Chapter 19
Impact of the 2011 Tohoku-oki Earthquake Tsunami on Cultivated Soil in Miyagi Prefecture, Northeastern Japan: An Overview

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Abstract To investigate damage resulting from the 2011 Tohoku-oki earthquake tsunami on cultivated soil, a regional soil survey covering 344 sites of coastal farmland in Miyagi Prefecture was conducted in May 2011 as an initiative of the Agriculture Promotion Division of Miyagi Prefecture. Samples numbering 390, 344, and 340 were carefully collected from the tsunami deposit layer (TD), the surface 10-cm layer (SL1), and the next 10-cm layer (SL2) of the cultivated soil, respectively, and were used for laboratory analyses. Tsunami deposits covered the surfaces of 275 field sites of the total 344 field sites. The cumulative thickness of TD at each site represented a log-normal distribution with a median of 4.8 cm (maximum, 40.3 cm) and decreased with increasing inland distance from the shoreline. An electrical conductivity of 1:5 water leachate ($EC_{1:5}$) of TD showed a median of 5.9 dS m^{-1}, whereas that of the cultivated soil layers SL1 and SL2 was 2.1 and 1.2 dS m^{-1}, respectively. TD with high $EC_{1:5}$ mostly comprised muddy TD and that with a distribution biased to 2–4 km inland. Due to the direct impact of seawater, the $EC_{1:5}$ values of SL1 and SL2 were relatively high at the inland sites with a thin layer or no sediment. The ion exchange reaction between sodium in seawater and calcium held by soil particles caused an increase in water-soluble calcium and exchangeable sodium within the tsunami-affected area. The similarity in the exchangeable components in TD and SL1 strongly suggests that the deposits of the inland tsunami are derived from the eroded soil surface of neighboring farmland. As a result of 5 years of government-sponsored reconstruction and salt removal, the restoration of farmland has been completed in 88% (11,411 ha) of the target area in Miyagi Prefecture.

Keywords Miyagi Prefecture 2011 • Tohoku-oki earthquake • Tsunami • Farmland • Tsunami deposit

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V. Santiago-Fandiño et al. (eds.), *The 2011 Japan Earthquake and Tsunami: Reconstruction and Restoration*, Advances in Natural and Technological Hazards Research 47, DOI 10.1007/978-3-319-58691-5_19

19.1 Introduction

The Tohoku-oki earthquake (the Great East Japan Earthquake, GEJE) that occurred on March 11, 2011, followed by a devastating tsunami, resulted in serious damage to farmland along the Pacific coast of eastern Japan. The total area of tsunami-hit farmland in the Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba prefectures was estimated to be 23,600 ha, 85% of which was used as paddy field (Rural Development Bureau of Ministry of Agriculture, Forestry and Fisheries 2011a). Furthermore, 97% of the area of the damaged farmland concentrated in Tohoku region and 66% (15,002 ha) of it in Miyagi Prefecture, whose area occupied 11% of the farmland in Miyagi Prefecture. In September 2011, the Rural Maintenance Division of Miyagi Prefecture (2011) announced the prospects of restoration for the damaged farmland and set the target area of restoration as 13,000 ha.

In general, the major damages to a farmland by seawater inundation caused by the tsunami included the following: (i) infiltration of seawater or salt to soil, (ii) deposition of sediment or debris overlaying the soil surface, and (iii) erosion of fertile soil. The GEJE tsunami in particular caused widespread destruction of irrigation and drainage facilities along the coastline, thereby seriously delaying the restoration of farmland.

Many post-GEJE tsunami surveys have been conducted by various researchers. Chagué-Goff et al. (2012) collected tsunami sediments and underlying soil along a transect line near Sendai Airport to assess the environmental impact of the tsunami. Goto et al. (2012) summarized the current understanding of the sedimentological, geochemical, and paleontological features of the onshore and offshore deposits based on the geological data, which were obtained by the many post-GEJE tsunami surveys involving >1,000 survey pits. Goto et al. (2014) also investigated the total balance of sedimentation and erosion and the relationship between the hydrodynamic features of the tsunami and sediment characteristics (e.g., thickness) along Sendai Bay according to the field survey of Miyagi Prefecture/Midori-net Miyagi during June–July 2011. These geological knowledge is useful for analyzing the GEJE tsunami itself and for understanding paleotsunami events. However, is insufficient to estimate the damage of the GEJE tsunami on cultivated soil and to assist in planning for recovery of the tsunami-affected farmland.

To investigate the damage caused by the GEJE tsunami on agricultural fields in Miyagi Prefecture, two types of regional surveys were separately conducted. Miyagi Prefecture/Tohoku University conducted the field survey covering 344 sites of coastal farmland as an initiative of the Agriculture Promotion Division of Miyagi Prefecture during May 2011 as a collaboration between Miyagi Prefecture and Tohoku University (Agriculture Promotion Division of Miyagi Prefecture 2011). Miyagi Prefecture/Midori-net Miyagi also conducted an another field survey covering 3,000 pits during June–July 2011 and studied the thickness and electrical conductivity (EC) of the deposits (Goto et al. 2014).

