1.2	0.07	0.1	11
Bw_{1-2}	16-40	52	19	5.2	0.4	30	1.8	0.7	0.00	0.2	9
$2Bw_{1-2}$	40-95	35	34	5.2	0.3	20	2.8	1.4	0.04	0.3	15
$2BC_{1-2}$	96-146	4	64	7.0	0.1	30	17.0	7.7	0.04	2.8	27
NAD 1 (Nusa Village; 05˚30' 03"N; 95˚16'17"E; Fluvio marine plain; 5 m asl; **May 2005, five months after tsunami**)											
O1	*0-5*	*9*	*48*	*7.9*	*6.1*	*730*	*39.9*	*20.9*	*1.44*	*7.6*	*35*
O2	*5-11*	*84*	*10*	*8.0*	*0.8*	*390*	*33.8*	*5.6*	*0.28*	*7.4*	*10*
Ap	11-25	28	31	6.1	1.1	120	5.8	3.7	0.28	7.2	13
Bw	25-42	27	43	7.1	0.3	60	9.8	4.7	0.07	1.5	16
Bwg	42-98	31	41	7.7	0.2	50	8.2	4.5	0.06	1.1	15
BC	98-147	22	39	8.1	0.1	360	9.6	5.4	0.07	1.7	16
NAD 1 (Aug 2007; 32 months after tsunami)											
O	0-5	69	19	8.1	1.5	430	19.5	4.5	0.30	1.2	8
Ap	5.-20	28	43	7.6	0.7	90	7.4	3.5	0.12	2.3	10
Bw	20-37	17	51	7.6	0.4	60	10.5	4.7	0.12	3.2	9
Bwg	37-90	21	48	7.8	0.1	80	10.7	4.8	0.12	2.0	8
BC	90-142	21	48	8.2	0.1	170	9.4	4.2	0.09	1.5	12
NAD 2 (Beradeun village; 05˚30' 06" N; 95˚16' 21" E; Peneplain; 18 m asl.; **May 2005; five months after tsunami**)											
O1	*0-9*	*42*	*35*	*8.0*	*9.8*	*360*	*27.8*	*12.8*	*0.49*	*3.6*	*32*
Ap	9-29	22	37	5.8	1.5	80	7.6	2.6	0.09	2.1	16
Bw1	29-52	20	43	5.0	0.6	50	7.2	3.2	0.07	0.9	17
Bw2-3	52-83	17	59	6.0	0.3	20	14.8	6.7	0.09	1.4	28
BC	83-149	44	32	6.7	0.1	50	6.7	3.3	0.04	0.8	12
NAD 2 (Aug 2007; 32 months after tsunami)											
O1	0-2	33	28	7.8	3.0	270	27.4	4.5	0.32	1.1	16
Ap1	2.-16	25	29	7.2	1.9	110	9.8	2.8	0.12	0.7	11
Ap2	16-27	26	35	6.3	1.0	70	6.8	2.7	0.09	1.2	8
Bw1	27-50	30	35	5.9	0.6	50	6.1	3.1	0.09	1.4	9
Bw2-3	50-83	40	33	6.5	0.4	60	9.0	4.8	0.12	1.6	10
BC	83-140	49	30	6.5	0.4	60	8.5	4.5	0.11	1.5	9
NAD 4 (Surah village; 05˚32' 25" N; 95˚16'05" E; Fluvio marine plain, 5 m asl.; **May 2005; five months after tsunami**)											
O	*0-17*	*93*	*5*	*8.4*	*0.1*	*1100*	*5.4*	*2.1*	*0.22*	*1.7*	*7*
Ap	17-24	21	37	6.3	1.1	450	11.0	11.9	0.45	8.0	27
Bwg1	24-43	17	31	6.6	0.4	840	18.6	16.5	0.15	1.5	26
Bwg2	43-83	30	20	7.4	0.2	950	16.9	15.6	0.11	0.5	25
NAD 4 (Aug 2007; 32 months after tsunami)											
O	0-5	73	14	7.7	1.1	890	10.3	4.5	0.88	0.5	10
Ap	5.-13	27	42	7.6	0.8	140	12.6	8.5	0.65	1.1	14
Bwg1	13-30	19	48	7.6	0.2	130	16.5	14.5	0.54	1.9	17
Bwg2	30-70	11	59	7.4	0.3	180	19.5	17.8	0.49	1.8	24

