

Field Monitoring of 2010-Tsunami Impact on Agricultural Soils and Irrigation Waters: Central Chile

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Abstract An in situ post tsunami study was conducted to assess the effect of water management and rainfalls in soil properties and water quality at a low-lying coastal area of central Chile affected by Mw8.8 Earthquake Tsunami the night of 27 February 2010. Soil samples were taken at two depths (0 to 20 and 20 to 40 cm) during 2010 and late 2012. Water quality in a local shallow well was also monitored in 2010 and 2012. High soil salinity was recorded 2 months later than tsunami occurs, closely associated to water-soluble chloride and cations ($\text{Cl}^- \gg \text{Na}^+ \gg \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$), ionic toxicities, and vegetal inhibition (*Vasconcellea pubescens*) by less available water to plants. An initial reduction in soil pH due to ionic strength and coarse-textured class of soil was observed and the sodium adsorption ratio (SAR) in soil varied between 5.7 and 11.2 (mmol L^{-1})^{0.5} showing to be saline. Although SARw values are very high (>18 (mmol L^{-1})^{0.5}), it does not exist risks of reduction on soil infiltration rates according to ECw (>5 dS m⁻¹) obtained. After 2 years, soil salinity was drastically reduced in the affected areas due to high soil permeability and natural attenuation (rainfalls and leaching effects), with sulfate and bicarbonate concentrations showing excessive values. Further, irrigation water quality returned to pre-tsunami situation, with only levels of sodium slightly exceeding desirable range from health point of view. Finally, it is suggested a

proper design of irrigation systems before implementing other management practices.

Keywords Tsunami · Seawater · Physical and chemical soil properties · Water quality

1 Introduction

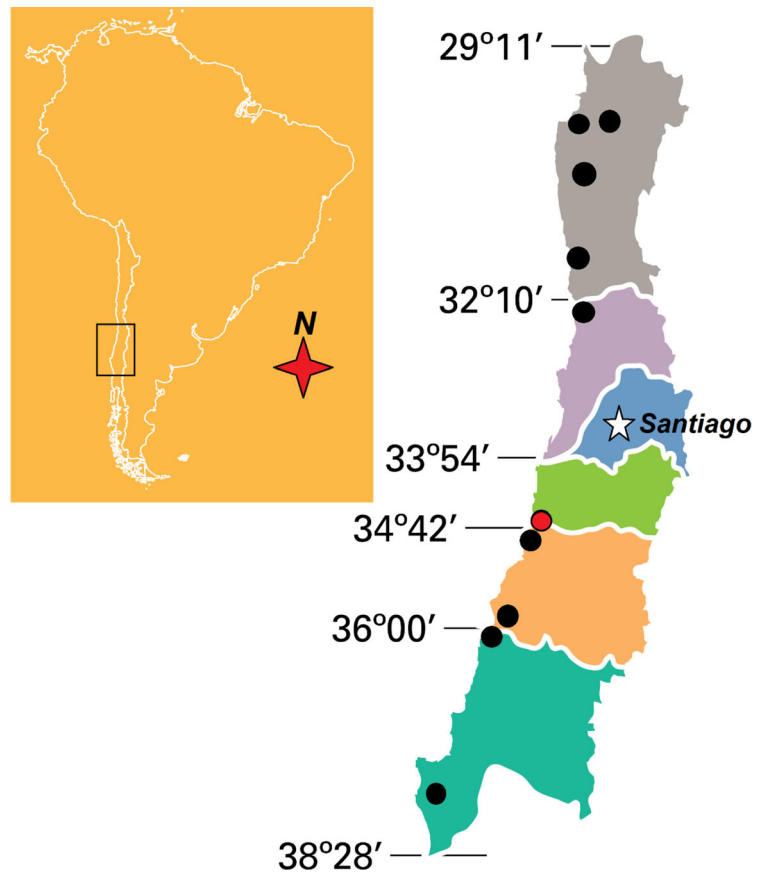
Seawater intrusion onto land, as occurred in recent tsunami-affected regions, can deposit large amounts of salts in coastal land soils. If all of the inlets and islands are considered, the coastline of Chile extends for 83,500 km in length parallel to the uplifted longitudinal Coastal Range in South America. At the west side of the Coastal Range and with a long history of great subduction-zone earthquakes (Fig. 1), most segments are vulnerable to tsunami inundation.

On 27 February, 2010, a magnitude 8.8 earthquake (Richter scale) showed a fault-rupture length of about 500 km, where several waves inundated the coastline for more than 800 km alongshore of central of Chile. At a focal depth of about 35 km, the epicenter was located (35.826° S, 72.668° W) immediately to the north of the rupture zone of the Mw = 9.5 Great Chilean Earthquake of 1960, i.e., the strongest earthquake ever instrumentally recorded.

Vargas et al. (2011) pointed that the tsunami effects were highly variable along the Chilean coast as a result of geomorphic and bathymetric local conditions, in addition to potential complexities induced by the main shock. With the intention of providing insights into the

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Fig. 1 Location of study area (red circle) and others localities (black circles) where *Vasconcellea pubescens* is commonly produced in Chile



processes and morphological changes associated with tsunami inundation and return flow, Morton et al. (2011) performed several studies (topographic surveys, flow depths, flow directions, scour depths, and deposit thicknesses) in Chilean territory. In particular, Quezada et al. (2012) and Fariás et al. (2010) reported that the earthquake and tsunami caused a significant subsidence of marine abrasion platform in northern coastal segment, between the regions of Valparaíso and Maule (33° S–36° S).

Despite the limited amount of studies about the effects of tsunamis on Chilean soils (Wright and Mella 1963; Cisternas et al. 2005; Yoshii et al. 2013), there are several studies for extensive agricultural lands in coastlines and islands worldwide to date that show the many effects of seawater intrusion on soils. Increased soil salinity (Roy et al. 2014; McLeod et al. 2010; Chagué-Goff et al. 2012; Agus et al. 2012), soil sodicity and water-soluble ions (Chaudhary et al. 2006; Raja et al. 2009), or sulfate and chloride contents (Raja et al.