In the former regional survey, Miyagi Prefecture/Tohoku University uniquely focused on the cultivated soil possibly altered by the inundation of seawater as well as the introduction of tsunami deposits. The current paper provides an overview of the impact of the GEJE tsunami on cultivated soil based on the field survey conducted by Miyagi Prefecture/Tohoku University and the progress made of 5 years of farmland restoration in Miyagi Prefecture.

19.2 Regional Soil Survey Covering 344 Sites of Coastal Farmland in Miyagi Prefecture

Large areas of farmland were inundated by the GEJE tsunami in Miyagi Prefecture. To estimate the damage cause by the GEJE tsunami on cultivated soil and to assist in determining the plan for recovery of the tsunami-affected farmland, decision makers need to know the following: (1) the amount and composition of the sediment, which had been introduced by the tsunami; (2) the effect of seawater intrusion into the cultivated soil; and (3) the status of topsoil loss due to erosion. Therefore, the Agriculture Promotion Division of Miyagi Prefecture planned a regional soil survey covering the tsunami-affected farmland as a collaborative work between the Miyagi Prefectural Government and Tohoku University.

19.2.1 Study Area and Sampling Method

The previously selected three or four sites representing various land uses, with each 1-km grid of the tsunami inundation area were investigated with the assistance of local officials on May 11, 13, 16, 17, 18, and 19, 2011. The number of survey sites was 344, consisting of 23 in Kesennuma City, 15 in Minamisanriku Town, 11 in Ishinomaki City, 12 in Higashimatsushima City, 3 in Matsushima Town, 6 in Tagajo City, 5 in Shichigahama Town, 61 in Sendai City, 50 in Natori City, 31 in Iwanuma City, 88 in Watari Town, and 39 in Yamamoto Town (Fig. 19.1).

Samples were collected from the tsunami deposit layer (TD), the surface 10-cm layer (SL1) and the next 10-cm layer (SL2) of the cultivated soil in duplicate on the diagonal line for each site. If the sediment could be divided into multiple layers of muddy or sandy subgroups based on a judgment of the onsite texture, the thickness of TD was separately measured. From the 344 sites, samples numbering 390, 344, and 340 were collected from TD, SL1, and SL2 layers, respectively, with the exception of very thin sediment.