Note: Exchangeable cations (Ca, Mg, K, Na) in this table are mixtures of soluble and exchangeable cations as there were no separation of soluble cations in the analysis.

tsunami affected Profiles NAD 1 and NAD 2, soil pH, organic carbon content, exchangeable cations (potassium, calcium, magnesium and sodium) and total phosphorus were significantly higher in the tsunami formed 'O' horizon than in the underlying layers. However, for Profile NAD 4, where the O layer was dominated by sand fraction, this increase was not observed, except for soil pH. The Ap horizons of NAD 1 and NAD 4 were much higher in sodium up to 7.2 cmol (+) kg^{-1} compared to those in the underlying layer which were only <1.5 cmol (+) kg^{-1}. This elevated concentration is believed to be resulted from sodium leaching from the O horizon.

Thirty two months after the tsunami, the depth of the O horizon decreased because of incorporation into the Ap horizon and the difference in soil properties between the O and Ap horizons became rather unclear. Sodium concentration has practically returned to the pre-tsunami condition. Consistent with the soil profile data in Table 3, the concentration of exchangeable cations in other sites have also elevated in the first 20 cm and it also decreased over time (Fig. 2).

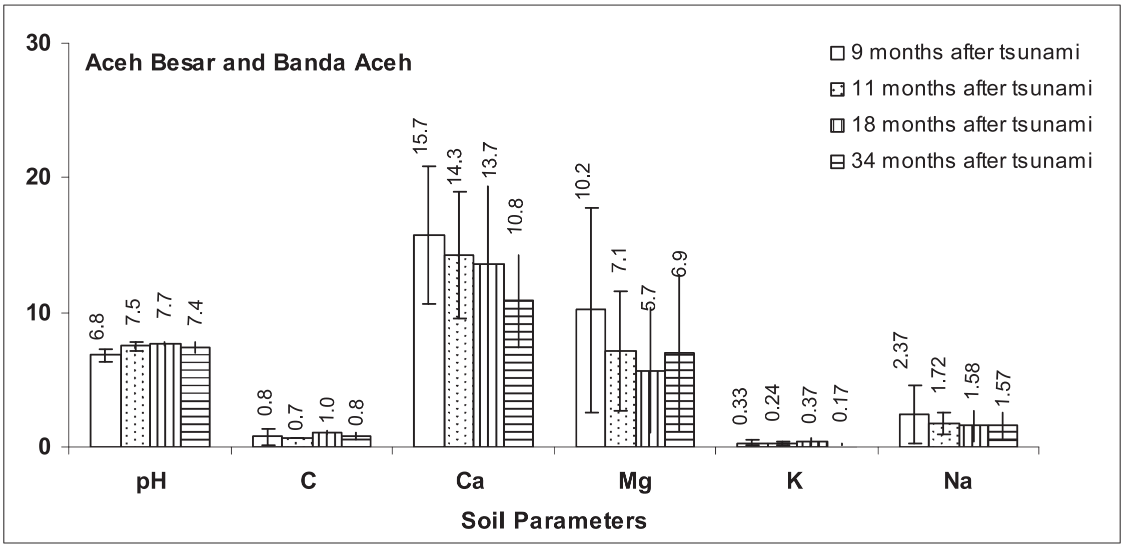

Fig. 2. Mean (histogram) and standard errors (bars) of 0-20 cm depth soil chemical properties over time in Aceh Besar and Banda Aceh Districs. C is in %, Ca, Mg, K, and Na are in cmol(+) kg^{-1}. Source: Rachman et al. (2008b)