2009). Effects in soil pH are contradictory, in some cases have been informed non-significant impacts (Kume et al. 2009), whereas in others alkalization (Arslan and Demir 2013; Nayak et al. 2010; Agus et al. 2012) or acidification is consigned (Sandoval et al. 2013). Only Hulugalle et al. (2009) and Chappell et al. (2013) describe physical soil degradation by seawater. Additional studies show that the tsunami negatively affect groundwater and surface water quality, with an increased water salinity as commonly described (Kume et al. 2009; Raja et al. 2009), whereas an increased turbidity and hardness, and a decreased oxygen level were found by Swamy et al. (2006).

Factors such as tsunami characteristics, soil and vegetation type, climate and management practices will help to determine the resulting magnitude of devastating effects of tsunami on soils and water resources. Practices of soil restoration involving living organisms (revegetation, phytoremediation, and bioremediation) have been suggested (Qadir et al. 2007; Moqsud and Omine 2013;

Hasanuzzaman et al. 2014). However, amendment (organic and inorganic) applications are particularly recommended in Chile by Sandoval et al. (2013) and Quezada et al. (2016) working, respectively, at laboratory and greenhouse levels with soils flooded by the 2010 tsunami. These authors noted that in order to validate their results, field studies are required considering that under the present climate and soil conditions, the negative effects on soil properties caused by seawater inundation would continue between 5 and 7 years. The same authors concluded also that the agricultural production in coastal soils could be restored faster with the application of organic amendments, gypsum, and leaching processes.

Certainly relying on natural attenuation by leaching could be preferable option. Central zone of Chile is characterized by a strong seasonal rainfall distribution with most of it (75 %) concentrated in autumn-winter months (Pizarro et al. 2012; Montecinos and Aceituno 2003), and similar mean annual precipitation and mean potential evapotranspiration (740 mm). Nevertheless, the rate of desalinization by rainfalls should be lower than the reported in other areas affected by tsunamis (Szczuciński et al. 2007; Raja et al. 2009), where authors found that the salinity levels have drastically reduced to almost pre-tsunami levels.

In addition to monitoring water quality in a shallow well, the main goal of this study was to assess the effect of irrigation management and natural rainfalls in some physical and chemical properties of a well-drained coarse-textured soil affected by 2010 tsunami near to shoreline of central Chile.

2 Material and Methods

Located at 100 m from the Pacific shoreline, the study site corresponds to Lipimávida, a coastal locality (34° 51' S, 72° 08' W) in Central Chile at the west side of the Coastal Range, which was partially submerged during the tsunami that struck the Maule Region on 2010. Before the tsunami, an orchard with highland papaw (*Vasconcellea pubescens* [Lenné et C. Koch] Badillo) was established. After the tsunami, the orchard was seriously affected by the seawater intrusion given that flooding for 48 h results fatal for the species (Khondaker and Ozawa 2007). Native to Andean regions from it would have been introduced to Chile (Carrasco et al. 2009), the highland papaw is a relative of the tropical

papaw (*Carica papaya* L.) but although there are two lineages within the *Caricaceae* family, some members of *Vasconcellea* are more closely allied to *C. papaya* than others (Van Droogenbroeck et al. 2004). It is cultivated in cold climates, including northern Chile and near-sea-level. Figure 1 shows the zones where this species is mainly produced in Chile, 30° to 33° S in the north but also southern smaller orchards are observed in the coast between 35° and 38° S.

The soils are classified as *Typic Ustipsamments* (Casanova et al. 2013), coarse-textured, moderately deep and with a rapid internal drainage. According to the Köppen–Geiger system, the climate in the zone is classified as *Csb*, i.e., temperate with dry and warm summer seasons (Peel et al. 2007) or coastal Mediterranean, with mean annual rainfalls around 250 mm (Montecinos and Aceituno 2003; Pizarro et al. 2012).

2.1 Water Budget

Leaching of salt in the soil profile is obtained from excess water on surface that causes deep percolation (*DP*), flushing salt water out of the profile with appropriate drainage conditions. As this excess water results from a positive water budget, monthly *DP* was estimated considering irrigation rate (*I*, with an efficiency of 0.90 for condition T0), crop evapotranspiration (*ET_c*, Penman-Monteith equation), rainfall (*P*, meteorological station data). The estimated leaching fraction (*LR*, additional water needed above crop requirements) at T1 was:

$$LR = \frac{EC_w}{5(EC_c) - EC_w} \quad (1)$$

where *LR* is the minimum leaching requirement needed to control salts within the tolerance of the crop with irrigation. *EC_w* is the salinity of applied irrigation water (dS m⁻¹) and *EC_c* is the average salinity (dS m⁻¹) tolerated by the crops as measured on a soil saturation extract. So that the total annual depth of water applied (*AW*, mm year⁻¹) to meet both the crop demand and leaching requirement was:

$$AW = \frac{ET_c}{1 - LR} \quad (2)$$

2.2 Soil and Water Analyses

During the study period (April 2010 to July 2012), a chemical soil characterization was carried out at the site, according to the methodologies proposed for Chilean soils (Sadzawka et al. 2006) sampling at two depths (0 to 20 and 20 to 40 cm) during 2010 and late 2012 (Table 1). Electrical conductivity (EC) in an extract of saturated paste with a conductivimeter (Hanna, HI4321), pH in deionized water (1:1) by pH meter (Hanna, HI3221), soil organic matter (SOM) by Walkley–Black chromic acid wet oxidation method, soluble cations by extraction method using atomic absorption spectrophotometer for Ca and Mg and flame photometer for K and Na were included. Soluble chloride contents by manual titration with AgNO_3 , and sulfate contents extracted with $\text{Ca}(\text{H}_2\text{PO}_4)_2$ (0.01 mol L^{-1}) were analyzed. In addition, cation exchange capacity of soils (NaOAc 1N, pH 8.2), soluble carbonate and bicarbonate by potentiometric titration with H_2SO_4 (saturated extract) were determined.