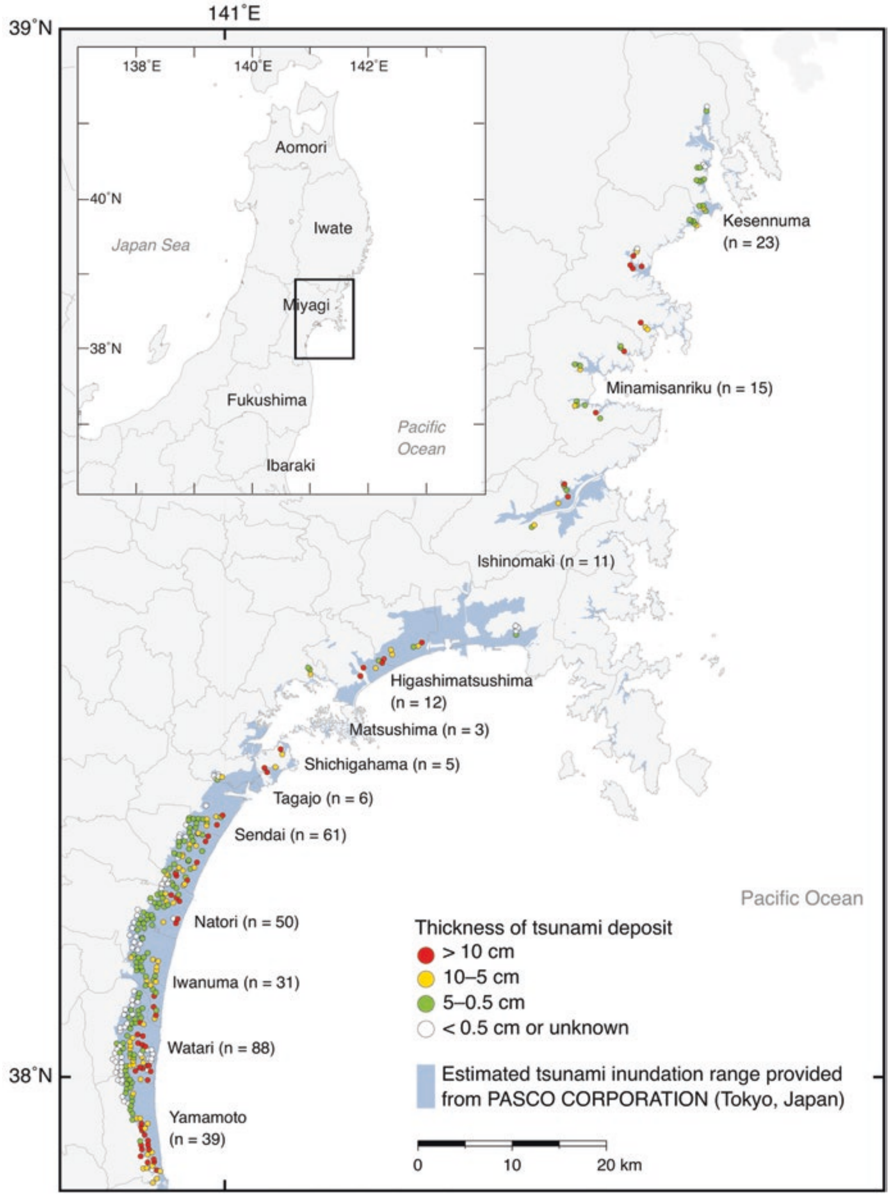

Fig. 19.1 Location and thickness of the tsunami deposit on coastal farmland (n = 344) surveyed in the Motoyoshi District (Kesennuma City and Minamisanriku Town) on May 13, in the Ishinomaki District (Ishinomaki City and Higashimatsuhima City) on May 11, in the Sendai District (Matsushima Town, Shichigahama Town, Tagajo City, and Sendai City) on May 19, and in the Watari District (Natori City, Iwanuma City, Watari Town, and Yamamoto Town) on May 16–18, 2011 (Kanno et al. 2012)

19.2.2 Analytical Methods

Air-dried fine earth fractions were used to determine selected chemical properties. Electrical conductivity ($EC_{1:5}$) values equivalent to those at the standard 25 °C were measured using a conductivity electrode at a soil/water ratio of 1:5. Water-soluble and exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) were determined using the sequential batch extraction procedure described below, where Ca, Mg, K, and Na were determined by atomic absorption photometry. The extract of 5 g/sample with 25 mL of distilled water for 1 h shaking contained the water-soluble cation. The residue was then extracted twice with 25 mL of pH 7.0 1 *M* ammonium acetate with 30 min shaking (Thomas 1982). The composite extracts with ammonium acetate included exchangeable cations.

Several reports using the same sample set are available (Agriculture Promotion Division of Miyagi Prefecture 2011; Kanno et al. 2012; Kanno 2012; Shima et al. 2012; Inao et al. 2013; Kanno 2014; Nanzyo 2015; Takahashi 2015). In particular, for undried TD samples, Shima et al. (2012) and Inao et al. (2013) reported detailed results of pH (H_2O), $EC_{1:5}$, pH (H_2O_2), and 1 *M* HCl extractable cadmium (Cd), copper (Cu), and arsenic (As).

19.3 Impact of the GEJE Tsunami on Cultivated Soil in Miyagi Prefecture

19.3.1 Thickness and Salinity of the Tsunami Deposits

On July 21, 2011, the Agriculture Promotion Division of Miyagi Prefecture (2011) held a press announcement regarding the preliminary results of the regional soil survey conducted in May 2011. At the time, this survey was particularly important for determining the recovery plan, as the survey determined the TD thickness as well as whether TD contained harmful substances. The survey reported the thickness and salinity status of the sediment, the possible risk of acidification by sulfide in some areas, and a marginal contamination by toxic metals accompanying the sediment (Agriculture Promotion Division of Miyagi Prefecture 2011; Shima et al. 2012; Inao et al. 2013). Fortunately, most of the sediment was of sufficiently small volumes and low Cd, Cu, and As concentrations to judge the land to be safe for use as farmland.

As demonstrated in the press announcement (Agriculture Promotion Division of Miyagi Prefecture 2011), the sediment covered the surfaces of 275 field sites of the total 344 field sites. The cumulative TD thicknesses of the sites indicated an average of 6.5 cm and median of 4.8 cm (maximum, 40.3 cm). A histogram of thicknesses represented the log-normal distribution (n = 275, Fig. 19.2). The sandy TD subgroup (median 5.1 cm) had a large contribution to the thickness as compared with the muddy TD subgroup (median 2.0 cm).

