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Comparative effects of drying and disturbance on the hydraulic parameters of a recent lapilli deposit overlying fine andosols: case of the Hudson Volcano, Chilean Patagonia

Efecto comparativo del secado y perturbaciones en los parámetros hidráulicos de un lapilli reciente que cubre andosols fino: caso del Volcán Hudson, Patagonia Chilena

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ABSTRACT

Explosive volcanic eruptions have significant long lasting effects on the landscape due to the deposition of tephra and subsequent formation of andosols. Usually, tephra has high water retention capacity, high permeability, as well as low bulk density when compared to other soil types, and these properties may be irreversibly affected by natural or human disturbance.

Together with the high spatial and temporal heterogeneity from successive eruptions, these factors taken in concert can be significant in terms of hydrological change, and risk scenarios for soil stability/erosion. However, accurate hydraulic parameters for tephra, considering the broad range of grain sizes and the effects of disturbance, are scarce. Bulk density (ρ_t), porosity (η), volumetric water content at field capacity (Θ_{fc}) and saturated hydraulic conductivity (Ks) were measured for minimally disturbed cores for two contrasting soils in the plume of the Hudson Volcano in southern Chile (46º S): a recent, coarse tephra, and an old, fine andosol.

Cores were then physically reworked, subjected to two successive treatments of drying at 45º and 105º C, and the parameters were re-measured for each case. Coarse tephra and fine andosol bulk density (0.78 ± 0.03 and 0.53 ± 0.04 g cm^{-3}, respectively) were least affected by the manipulation, with a 17% decrease for the fine material following only the 45º C treatment. The respective porosities (60 ± 1.1%; 75 ± 1.2 %) and moistures at field capacity (32 ± 0.8%; 60 ± 1 %) for the coarse and fine materials decreased progressively with each treatment, with 2x stronger effect on the coarse (-32% porosity, -34% field capacity) as compared to the fine soil (-19% and -17%, respectively). Ks (coarse: 20.6 ± 14.8 cm h^{-1}; fine: 3.8 ± 4.4 cm h^{-1}) was substantially affected by disturbance (overall increase by 1.5x and 3.1x, respectively) for the 45º C treatment.

Our results are the as yet southern-most characterization for these volcanic soil parameters. In addition, we provide evidence of natural reworking of both coarse and fine horizons at the field site, together with laboratory-demonstrated effects of disturbance on properties of volcanic soils of widely ranging clast sizes and age.

We emphasize the need for a more comprehensive understanding of the hydraulic parameters of tephra, their sensitivity to alteration following disturbance, and the corresponding implications for engineering applications and catchment hydrology.

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CHAPTER 1 INTRODUCTION

1.1 Motivation

Hundreds of explosive volcanic eruptions occur every decade (Simkin *et al*., 1981; Newhall and Self, 1982; Simkin and Siebert, 2000). These eruptions have left deposits of tephra worldwide (Machida, 2002), and derived volcanic ash soils on all continents but Antarctica (Takahashi and Shoji, 2002). Even though volcanic ash soils occupy only 0.7 to 0.8% of the world's land surface (Leamy, 1984; Soil Survey Staff, 1999), they occur in regions with high population densities (e.g., Loughlin *et al.*, 2015), and can make up a large proportion of a country (18% of Japan, Takahashi and Shoji, 2002; 13% of New Zealand, Lowe, 2010) and/or of its arable land (50 to 60% in Chile, Dörner *et al*., 2009). Volcanic eruptions also cause a series of hazards and risks, both during and after events (Loughlin *et al*., 2015; Papale, 2015).