Changes in soil salinity

Fig. 3 shows the EC_e by soil depth and Fig. 4 of average EC_e in the 1.2 m soil profile. EC_e varied spatially and decreased significantly with time due to natural leaching by rain water. Some of the soluble salts have been leached downward and increased the EC_e at the deeper depth to a higher level (>5 dS m^{-1}) such as in the cases Cot Lheu Rheng, C. Nusa, and D. Peuneung sites based on the Sep. 2005 and Nov. 2005 observations (Fig. 3). The downward movement of soluble salt may have occurred mostly during the first week after tsunami where standing sea water lasted for 1 to 6 days. The downward movement continues as rain water infiltrates into the soil. The four site measurement in the end of 2007, using EC meter, did not show any site and any soil layer with EC_e higher than 3 dS m^{-1}. The profile average EC_e, based on EM38 measurement, also decreased with time, but some sites still had ECe higher than 8 dS m^{-1} (Fig. 4). This is especially the case in paddy field areas where both lateral water movement is retarded by the dike, while vertical water movement is retarded by the plow pan (McLeod et al., 2010).

Crop responses

Productivity of rice decreased with increased salinity levels. In 2005 cropping most of rice (90%) died, the rest grew poorly with <2 t ha^{-1} yield. In the 2006/2007 cropping the growth recovered with reasonable yield of 3-4 ton ha^{-1}. In the end of 2007, most (70%) of rice field affected by tsunami regained normal yield of 5-6 ton ha^{-1}, especially in areas with good irrigation system (Irhas et al., 2008). There seems to be a complexity of extreme soil conditions affecting crop growth and production, including the low ratio of calcium to magnesium, increased uptake