A comparative soil physical characterization was carried out after 9 months of tsunami event for unaffected (T0) and affected soils (T1), including soil texture (Bouyoucos method), bulk density (clods), and pF curve as described by Sandoval et al. (2012).

Water quality was also determined (April 2010 and July 2012) in a shallow well situated at 50 m and at same altitude (20 m asl) of the orchard, also inundated by tsunami waves. Samples were handled in coolers to the laboratory where they were analyzed for pH, EC, soluble cations and anions, according to Chilean standard methods (Sadzawka 2006). At the end of the study period (July 2012), water turbidity was measured in laboratory, with a turbidimeter (Hanna, HI83414) based in nephelometry and proposed by USEPA (1993). Water dissolved oxygen was determined in situ with a portable equipment (Hanna, HI9146).

Table 1 Description of studied soil conditions according to sea-water intrusion, crops, and water source

Conditions	Description	Soil use/water supply
T0	Soil unaffected by tsunami	<i>V. pubescens</i> /drip irrigation + rainfalls
T1	Soil affected by tsunami	Fallow-weeds/rainfalls

Preliminary general data from soil analyses 2 months later the tsunami (April 2010) were compared with final values (July 2012), which were statistically explored. Analysis of variance was performed and a Tukey test was used as a post hoc test ($p < 0.05$).

3 Results and Discussion

3.1 Physical Properties of Soils

Soil physical properties are characteristics of coarse textured Entisols (Table 2), i.e., aerated profile, excessively drained and a low water retention capacity. However, in contrast to many other tsunamis, the quite common deposition of organic and inorganic materials (sand or coarser), desurfacing and compaction of topsoil (Bahlburg and Weiss 2007; Mastronuzzi and Sansó 2004) were not observed on Lipimávida lands affected by 2010 tsunami. Compared with unaffected soils, both silt contents and total soil porosity (10 %) were increased, and soil bulk density was found inferior at the damaged sectors (Table 2).

According to the pF curves, water contents are slightly higher for tsunami-affected soils (Fig. 2), with water retention (at all the pressure heads used) above those measured on soil horizons unaffected by tsunami intrusion. Physically, soil salinity produces an osmotic effect that contributes to total soil water potential, where added energy required to uptake water from the salinized soil (osmotic potential) is additive to the energy required to uptake water from a salt-free soil. This finding, reported by several authors (Basile et al. 2012; Waller and Yitayew 2016), shows higher retention values in soil with higher salt content following a primary or secondary salinization. However, available water (between 10 and 1,000 kPa, for coarse-textured soils) for the crop was reduced in surface (1.1 %) and in subsurface horizon (0.8 %) as salinity increased.

3.2 Chemical and Physicochemical Properties of Soils

Soil samples obtained in another Chilean area (Arauco, 400 km at south of Lipimávida) show EC values between 1.0 and 8.6 dS m^{-1} (Yoshii et al. 2013). More extreme values of soil salinity during the first evaluation date are observed (Table 3) for the top soils (12 dS m^{-1}) and a lesser degree of increase for the subsoil (8 dS m^{-1}) at Lipimávida sector, with sodium adsorption ratio

Table 2 Soil physical properties measured in depth

Conditions	Soil depth (cm)	Clay Silt Sand			Bulk density (Mg m ⁻³)	Particle density
		----- (%) -----				
T0	0–20	1.4	3.1	95.5	1.95	2.87
	20–40	2.4	3.1	94.5	1.89	2.86
T1	0–20	1.2	5.9	92.9	1.68	2.87
	20–40	1.2	6.4	92.4	1.68	2.84

(SAR) reaching 11.2 and 5.7 (mmol_c L⁻¹)^{0.5}, respectively, showing to be a saline soil.

Even though leaf damage and necrosis or obvious injuries to the plant are only noticeable after prolonged exposure to relatively high salinity, papaw plants at T1 site show effects closely analogous to those of drought as result in water stress (Fig. 2). Classified as moderately sensitive with effects at 3 dS m⁻¹ and moderately tolerant at soil EC between 2 and 4 dS m⁻¹ (Wu and Dodge 2005; Francois and Maas 1999), the effect of salinity on papaw plants may vary among genotypes of the same species.

The decrease in the soil solution pH in tsunami-affected soils (Table 3) could be explained by the increase of ionic strength in soil solution. Jesus et al. (2015), applying simulated seawater, report similar pH reduction on organic and mineral soils. Increased salt content tends to give lower pH values in temperate zone soils (Thomas, 2006) and for sandy soils this effect is more pronounced (Lu et al. 2004). In acid soils, the

effect apparently is due to both displacement of Al³⁺ from the exchange complex and to increased hydrolysis of various kinds of Al species (Nayak et al. 2010). In calcareous soils, an effect of about the same magnitude also is observed. Nevertheless, soil pH is generally not a limiting factor for papaw, preferring neutral soils (Ayers and Westcot 1994) according to the interaction of soil pH with nutrient availability. In fact, germination and growth of seedling are unaffected until soil pH 9.0 (Marler 2007).

Waterlogging and salinity have clear effects on electrochemical properties of soils, increasing concentration of water-soluble cations and anions (Table 4). As reported by Lu et al. (2004), waterlogging increase the concentrations of water-soluble K⁺, Ca²⁺, and Mg²⁺ in the soil, being attributed to an increased competition between cations for the negatively charged sites under reducing conditions. In addition, increased salinity level, due to higher concentrations of Na⁺ to displace these cations in the exchange complex, resulted in increases of the concentrations of water-soluble cations also.

The cation exchange capacity of soil is very low and linked ($r=0.567$) to the organic carbon content, which is fairly reduced also but a slight increase in time is observed as consequence of debris accumulation.