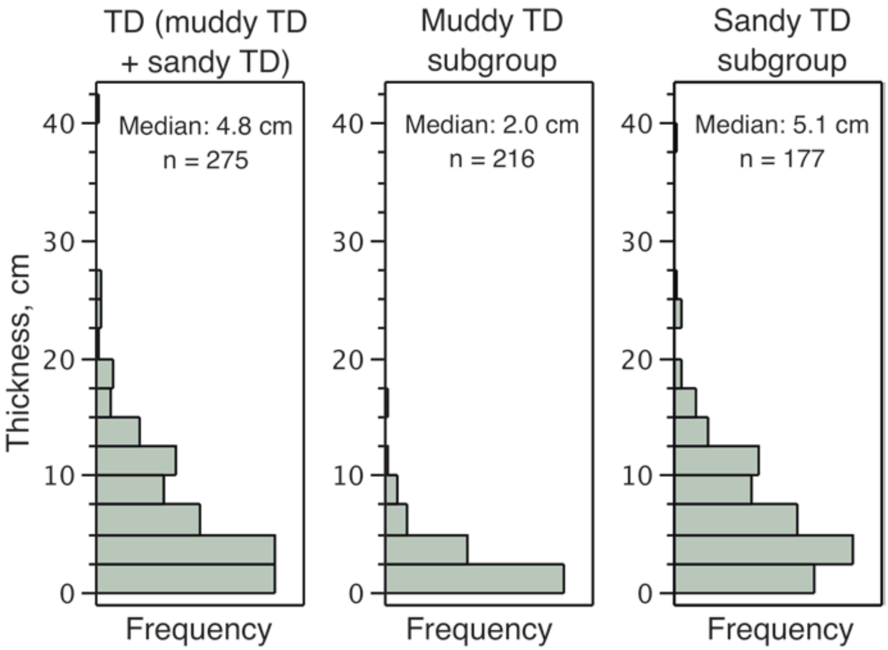

Fig. 19.2 Frequency distributions of thickness (≥0.5 cm) of the tsunami deposit (TD, n = 275), muddy TD subgroup (n = 216), and sandy TD subgroup (n = 177) on the basis of the press announcement (Agriculture Promotion Division of Miyagi Prefecture 2011)

Figure 19.1 shows that the thickness of the tsunami deposit exhibits an inverse relationship with the inland distance throughout the entire region. On the paddy field of Sendai Plain (n = 240), the spatial variability in thickness of TD according to the inland distance of each site is apparent (Fig. 19.3). The deposits thicker than 5 cm were mainly observed within 2 km from the shoreline, whereas those thinner than 5 cm were predominantly ≥2-km inland. No sediment was observed at 48 sites, with 65% of these located >4 km from the shoreline (near the inundation limit). A similar spatial trend of TD thickness was reported by Goto et al. (2014) using the dataset of the field survey conducted by the Miyagi Prefecture/Midori-net Miyagi during June–July 2011.

Electrical conductivity of 1:5 water leachate ($EC_{1:5}$) represents the salinity status and can be used as an indicator of salt damage to crops. The $EC_{1:5}$ of TD showed a median of 5.9 dS m^{-1} using the weighted average at each site, and varied depending on the nature of deposits (Fig. 19.4). TDs with a high $EC_{1:5}$ value mostly consisted of muddy TD (dark colored columns in Fig. 19.4), since muddy TD indicated a higher $EC_{1:5}$ value (n = 173; median, 12.8 dS m^{-1}; maximum, 37.8 dS m^{-1}) than those of sandy TD (n = 164; median, 2.1 dS m^{-1}; maximum, 20.0 dS m^{-1}). Generally, mud (fine particles) has a poor permeability and high water-holding capacity. Therefore, muddy TD could hold more seawater and indicates a higher $EC_{1:5}$ value than sandy TD.

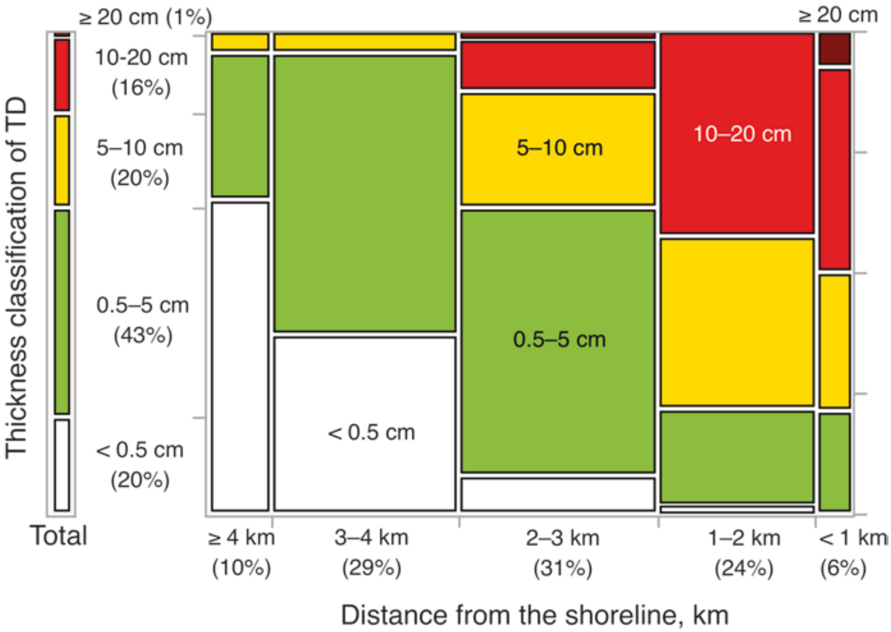

Fig. 19.3 Spatial variability of the thickness of the tsunami deposit (TD) on the paddy field of Sendai Plain (n = 240). *Computation of the inland distance at each site was conducted in cooperation with Dr. C. Yonezawa (Tohoku University)*