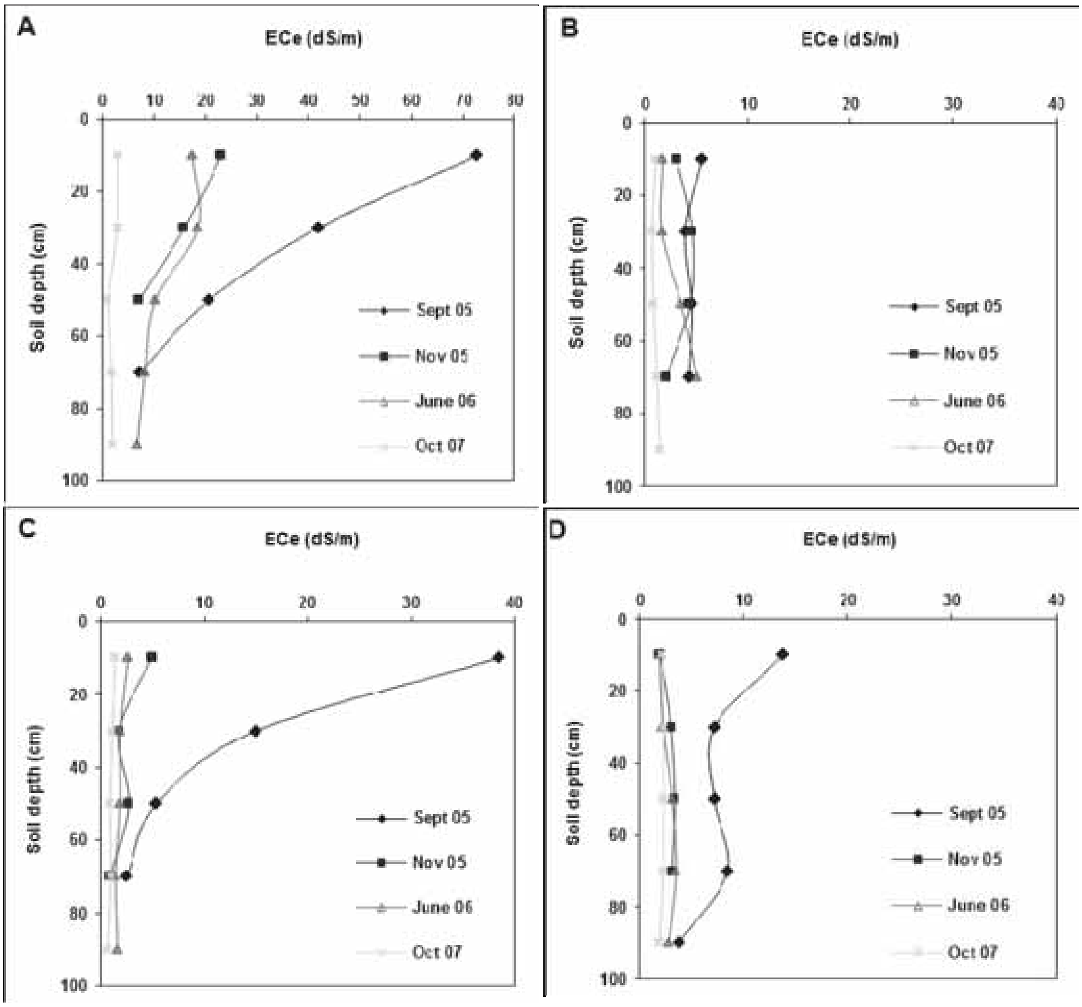

Fig. 3. Changes in EC_e values over time by soil depth at A. Cot Lheu Rheng, B. Panteraja, C. Nusa, and D. Peuneung sites. Source: Rachman et al. (2008a, b)

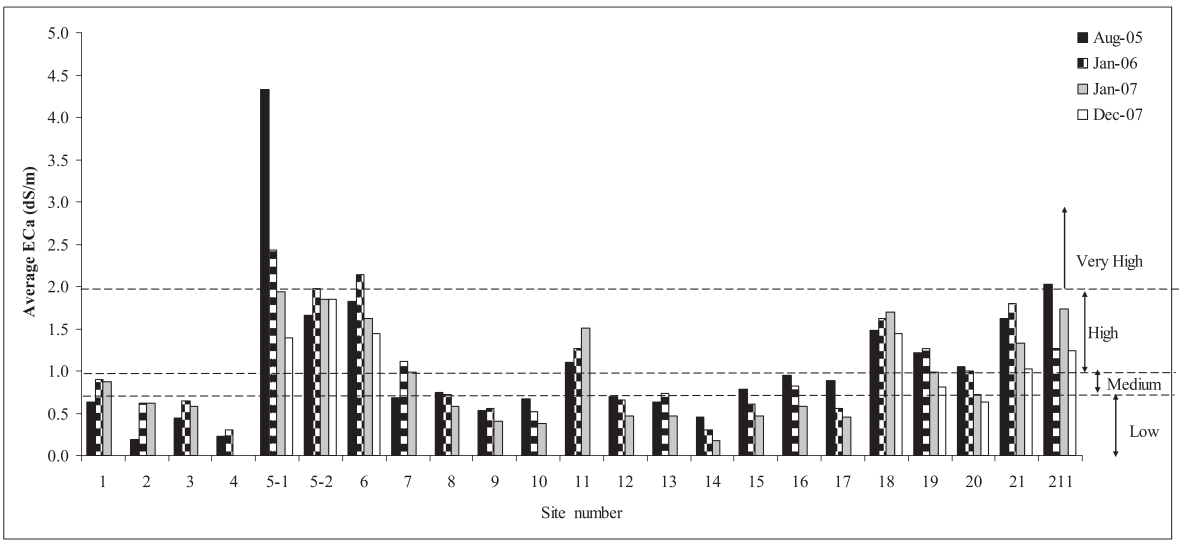

Fig. 4. Average profile effective electric conductivity, EC_e, across 23 assessment sites over time. The dotted line indicates soil salinity levels based on equivalent EC_e values following Slavich (2002). Reproduced from McLeod et al. (2010).

of sodium which affect the plant turgor, deficiency of micro nutrients, and surface sealing and crusting.

The local farmers observed a better crop performance for most crops, especially for the surviving tree crops, but empty seed of rice and pods of peanut was a concern. Most of the surviving tree crops in the affected areas seemed to benefit from the cation enrichment (Subiksa, 2006). Hybrid coconut, for example, yielded much higher in Aceh Barat District. Rachman et al. (2008a) reported the low ratio of calcium to magnesium of <1 for Panteraja, <1.5 for Cot Lheu Rheng, and <2 for Peuneung sites. The ideal calcium to magnesium ratio on the exchange complex for most crops is around 6 (McLean 1977). The relatively high proportion of Mg might have suppressed Ca uptake, the important element for pod filling, especially for peanut. Neumann et al. (2008), however, observed unhealthy performance of mango trees on tsunami affected sites. They found substantial increase of Na uptake in the trees while the uptakes of Ca, K and Mg did not seem to be suppressed by the elevated Na concentration. The authors attributed the unhealthy mango trees to elevated Na uptake.