Accumulation of sodium chloride is the main reason for salinization in agricultural soil exposed to tsunami waters, then a much higher concentration of Na⁺ and Cl⁻

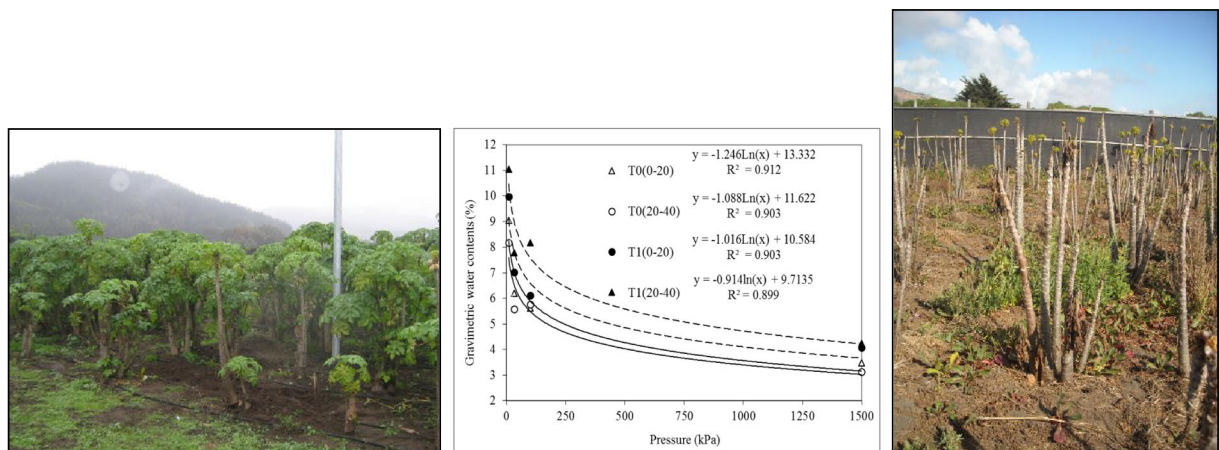


Fig. 2 Water retention curves at two depths (0–20 cm and 20–40 cm) on soil non-affected (T0, above and left) and affected (T1, above and right) by tsunami ($n = 3$). *Vasconcellea pubescens* plants at Lipimavida sector (central coast of Chile)

Table 3 Soil chemical properties measured during the study period at two soil depths

Soil depth (cm)	Conditions		Apr 2010	Jun 2012
0–20	T0	pH	6.2	7.12 ± 0.02ab
			T1	5.5
20–40	T0		7.3	6.36 ± 0.33b
			T1	5.9
0–20	T0	EC (dS m ⁻¹)	0.8	0.63 ± 0.10a
			T1	12.6
20–40	T0		0.5	0.30 ± 0.02b
			T1	8.6
0–20	T0	SOM (%)	0.6	1.26 ± 0.08a
			T1	0.9
20–40	T0		0.1	0.41 ± 0.10a
			T1	0.5
0–20	T0	CEC (cmol _c kg ⁻¹)	5.0	7.65 ± 1.34a
			T1	7.0
20–40	T0		4.6	7.56 ± 2.67a
			T1	6.1
0–20	T0	SAR (mmol _c L ⁻¹) ^{0.5}	1.8	1.76 ± 0.51a
			T1	11.2
20–40	T0		3.4	2.66 ± 0.31b
			T1	5.7

$p < 0.05$, EC soil electrical conductivity, SOM soil organic matter, CEC cation exchange capacity, SAR sodium adsorption ratio of soil, $\text{Ca}/(\text{Mg}^{2+} + \text{Ca}^{2+})^{0.5}$

shortly after the event is observed also at topsoil level by several authors (Chagué-Goff et al. 2012; Roy et al. 2014). This is also suggested by the strong positive correlation between both elements ($r = 0.999$), although it does not exclude other salts, such as KCl. It was found (Fig. 3) that salinity levels were closely associated to chloride and basic cations ($\text{Cl}^- \gg \text{Na}^+ \gg \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$) rather than with water-soluble sulfate and bicarbonate. Therefore, in addition to osmotic forces, these toxic levels of both ions (even at 40 cm depth) are responsible of the damaging effects on plants observed. For instance, Chesworth (2008) reported that the most chloride-tolerant plants are injured only at concentrations above 30 mmol_c L⁻¹.

Sulfate in the soil solution is within the range (0.16 to 0.63 mmol_c L⁻¹) of most temperate zone soils (McGrath et al. 2014) and drastically increases with the tsunami (Table 4).

Table 4 Soluble anions and cations (mmol_c L⁻¹) measured in saturated extract and during the study period, at two soil depths

Soil depth (cm)	Conditions	Water-soluble ions	Apr 2010	Jun 2012
0–20	T0	Ca ²⁺	1.0	1.17 ± 0.45a
			T1	14.0
20–40	T0		0.6	0.44 ± 0.21a
			T1	17.8
0–20	T0	Mg ²⁺	1.6	1.66 ± 0.26a
			T1	7.4
20–40	T0		0.3	0.51 ± 0.05a
			T1	9.1
0–20	T0	Na ⁺	3.0	2.96 ± 1.01a
			T1	51.6
20–40	T0		3.2	2.59 ± 0.10a
			T1	29.8
0–20	T0	K ⁺	1.2	1.35 ± 0.26a
			T1	2.9
20–40	T0		0.2	nd
			T1	1.0
0–20	T0	Cl ⁻	4.1	1.03 ± 1.79a
			T1	115.6
20–40	T0		1.3	0.0
			T1	67.4
0–20	T0	HCO ₃ ⁻	2.4	0.88 ± 0.32a
			T1	1.0
20–40	T0		2.7	0.73 ± 0.30ab
			T1	1.2
0–20	T0	SO ₄ ²⁻	0.2	4.43 ± 0.65a
			T1	5.7
20–40	T0		0.2	4.06 ± 1.12a
			T1	3.4