19.3.2 Salinity of the Cultivated Soils

The improvement in salinity status of cultivated soil is essential to restore crop production as well as the removal of the sediments or debris. Although the $EC_{1:5}$ of TD showed a median of 5.9 dS m^{-1}, those of the cultivated soil layers SL1 and SL2 were 2.1 and 1.2 dS m^{-1}, respectively (Fig. 19.4). According to the guideline announced by ZEN-NOH (2011), the $EC_{1:5}$ range required to avoid salt damage of paddy rice is ≤0.6–0.3 dS m^{-1} (salinity ≤0.2% or chlorinity ≤0.1%). During May 2011 (before the rainy season), $EC_{1:5}$ values of the cultivated soil exceeded the critical level in most sites investigated within the regional soil survey.

On the paddy field of Sendai Plain (n = 240), the spatial distribution of TDs with high $EC_{1:5}$ (≥10 dS m^{-1}) predominantly occurred within 2–4 km inland (Fig. 19.5). Although the muddy TD mainly increased the $EC_{1:5}$ value of TD, the presence of the muddy sediment layer with poor permeability resulted in the opposite effect to cultivated soil. The proportions of the moderate $EC_{1:5}$ class (2–10 dS m^{-1}) in SL1 and SL2 showed relative increases from 3 to ≥4 km inland. The sites with no sediment in which seawater directly infiltrated the cultivated soil occupied 37% of sites 3–4 km inland and 65% of sites of >4 km inland (near the inundation limit). This particular spatial trend of $EC_{1:5}$ clearly appears in SL2, where $EC_{1:5}$ increased with increasing inland distance (Fig. 19.5). Therefore, TD appears to act as a defensive

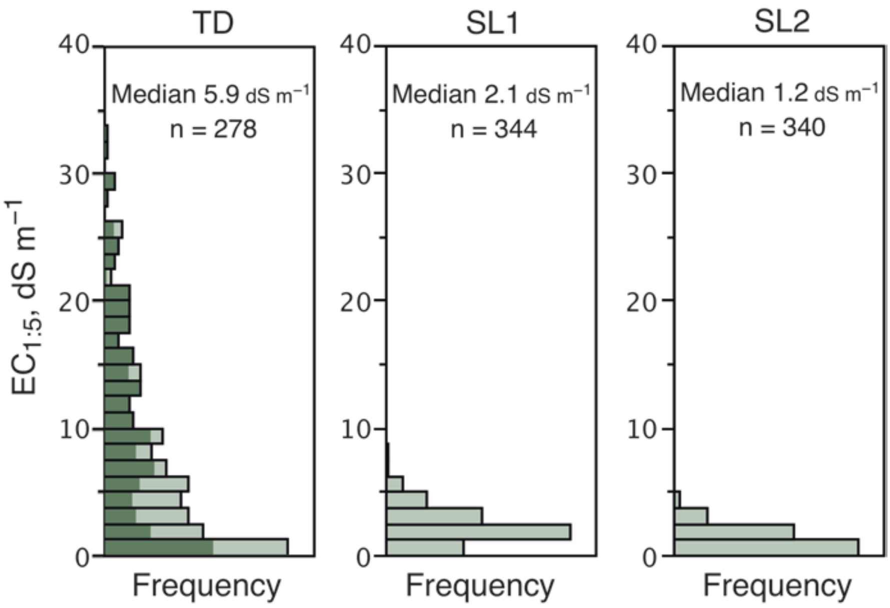

Fig. 19.4 Frequency distributions of the electrical conductivity of 1:5 water leachate ($EC_{1:5}$) of the tsunami deposit (TD, n = 278), 10-cm cultivated soil layer (SL1, n = 344), and the next 10 cm (SL2, n = 340) from the surface. Dark colored columns indicate TD composed predominantly of mud

barrier against seawater penetration into the cultivated land (salt infiltration). Chagué-Goff et al. (2012) similarly concluded that soils not covered by tsunami deposits were strongly affected by salt contamination as a result of a survey along the transect line near Sendai Airport that were set parallel to the flow direction.

19.3.3 Water-Soluble and Exchangeable Cation of Tsunami Deposits and Cultivated Soil Layers

Seawater contains approximately 35 g L^{-1} of dissolved salts and has a salinity of approximately 3.5% (US Department of Energy 1994). The most abundant dissolved ions in seawater are sodium (Na^+), chloride (Cl^-), magnesium (Mg^{2+}), sulfate (SO_4^{2-}) and calcium (Ca^{2+}) with the relative molar charge ratio of the cations Na^+:Mg^{2+}:Ca^{2+} of 0.79:0.18:0.03, whereas that of anions Cl^-:SO_4^{2-} is 0.91:0.09.