The tephra fall that follows an explosive volcanic eruption can cause profound changes in the landscape; recent reviews by Arnalds (2013) and Pierson and Major (2014) cover the ecological and hydrogeomorphic effects of such events, respectively. The deposition of layers of pyroclastic materials affects the hydrological response, both at the hillslope and catchment scale, as the presence of a new stratum modifies the original mechanisms of runoff generation. A typical eruption depositing a large plume of finer ash may be followed by a decrease in permeability and, depending on the depth of deposition and slope, an increased frequency and magnitude of Hortonian overland flow events (Miyabuchi *et al*., 1999; Major and Yamakoshi, 2005). This in turn may lead to large increases in erosion rates (Fiksdal, 1981; Leavesley *et al*., 1989; Ogawa *et al*., 2007; Pierson and Major, 2014). In the case of explosive eruptions that deposit lapilli (Shimizu and Ono, 2015), the new overlying parent material with higher permeability than the underlying paleosols (Rettallack, 2008), often tens to hundreds of kilometers from their source, can result in a shift toward subsurface flow paths over significant areas.

Knowledge about the hydraulic properties of the deposited pyroclastic material is needed to understand the potential changes in hydrological behavior of catchments affected by tephra fall. Characterizing these soils is also important when assessing the potential for hazardous masswasting events (e.g., Basile *et al*., 2003; Frattini *et al*., 2004; Shimizu and Ono, 2016), as well as for understanding soil-water-plant interactions (Hillel, 1998) and establishment or recovery of vegetation (Tsuyuzaki *et al*., 1997).

It is well known that soils derived from volcanic materials have distinct mechanical and classification properties (Forsythe *et al*., 1969; Maeda *et al*., 1983; Wada and Kakuto, 1985; Warkentin, 1985; Nanzyo, 2002; Bommer *et al*., 2002; Verdugo, 2008; Wesley, 2010, pp. 189-222) that are irreversibly affected when the soil is reworked (Jacquet, 1990; Wesley, 2010, p. 193) or dried (e.g.: Schalscha *et al*., 1965; Kubota, 1972; Maeda *et al*., 1977; Singleton *et al*., 1999; Bartoli *et al*., 2007; Verdugo, 2008; Wesley, 2010, p. 194). Because of such effects, many researchers have questioned the common laboratory methods when dealing with such soils (Maeda *et al*., 1977; Fontes *et al*., 2004; Bartoli and Burtin, 2007; Bartoli *et al*., 2007), or explicitly recommend using only field-moist samples when describing their properties (Schalscha *et al*., 1965; Warkentin, 1985; Singleton *et al*., 1999; Verdugo, 2008; Wesley, 2010, p. 194).

The effects of drying and reworking on the hydraulic properties of volcanic soils have been somewhat less investigated. Maeda *et al*. (1977, pp. 247-250), Maeda *et al*. (1983), Karube and Abe (1998), Basile and De Mascellis (1999), Fernandez *et al*. (2004), Basile and Coppola (2004) and Bartoli *et al*. (2007), all found that water retention decreases after air or oven-drying, over a broad range of matric potential. On the other hand, drying results in a marked increase in saturated hydraulic conductivity (Maeda *et al*., 1977, pp. 250-252; Basile and De Mascellis, 1999; Bartoli *et al*., 2007), and unsaturated conductivity curve values (Basile and Coppola, 2004; Fontes *et al*., 2004).

These effects are due to the fact that soils weathered from volcanic ash often contain allophane, imogolite, and other clay-size mineraloids that suffer irreversible micro-aggregation under drying (Kubota, 1972; Karube and Abe, 1998; Basile and De Mascellis, 1999; Nanzyo, 2002). As a result, dried volcanic soil may be considered to be a different material altogether (Maeda *et al*., 1977). These findings are relevant not only from a methodological perspective (i.e., accurate parameter estimation), but also have implications for assessment of hazards and hydrological change, following a change in land use (Dörner *et al*., 2009) or disturbance such as wildfire (Ebel and Moody, 2013, 2017).

In this broader context, and considering the wide range of total potential grain sizes that may be commonly encountered in the field (e.g., overlapping ash plumes at the landscape scale, Vandekerkhove *et al*., 2015), clearly there has been insufficient characterization of hydraulic parameters for tephras and andosols, especially with respect to their sensitivity to alteration.