nd not detected. $p < 0.05$

3.3 Water Quality

Assessment of water quality in the shallow well has shown that the surface water was contaminated due to the tsunami. In fact, there is a very strong correlation ($I_{\text{water-well}} = 0.0741 \cdot I_{\text{seawater}}$; $r = 0.999$) between of typical ionic concentrations of seawater and measured values at the shallow well in April 2010 (Table 5). According to Ayers and Westcot (1994), the use of water exceeding 3 dS m⁻¹ (Table 5) is quite restrictive due to soil salinization risks. On the other hand, although

sodium adsorption ratio of the irrigation water (SAR_w) is very high ($>18 \text{ (mmol L}^{-1})^{0.5}$) and since the obtained electrical conductivity of the irrigation water (EC_w) is above 5, a reduction in soil infiltration rates it is unlikely (Oster and Schroer 1979). Considering safe ranges (from health point of view) for water (Rosborg and Kozisek 2015), most water-leachable cations (Mg^{2+} , K^+ , and Na^+) and some water-leachable anions (HCO_3^- and Cl^-) exceed these ranges immediately after the incursion of tsunami seawater.

Due to large displacement and strong mixing caused by tsunamis, both dissolved oxygen and turbidity exhibit post-tsunami changes and in this case reach values within the desirable ranges (Table 5).

3.4 Natural Attenuation

The Environmental Protection Agency of USA (USEPA 1999) defines natural attenuation as a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. Coarse-textured soils have a high infiltration rate and a limited capacity to fix and retain salt, reason why a small amount of fresh water can leach out salts from these types of soil profiles. After 2 years, soil salinity (Table 3) was drastically reduced ($<0.7 \text{ dS m}^{-1}$) at both soil depths (T1) because of high soil

permeability, rainfalls, and leaching effects (Fig. 4). Final sulfate concentration shows a range between 4.06 and $8.55 \text{ mmol}_c \text{ L}^{-1}$, but higher values ($260 \text{ mmol}_c \text{ L}^{-1}$) than those reported here are informed by Sandoval et al. (2013) for the same event in Chilean soils ($36^\circ 31' \text{ S}$ – $72^\circ 55' \text{ W}$, $\sim 17 \text{ m asl}$). Bicarbonate concentrations increase ($4.64 \text{ mmol}_c \text{ L}^{-1}$) and do not relate to the observed neutral pH of water, but it is known that their presence without carbonates usually will have a $\text{pH} < 8.3$ (Ritter 2010), then bicarbonate equals total alkalinity. On the other hand, Ploethner et al. (2008) report that the main driving force for the relatively high bicarbonate concentrations is the oxidation of organic carbon which in turn accounts for the decomposition of sulfates.

It was observed from this monitoring that the irrigation water quality, 2 years after the tsunamis, was close the pre-tsunami scenario, with only levels of sodium slightly exceeding desirable range from health point of view.

Finally, according to Jesus et al. (2015), future research on soil salinization should focus on remediation options and how their efficiency might be affected by different soil types. Certainly some strategies will produce inferior results than taking no action at all (i.e., relying on natural attenuation by leaching). Moreover, site-specific recommendations must be provided to farmers in the studied sector since the soils are coarse-textured with low organic carbon, advising a proper

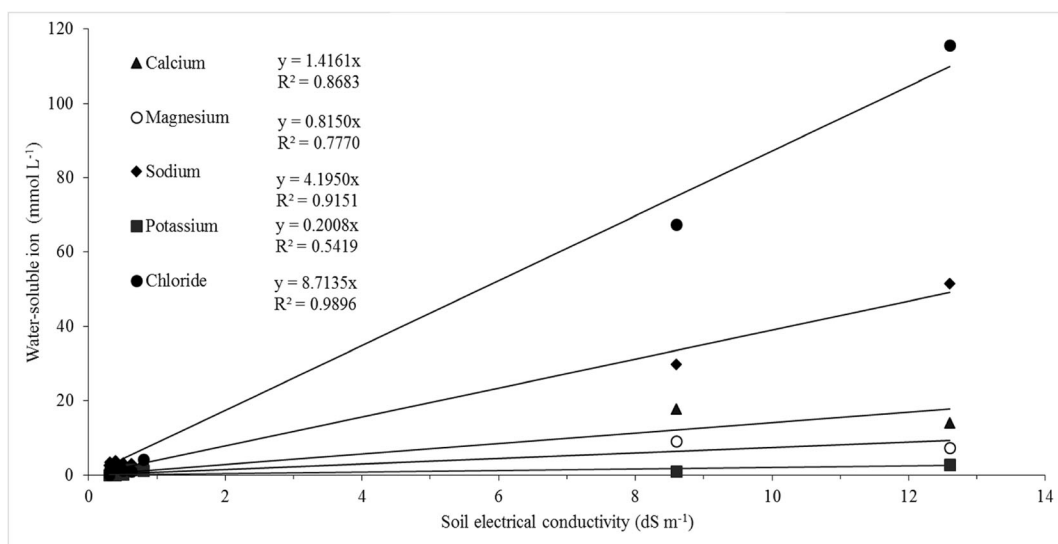


Fig. 3 Relationships between soil salinity and water-soluble ions. Coastal soils of central Chile (2010–2012)

Table 5 Comparison of irrigation water quality parameters from well affected by tsunami with seawater and desirables values, at study site (2010–2012)

	Units	Apr 2010	Jun 2012	Desirable ranges ^a	Seawater ^b
Cations					
Ca ²⁺	mmol _c L ⁻¹	0.51	1.10	(0.50–2.00)	(10.5)
Mg ²⁺		3.30	0.97	(0.41–2.06)	(53.9)
K ⁺		1.23	0.23	(0.13–0.26)	(10.4)
Na ⁺		36.20	4.72	(0.87–4.35)	(476.0)
Anions					
CO ₃ ²⁻	mmol _c L ⁻¹	0.00	0.00	(0)	(0.29)
HCO ₃ ⁻		1.36	4.64	(1.64–4.92)	(2.25)
Cl ⁻		40.30	1.63	(0.56–2.82)	(554.0)
SO ₄ ²⁻		1.83	0.26	(0.52–2.60)	(28.6)
Others					
Turbidity	NTU	nd	0.32	(<5)	–
Dissolved O ₂	mg L ⁻¹	nd	7.70	(>5)	–
pH	–	7.80	7.01	(7.0–8.0)	–
EC _w	dS m ⁻¹	5.41	1.07	–	(50–55)
SAR _w	(mmol L ⁻¹) ^{0.5}	18.5	3.3	–	(59.3)