Due to the high salinity (predominantly Na^+ and Cl^-), inundation by seawater not only increased $EC_{1:5}$ values of the cultivated soil (Figs. 19.4 and 19.5), but also largely changed the original compositions of water-soluble ions. The sum of water-soluble cations ($cmol_c$ kg^{-1}) positively correlated with $EC_{1:5}$ values (data not shown). On the paddy field of Sendai Plain (n = 240), Na^+ was the most abundant water-soluble

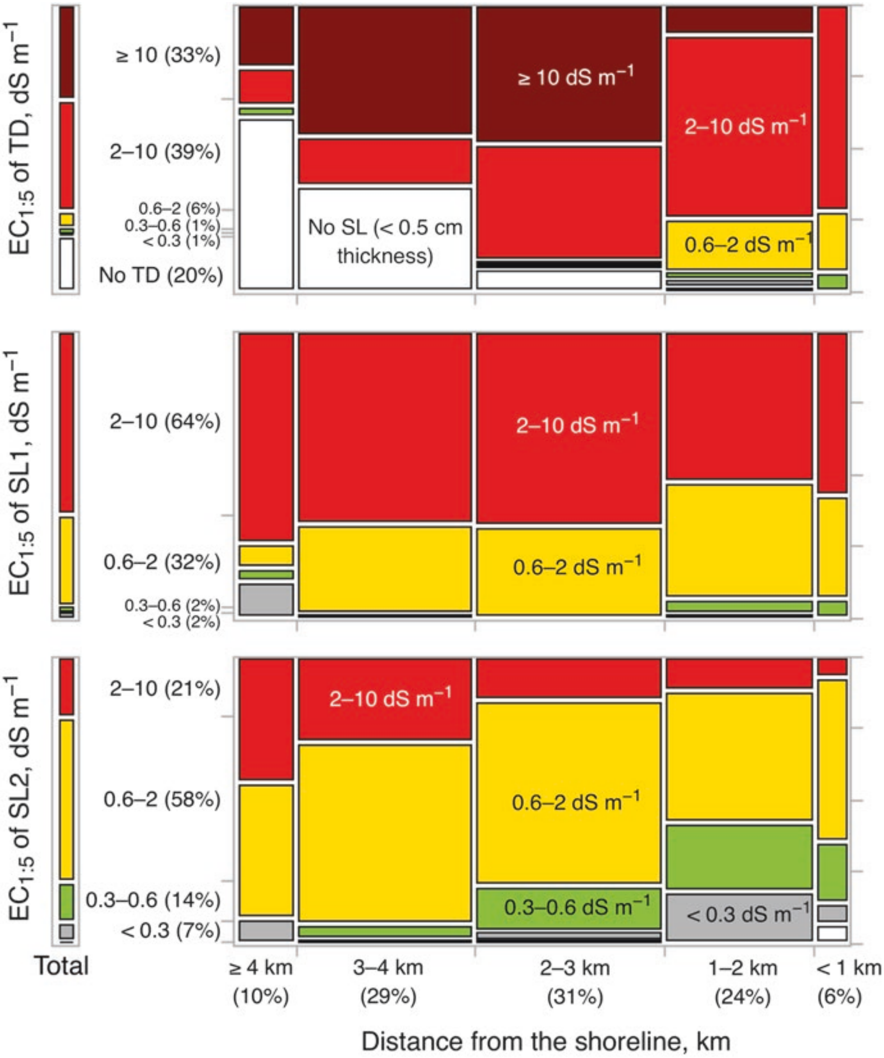

Fig. 19.5 Spatial variability of the electrical conductivity of 1:5 water leachate ($EC_{1:5}$) of the tsunami deposit (TD), 10-cm cultivated soil layer (SL1), and the next 10 cm (SL2) from the surface in the paddy field of Sendai Plain (n = 240). *Computation of the inland distance at each site was conducted in cooperation with Dr. C. Yonezawa (Tohoku University)*

cation within the three layers (Fig. 19.6). Although water-soluble Na^+ in TD indicated an extremely high level (33.3 $cmol_c$ kg^{-1}), the molar charge ratios of water-soluble Na^+/Mg^{2+} at each depth still appeared to reflect that of seawater; however, there was a large difference in water-soluble Ca^{2+}, whose molar charge ratio to Na^+ increased in TD, SL1, and SL2.