Increased heavy metal concentrations were also documented by Wenzel et al., (2008).

In general, the heavy metal effects diminished after a few years and the remaining hot spots of pollution may be treated using phytoextraction of heavy metals and phytodegradation of organic pollutants. Arbuscular mycorrhizal fungi, a group of symbiotic soil microorganisms which may contribute to plant nutrient uptake, did not appear to be suppressed on tsunami affected soils. Roots of the halophyte 'kuda-kuda' (*Ipomoea pres-caprae*), which are very abundant on tsunami affected soils showed a particularly high degree of mycorrhizal root colonization (Neumann et al., 2008).

Possible management interventions include organic amendments such as compost or manure, and minimum tillage options such as permanent beds or zero tillage with retention of crop residues as *in situ* mulch together with suitable cover crops (Hulugalle et al., 2009; Lal, 1987; Roth et al., 2005). The relatively higher salinity level of paddy field areas for extended period of time (McLeod et al., 2010; Rachman et al. 2008b) because of low water percolation through the plowpan and blocking of the mud by the dykes suggests the importance of good irrigation and drainage systems.

Conclusions

Elevated soil salinity, very high sodium concentration on the tsunami deposit, land inundation, too sandy or too clayey mud, and surface crusting are among the extreme soil conditions in the tsunami affected area. Extremely high salinity level of >80 dS m^{-1} was measured a few weeks after the tsunami, but it decreased naturally relatively quickly. High soil salinity level (EC_e >4 dS m^{-1}) sustained in areas where lateral/vertical drainage is restricted. The yield of food crops such as rice in the poorly drained areas and peanuts in the severely affected areas has been affected until more than three years after tsunami.

The soil problem is more than just salinity. In areas where salinity had subsided to a negligible level, we observed poor peanut pod filling despite the seemingly thriving vegetative growth. Paddy areas with poor drainage also exhibited empty seeds. Other soil factors, singly or combination of more than one factor, may have caused the problems. These include elevated sodium uptake because of the soil sodicity, low ratio of calcium to magnesium, deficiency of micro nutrients and surface sealing and crusting. Fixing the irrigation and drainage systems to enable flushing of excessive salts and application of organic matter appears promising in remediation of these problem soils.

There are still researchable questions with respect to nutrient imbalance (dominance of Mg relative to K and Ca) and micro nutrients deficiency. These questions are more serious for annual crops than perennial crops. Perennial crops seem more resilient and able to cope with the complexity of the soil properties.

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References

Agus, F., H. Subagjo, H. Rachman and I. G. M. Subiksa (2008) Properties of tsunami affected soils and the management implication. Paper presented at 2nd International Salinity Forum, 31 March–3 April, Adelaide, South Australia http://www.internationalsalinityforum.org/Final%20Papers/

agus_B2.pdf. (Accessed Aug. 2011).

Emerson, W. W. and A. C. Bakker (1973) The comparative effects of exchangeable calcium, magnesium and sodium on some physical properties of red-brown earth subsoils: 2. The spontaneous dispersion of aggregates in water. Aut. J. Soil Res., 11: 151-157.

FAO (Food and Agricultural Organization) (2005) FAO Field Guide: 20 things to know about the impact of salt water on agricultural land in Aceh Province. United Nations Food and Agriculture Organization. www.fao.org/ag/tsunami/docs/saltwater-guide.pdf. (Accessed Aug. 2011)

Hulugalle, N. R., R. Jaya, G. C. Luther, M. Ferizal, S. Daud, Yatiman, Irhas, Z. A. Yufniati, F. Feriyanti, Tamrin and B. Han (2009) Physical properties of tsunami-affected soils in Aceh, Indonesia: 2½ years after the tsunami. Catena, 77: 224-231.