NTU Nephelometric Turbidity Units, EC_w electrical conductivity of the irrigation water, SAR_w sodium adsorption ratio of the irrigation water

^aDesirable ranges in drink water from health point of view (Rosborg and Kozisek 2015)

^bTypical values (Hazelton and Murphy 2007)

irrigation system before expensive amendment application to soils.

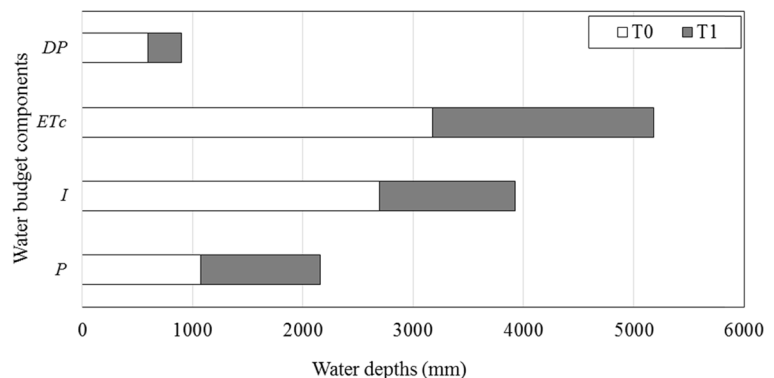
4 Conclusions

Located in a tectonically active zone, Chile is a country prone to seismic activity causing earthquakes, volcanic eruptions and much of its coastline is considered at risk from destructive tsunamis. Seawater intrusion onto land from the Pacific Ocean tsunami in February 2010 damaged irrigation, drainage and road infrastructures, but also salinized and damaged agricultural soil. Even

though the type and nature of damage was highly variable, the general agricultural productivity of coastal lands was severely impaired.

At the study area, toxic levels of seawater salts inhibited the vegetal (*Vasconcellea pubescens*) growth, because it makes the water less available to plants. High electrical conductivity values in soil (>12 dS m⁻¹) and water (>5 dS m⁻¹) were recorded in April 2010 attributed to evaporation, combined with low rainfall in the 2 months following the tsunami. Besides, most soil horizons affected by tsunami showed that the ratio of (CO₃ + HCO₃)/(Cl + SO₄) and Na/(Cl + SO₄) < 1, being treated as saline soils.

Fig. 4 Water budget at experimental site (2010–2012). *P* rainfall, *I* irrigation, *ETc* crop evapotranspiration, *DP* deep percolation



A clear reduction in soil pH in depth (1.4 units) and surface (0.7 units) resulted as consequence of ionic strength generated and the coarse-textured soil. On the other hand, the soil collected in the tsunami-inundated area was rich in water-soluble ions (Ca^{2+} , K^+ , Na^+ , Mg^{2+} , Cl^- , and SO_4^{2-}) compared with the samples collected in the non-inundated areas.

Seawater intrusion not only affected the standing crop and soils but also resulted in the salinization and increased ion concentrations at water bodies. However, only the levels of sodium in irrigation water exceeded slightly desirable range from health point of view. The results indicate the gradual recovery process of the soil affected, which can be attributed to natural attenuation (rainfalls and leaching effects). Therefore, some site-specific recommendations based on conditions and characteristics of soils must be provided to local farmers, advising assess a proper (well designed) sprinkler or drip irrigation system before regularly amendment applications.