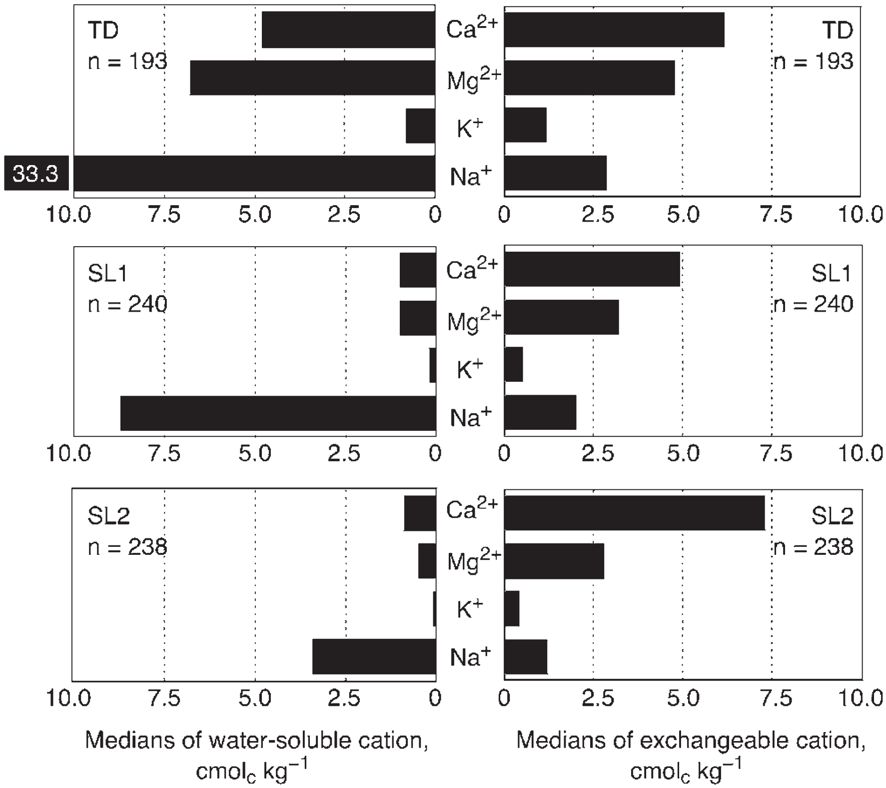

Fig. 19.6 Medians of water-soluble and exchangeable calcium, magnesium, potassium, and sodium content in the tsunami deposit (*TD*), 10-cm cultivated soil layer (*SL1*), and the next 10 cm (*SL2*) from the surface in the paddy field of Sendai Plain (n = 240)

The exchangeable cations are held on or near the surface of a solid particle (e.g., clay or organic matter) by a negative charge. In most cultivated soils, exchangeable Ca^{2+} occurs in larger quantities than other cations due to the soil improvement and fertilization, whereas Na^+ is very low and approaches only trace quantities in the soils of many humid regions. However, dissolved cations (predominantly Na^+) introduced by the tsunami increased water-soluble Na^+, and would stimulate the ion exchange reaction in the cultivated soil. The calcium ion was the most abundant exchangeable cation of the three layers (Fig. 19.6). Exchangeable Ca^{2+} was highest in the deep cultivated soil (SL2) and decreased with SL1 and TD in that order, whereas Mg^{2+} and Na^+ were the highest in the sediment and decreased with increasing depth.

The reaction of the seawater with the cultivated soil would increase water-soluble Ca^{2+} and exchangeable Na^+ and Mg^{2+}, particularly in the sediment layer. Surprisingly, the exchangeable component of TD and SL1 were similar (Fig. 19.6), regardless of the difference in water-soluble cations and $EC_{1:5}$ values. This similarity strongly suggests that inland tsunami deposits are derived from the eroded surface soil of the neighboring farmland. Based on the balance of the erosion and sedimentation volumes on the Sendai Plain, Goto et al. (2014) also concluded that the major source of the muddy TD was the paddy soil, although they could not exclude the contribution of offshore mud.

19.4 Farmland Restoration in Miyagi Prefecture

19.4.1 Salt Removal by Natural Rainfall

For the restoration of tsunami-affected farmland, flushing of salt in the cultivated soil using fresh water as well as the possible removal of sandy/muddy sediments are recommended to allow crop production to resume. In some cases, natural rainfall decreased the salinity of tsunami-affected farmland. Sato (2015) investigated various declining patterns of $EC_{1:5}$ in the paddy fields of Iwate Prefecture until after 235 days from the tsunami attack with a cumulative precipitation over that period of 1,019 mm, and demonstrated the dependency of the decrease on the water permeability of the soils, which is related to the soil hardness. Ito et al. (2015) also reported on the efficiency of salt removal by natural rainfall based on the half-year observation in Miyagi Prefecture. In the paddy fields containing no sediment, precipitation of 952 mm could effectively reduce the $EC_{1:5}$ value from 4.3 dS m^{-1} (May 16, 2011) to <0.6 dS m^{-1} (October 28, 2011). However, the salt removal by precipitation was not as effective in the paddy fields with a thin muddy or a thick sandy overlaying sediment layer.