Irhas, Chairunas and A. Gani (2008) Rice productivity in tsunami-affected areas and salinity levels, based on EM-38 observations in NAD Province, Indonesia. Abstract: International Symposium, Land Use after the Tsunami – Supporting Education, Research and Development in the Aceh Region, Banda Aceh, Indonesia, Nov. 4-6, 2008.

Jones, J. B., B. Wolf and H. A. Mills (1991) Plant analysis handbook: A practical sampling, preparation, analysis and interpretation guide. Micro-Macro Publishing Inc.

Leone, F., F. Lavigne, R. Paris, J. C. Denain and F. Vinet (2011) A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability. Applied Geography, 31: 363-375.

McLean, E. O. (1977) Contrasting concepts in soil test interpretation: sufficiency levels of available nutrient versus basic cation saturation ratios. In: Peck et al. Soil testing: Correlating and interpreting the analytical results. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America Inc.

McLeod, M. K., P. G. Slavich, Y. Irhas, N. Moore, A. Rachman, N. Ali, T. Iskandar, C. Hunt and C. Caniago (2010) Soil salinity in Aceh after the December 2004 Indian Ocean tsunami. Agricultural Water Management, 97: 605-613.

Neumann, E., Syakur, Safrizal, Syafruddin, Aiyen Barus, Hifnalisa and Zaitun (2008) Interpreting results of plant and soil analyses: nutrient imbalances on tsunami-affected sites? Abstract of International Symposium Land Use after the Tsunami – Supporting Education, Research and Development in the Aceh Region, Banda Aceh, Indonesia, Nov. 4-6, 2008.

Rachman, A., Subikse, D. Erfandi and P. Slavich (2008a) Dynamics of tsunami-affected soil properties. Proceedings of International Workshop on Post tsunami Soil Management. Bogor, 1-2 July 2008, pp. 52-71.

Rachman. A., F. Agus, M. McLeod and P. Slavich (2008b) Salt Leaching Processes in the Tsunami-Affected Areas of Aceh-Indonesia. Paper presented at 2nd International Salinity Forum, 31 March–3 April, Adelaide, South Australia. http://www.internationalsalinityforum.org/Final%20Papers/Rachman_B2.pdf. (Accessed Aug. 2011).

Shofiyati, R., R. D. Dimyati, A. Kristijono and Wahyunto (2005) Tsunami effect in Nanggroe Aceh Darussalam and North Sumatra Provinces, Indonesia. Asian J. of Geoinformatics, 5(3): 100-111.

Slavich, P. G. and G. H. Petterson (1990) Estimating average root zone salinity from electromagnetic induction (EM-38) measurements. Aust. J. Soil Res., 28(3): 453-463.

Slavich, P., M. McLeod, N. Moore, G. Tinning, R. Lines-Kelly, T. Iskandar, A. Rachman, F. Agus and P. Yufdy (2008) Tsunami impacts on farming in Aceh and Nias, Indonesia. Paper Presented at 2nd International Salinity Forum, 31 March–3 April. Adelaide, Australia. http://www.internationalsalinityforum.org/Final%20Papers/slavich_B2.pdf (Accessed Aug. 2011).

Subiksa, I. G. M., F. Agus and D. Erfandi (2006) The salt leached out and the soil fertility changes after tsunami. Presented at a multi-stakeholder workshop, 30 November 2006, Meulaboh. ICRAF South East Asia, Bogor.

Wahyunto and Widagdo (2005) Teknologi Penginderaan Jarak Jauh dan Sistem Informasi Geografi (SIG) untuk Efektivitas Inventarisasi Lahan Pertanian (Remote sensing and geographical information system for improved effectiveness of agricultural land inventory). Laporan akhir, Balai Penelitian Tanah, Bogor, Indonesia.

Wenzel, W. W., G. Wieshammer, M. Puschenreiter and I. Langer (2008) Soil pollution in tsunami-affected areas and strategies for mitigation. Proceedings of International Symposium Land Use after the Tsunami – Supporting Education, Research and Development in the Aceh Region, Banda Aceh, Indonesia, Nov. 4-6, 2008.