References

- Agus, F., Rachman, A., Wahyunto, Ritung, S., McLeod, M., & Slavich, P. (2012). The dynamics of tsunami affected soil properties in Aceh, Indonesia. <http://ir.library.tohoku.ac.jp/re/bitstream/10097/54435/1/AA12005506-2012-9-11.pdf>. Accessed 27 July 2016.
- Arslan, H., & Demir, Y. (2013). Impacts of seawater intrusion on soil salinity and alkalinity in Bafra Plain, Turkey. *Environmental Monitoring and Assessment*. doi:10.1007/s10661-012-2611-3.
- Ayers, R. S., & Westcot, D. W. (1994). *Water quality for agriculture*, irrigation and drainage paper 29, rev. 1. Rome: Food and Agriculture Organization of the United Nations.
- Bahlburg, H., & Weiss, R. (2007). Sedimentology of the December 26 (2004) Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya. *International Journal of Earth Sciences*. doi:10.1007/s00531-006-0148-9.
- Basile, A., Buttafuoco, G., Mele, G., & Tedeschi, A. (2012). Complementary techniques to assess physical properties of a fine soil irrigated with saline water. *Environmental Earth Science*. doi:10.1007/s12665-011-1404-2.
- Carrasco, B., Ávila, P., Pérez-Díaz, J., Muñoz, P., García, R., Lavandero, B., et al. (2009). Genetic structure of highland papayas (*Vasconcellea pubescens* (L'Herminier) C. Koch) Badillo cultivated along a geographic gradient in Chile as revealed by Inter Simple Sequence Repeats (ISRR). *Genetic Resources and Crop Evolution*. doi:10.1007/s10722-008-9367-1.
- Casanova, M., Salazar, O., Seguel, O., & Luzio, W. (2013). *The soils of Chile*. Dordrecht: Springer.
- Chagué-Goff, C., Niedzielski, P., Wong, H. K. Y., Szczuciński, W., Sugawara, D., & Goff, J. (2012). Environmental impact assessment of the 2011 Tohoku-oki tsunami on the Sendai Plain. *Sedimentary Geology*. doi:10.1016/j.sedgeo.2012.05.021.
- Chappell, M., Middleton, M., & Price, C. (2013). Chemical and physical changes in tropical soils from seawater exposure and subsequent rainwater washes. *Procedia Earth and Planetary Science*. doi:10.1016/j.proeps.2013.03.190.
- Chaudhary, D. R., Ghosh, A., & Patolia, J. S. (2006). Characterization of soils in the tsunami-affected coastal areas of Tamil Nadu for agronomic rehabilitation. *Current Science*, 91(1), 99–104.
- Chesworth, W. (2008). *Encyclopedia of soil science*. Dordrecht: Springer.
- Cisternas, M., Atwater, B. F., Torrejon, F., Sawai, Y., Machuca, G., Lagos, M., et al. (2005). Predecessors of the giant 1960 Chile earthquake. *Nature*. doi:10.1038/nature03943.
- Fariás, M., Vargas, G., Tassara, A., Carretier, S., Baize, S., Melnick, D., et al. (2010). Land level changes produced by the 2010 Mw 8.8 Chile earthquake. *Science*. doi:10.1126/science.1192094.
- Francois, L. E., & Maas, E. V. (1999). Crop response and management on salt-affected soils. In M. Pessarakli (Ed.), *Handbook of plant and crop stress* (pp. 169–201). New York: Marcel Dekker Press Inc.
- Hasanuzzaman, M., Kamrun, N., Alam, M. M., Bhowmik, P. C., Hossain, M. A., Rahman, M. M., et al. (2014). Potential use of halophytes to remediate saline soils. *BioMed Research International*. doi:10.1155/2014/589341.
- Hazelton, P., & Murphy, B. (2007). *Interpreting soil test results. What do all the numbers mean?* Sidney: CSIRO Publishing.
- Hulugalle, N. R., Jaya, R., Luther, G. C., Ferizal, M., Daud, S., Yatiman, et al. (2009). Physical properties of tsunami-affected soils in Aceh, Indonesia: 2½ years after the tsunami. *Catena*. doi:10.1016/j.catena.2009.01.001.
- Jesus, J., Castro, F., Niemelä, A., Borges, M. T., Danko, A. S., et al. (2015). Evaluation of the impact of different soil salinization processes on organic and mineral soils. *Water, Air & Soil Pollution*. doi:10.1007/s11270-015-2373-y.
- Khondaker, N. A., & Ozawa, K. (2007). Papaya plant growth as affected by soil air oxygen deficiency. *Acta Horticulturae*. doi:10.17660/ActaHortic.2007.740.27.
- Kume, T., Umetsu, C., & Palani, K. (2009). Impact of the December 2004 tsunami on soil, groundwater and vegetation in the Nagapattinam district, India. *Journal of Environmental Management*. doi:10.1016/j.jenvman.2009.05.027.
- Lu, S. G., Tang, C., & Rengel, Z. (2004). Combined effects of waterlogging and salinity on electrochemistry, water-soluble cations and water dispersible clay in soils with various salinity levels. *Plant and Soil*. doi:10.1023/B:PLSO.000047748.50435.fc.
- Marler, T. E. (2007). Papaya seed germination and seedling emergence are not influenced by solution pH. *Acta Horticulturae*. doi:10.17660/ActaHortic.2007.740.24.
- Mastronuzzi, G., & Sansó, P. (2004). Large boulder accumulations by extreme waves along the Adriatic coast of southern Apulia (Italy). *Quaternary International*. doi:10.1016/j.quaint.2004.01.016.