19.4.2 Reconstruction and Restoration of Farmland

The restoration of tsunami-affected farmland was conducted based on the procedure proposed by the Rural Development Bureau of the Ministry of Agriculture, Forestry and Fisheries (2011b). The excess salt in the farmland is removed by repeated flushing with freshwater; a process which completely depends on the restoration of the irrigation and drainage facilities. Flushing continues until the $EC_{1:5}$ value or chlorinity falls below the critical level. In Miyagi Prefecture, the sediment of ≥5 cm thickness removed at first, after which irrigated fresh water was used for the vertical salt infiltration method or the puddling and surface drainage method. For farmland in which the surface soil was severely eroded or under a large influence by ground subsidence, soil dressing was conducted. Moreover, many studies exist regarding the fertility of the tsunami-affected soil by Japanese researchers, and the findings of which were published as a special issue of the *Japanese Journal of Soil Science and Plant Nutrition* (Miura et al. 2015).

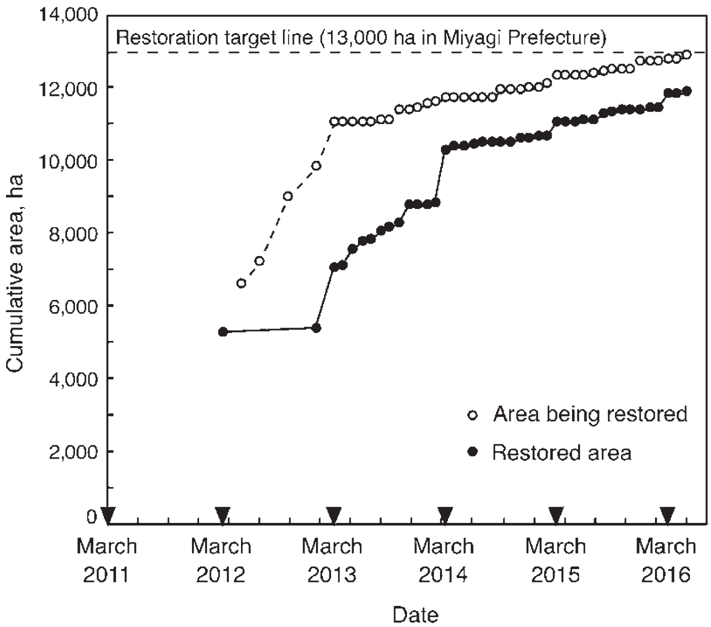

Fig. 19.7 Progress of 5 years restoration of the tsunami-affected farmland in Miyagi Prefecture on the basis of published data (Miyagi Prefectural Government 2016)

The Total area of farmland damaged by the GEJE tsunami was 15,002 ha in Miyagi Prefecture (Rural Development Bureau of Ministry of Agriculture, Forestry and Fisheries 2011a). Although the restoration of damaged farmland was severely delayed in 2011 due to the destruction of irrigation and drainage facilities, the area recovered has rapidly increased since 2012. Figure 19.7 shows the progress of the restoration of the tsunami-affected farmland in Miyagi Prefecture on the basis of published data (Miyagi Prefectural Government 2016). The restored area of the tsunami-affected farmland was 5,250 ha by the spring of 2012 and reached 10,253 ha by the spring of 2014. As a result of 5 years of reconstruction and salt-removal budgeted for by the Government, restoration has been completed in 88% (11,411 ha) of the target area in Miyagi Prefecture.

19.5 Conclusions

In this paper, an overview of the impact of the GEJE tsunami on cultivated soil based on the field survey involving 344 sites of coastal farmland in Miyagi Prefecture has been presented. A log-normal distribution in the cumulative thickness of tsunami deposit layers (TD) appeared although their thickness varied depending on their distance from the shoreline. A variation in electrical conductivity of 1:5 water leachate ($EC_{1:5}$) of TD also occurred depending on their textures and the distance from the shoreline.

Surface 10-cm layer (SL1) and the next 10-cm layer (SL2) of the cultivated soil were altered by the inundation of seawater as well as the introduction of tsunami deposits overlaying. An increase in water-soluble calcium and exchangeable sodium was found due to the reaction between sodium from seawater and calcium held by soil particles within the tsunami-affected areas. The analysis has also showed that the similarity in the exchangeable components of TD and SL1, strongly suggesting that the inland tsunami deposits are derived from the eroded soil surface from neighboring farmland.

For the restoration of tsunami-affected farmland except that the surface soil was severely eroded or under a large influence by ground subsidence, flushing of excess water-soluble components as well as the possible removal of the sediments were commonly conducted. In spite of the serious damage caused by the GEJE tsunami on agricultural fields, as a result of the continuous efforts undertaken through 5 years by the Japanese government-sponsored reconstruction and salt removal program, the restoration of farmland has been completed in 88% of the target area in Miyagi Prefecture.

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