- McGrath, J. M., Spargo, J., & Penn, C. J. (2014). Soil fertility and plant nutrition. In N. K. Van Alfen (Ed.), *Encyclopedia of agriculture and food systems* (pp. 166–184). Oxford: Elsevier.
- McLeod, M. K., Slavich, P. G., Irhas, Y., Moore, N., Rachman, A., Ali, N., et al. (2010). Soil salinity in Aceh after the December 2004 Indian Ocean tsunami. *Agriculture Water Management*. doi:10.1016/j.agwat.2009.10.014.
- Montecinos, A., & Aceituno, P. (2003). Seasonality of the ENSO-related rainfall variability in Central Chile and associated circulation anomalies. *Journal of Climate*. doi:10.1175/1520-0442(2003)0162.0.CO;2.
- Moqsd, M. A., & Omine, K. (2013). Bioremediation of agricultural land damaged by tsunami. In R. Chamy & F. Rosenkranz (Eds.), *Biodegradation of hazardous and special products* (pp. 39–50). Rijeka: Intech.
- Morton, R. A., Gelfenbaum, G., Buckley, M. L., & Richmond, B. M. (2011). Geological effects and implications of the 2010 tsunami along the central coast of Chile. *Sedimentary Geology*. doi:10.1016/j.sedgeo.2011.09.004.
- Nayak, A. K., Damodaran, T., Singh, C. S., Jha, S. K., Raja, D., Mishra, V. K., et al. (2010). Post tsunami changes in soil properties of Andaman Islands, India. *Environmental Monitoring and Assessment*. doi:10.1007/s10661-009-1225-x.
- Oster, J. D., & Schroer, F. W. (1979). Infiltration as influenced by irrigation water quality. *Soil Science Society of America Journal*, 43, 444–447.
- Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen–Geiger climate classification. *Hydrology and Earth System Sciences Discussion*. doi:10.5194/hess-11-1633-2007.
- Pizarro, R., Valdés, R., García-Chevesich, P., Vallejos, C., Sangüesa, C., Morales, C., et al. (2012). Latitudinal analysis of rainfall intensity and mean annual precipitation in Chile. *Chilean Journal of Agricultural Research*. doi:10.4067/S0718-58392012000200014.
- Ploethner, D., Dharma, D. B., & Jaskolowski, B. (2008). *Groundwater Quality along the Coast between Bireuen and Sigli in the Province Nanggroe Aceh Darussalam, Northern Sumatra, Indonesia*. Project “Management of Georisks in NAD”, Technical Report C2. Hannover: Federal Institute for Geosciences and Natural Resources (BGR).
- Qadir, M., Oster, J. D., Schubert, S., Noble, A. D., & Sahrawat, K. L. (2007). Phytoremediation of sodic and saline-sodic soils. *Advances in Agronomy*. doi:10.1016/S0065-2113(07)96006-X.
- Quezada, J., Jaque, E., Fernández, A., & Vázquez, D. (2012). Relief changes generated by the 2010 Mw = 8.8 February 27th earthquake in south-central Chile. *Revista Geográfica Norte Grande*. doi:10.4067/S0718-34022012000300003.
- Quezada, C., Sandoval, M., Stolpe, N., & Olmos, D. (2016). Use of organic and chemical amendments for the remediation of soils flooded by the 2010 tsunami in the area of Tomé, Chile. *Chilean Journal of Agricultural & Animal Sciences*, 32(Special issue 1), 13–22.
- Raja, R., Chaudhuri, S., Ravisankar, N., Swarnam, T., Jayakumar, V., & Srivastava, R. (2009). Salinity status of tsunami-affected soil and water resources of South Andaman, India. *Current Science*, 96(1), 152–156.
- Ritter, J. A. (2010). *Water quality: Principles and practices of water supply operations* (4th ed.). Denver: American Water Work Association.
- Rosborg, I., & Kozisek, F. (2015). Drinking Water Regulations Today and a View for the Future. In I. Rosborg (Ed), *Drinking Water Minerals and Mineral Balance*. (pp. 129–136). Switzerland: Springer International Publishing.
- Roy, K., Sasada, K., & Kohno, E. (2014). Salinity status of the 2011 Tohoku-oki tsunami affected agricultural lands in north-east Japan. *International Soil and Water Conservation Research*. doi:10.1016/S2095-6339(15)30005-8.
- Sadzawka, A. (2006). *Methods of analyses for irrigation waters*. Institute of Agricultural Research of Chile [In Spanish]. <http://www2.inia.cl/medios/biblioteca/serieactas/NR33999.pdf>. Accessed 5 July 2016.
- Sadzawka, A., Carrasco, M., Grez, R., Mora, M., Flores, H., & Neaman, A. (2006). *Methods of analysis recommended for soils of Chile*. Institute of Agricultural Research of Chile [In Spanish]. <http://www.inia.cl/medios/biblioteca/serieactas/NR33998.pdf>. Accessed 5 July 2016.
- Sandoval, M., Dörner, J., Seguel, O., Cuevas, J., & Rivera, D. (2012). *Methods of soil physical analyses. Chillán [In Spanish]*. Chillán: Universidad de Concepción.
- Sandoval, M., Celis, J., Pedreros, L., & Capulín, J. (2013). Chemical remediation of an agricultural soil: a case study of the tsunami-affected area of Chile. *Water, Air & Soil Pollution*. doi:10.1007/s11270-013-1590-5.
- Swamy, Y. V., Roy Chaudhury, G., Das, S. N., Sengupta, S., & Muduli, R. (2006). Assessment of water quality in tsunami affected Andhra coast. *Current Science*, 91(10), 1409–1412.
- Szczuciński, W., Niedzielski, P., Kozak, L., Frankowski, M., Ziola, A., & Lorenc, S. (2007). Effects of rainy season on mobilization of contaminants from tsunami deposits left in a coastal zone of Thailand by the 26 December 2004 tsunami. *Environmental Geology*, 53, 253–264.
- Thomas, G. W. (2006). pH. In Lal, R. (Ed), *Encyclopedia of soil science* (pp. 1270–1274). New York: Taylor & Francis.
- USEPA. (1993). *Determination of turbidity by nephelometry. EPA method 180.1. Environmental Monitoring Systems Laboratory. Office of Research and Development*. Ohio: United States Environmental Protection Agency.
- USEPA. (1999). *Use of monitored natural attenuation at Superfund, RCRA corrective action, and underground storage tank sites. Directive 9200.4-17P*. Washington D.C: United States Environmental Protection Agency- Office of Solid Waste and Emergency Response.
- Van Droogenbroeck, B., Kyndt, T., Maertens, I., Romeijn-Peters, E., Scheldeman, X., Romero-Motochi, J. P., et al. (2004). Phylogenetic analysis of the highland papayas (*Vasconcellea*) and allied genera (*Caricaceae*) using PCR-RFLP. *Theoretical and Applied Genetics*. doi:10.1007/s00122-003-1575-7.
- Vargas, G., Fariás, M., Carretier, S., Tassara, A., Baize, S., Melnick, D., et al. (2011). Coastal uplift and tsunami effects associated to the 2010 Mw8.8 Maule earthquake in Central Chile. *Andean Geology*. doi:10.5027/andgeoV38n1-a12.
- Waller, P., & Yitayew, M. (2016). Water and Salinity Stress. In: Waller, P., & Yitayew, M. (Eds), *Irrigation and Drainage Engineering* (pp. 51–65). Switzerland: Springer International Publishing.
- Wright, C., & Mella, A. (1963). Modifications to the soil pattern of South-central Chile resulting from seismic and associated

- phenomena during the period May to August 1960. *Bulletin of the Seismological Society of America*, 53(6), 1367–1402.
- Wu, L., & Dodge, L. (2005). *Landscape plant salt tolerance selection guide for recycled water irrigation* (Special Report). Department of Plant Sciences Davis: University of California.
- Yoshii, T., Imasura, M., Matsuyama, M., Koshimura, S., Matsuoka, M., Mas, E., et al. (2013). Salinity in soils and tsunami deposits in areas affected by the 2010 Chile and 2011 Japan tsunamis. *Pure and Applied Geophysics*. doi:[10.1007/s00024-012-0530-4](https://doi.org/10.1007/s00024-012-0530-4).