As part of a study on the effects of tephra fall on regional hydrological response following the 1991 explosive eruption of the Hudson Volcano in Chilean Patagonia, we estimated hydrologic parameters (bulk density, porosity, field capacity and saturated hydraulic conductivity) under conditions of minimal disturbance for two different soil layers that are widely found over a broad swath of land (thousands of km^2): recently deposited coarse material (lapilli, entisol) and the underlying fine textured paleo-andosol (hereafter referred to as coarse and fine horizons). We also evaluated the effects of disturbance from air-drying and physical reworking on these parameters, following laboratory reworking and successive drying at 45º C and 105º C.

1.2 Hypothesis

(i) The hydraulic properties of the new tephra differ from the preexisting soil.

(ii) The remolding and high temperature drying affect the hydraulic properties in tephra.

1.3 Objectives

1.3.1 General objective

Characterize *in-situ* thicknesses, and hydraulic properties in laboratory, of the old soil and the new tephra, in basins affected by the eruption of 1991 of the volcano Hudson.

1.3.2 Specific objectives

- Characterize the distribution of the predominant soil horizons in a basin affected by the deposition produced by the Hudson volcano in 1991

- Quantify the porosity, bulk density, moisture at field capacity and saturated hydraulic conductivity, of five undisturbed replicates , both the new tephra stratum and for the preexisting old soil

- Quantify the changes in the physical and hydrological properties of both soils, by remolding and drying at 45°C ("Air-Dried") the replicates, and then drying the samples at 105°C ("Oven-Dried). Compare the effects of different treatments

1.4 Methodology

Digging pits to the bedrock, on an irregular sampling mesh, characterized the soil strata in a headwater basin affected by tephra deposition. The basin does not present anthropogenic disturbance and has a homogeneous vegetation cover, smooth slope changes and permanent riverbed. Then the two characteristic strata were identified in the area: one deposited by the eruption of 1991 and the underlying, of weathered ancient tefra, taking five unaltered samples of each one.

These were subjected to laboratory tests to characterize their porosity, moisture at field capacity, saturated hydraulic conductivity, and bulk density, properties that govern the hydrological behavior of the soil. In addition, the samples were remolded, and then dried at 105 ° C, repeating the tests in each case, to quantify the effects of such disturbances. The effect of the treatments on bulk density, porosity and field capacity was tested by repeated measures ANOVA followed by Tukey's post hoc tests. For Ks the *H* statistic was calculated using non-parametric Kruskal-Wallis ANOVA.

1.5 Structure of the thesis

The following section presents the methods used in the field and laboratory to characterize watersheds and their soils, as well as the statistical methods used to evaluate the results obtained. Chapter three gives the results of the spatial distribution and the granulometry of the strata, and then the hydrological properties of the soils and how they respond to disturbances.

Finally in chapter four we present the discussion and the conclusions arisen from the analysis of the results and the literature studied.

CHAPTER 2 METHODS

2.1 Study site

Unknown prior to 1971, The Hudson Volcano has been identified as one of the most active volcanoes globally during the Holocene, with over 32 recent eruptive events documented via tephrochronology (Weller *et al*., 2014). This activity underscores the complex vertical heterogeneity of soils in the region (Vandekerkhove *et al*., 2015) and suggests corresponding effects on hydrologic parameters of soils and parent material derived from the volcano.

The 1991 eruption deposited somewhere between 4 and 11 km3 of pyroclastic material in a SE oriented plume, over an area estimated at 100,000 km2 in Chile and Argentina (Naranjo, 1991; Besoain *et al*., 1995; Naranjo and Stern, 1998). As much as 1 to 2 meters of coarse grained lapilli (5-15 mm) accumulated in Chile, with finer material (0.1-5 mm) falling out over much of Argentina as far as the Atlantic coast (Scasso *et al*., 1994). Physical, chemical and mineralogical characterization of the plume has been conducted, but only sparsely on the Chilean side (Besoain *et al*., 1995; Hepp and Stolpe, 2014). To date, there are no known hydrologic parameter estimates for this or any other tephra formation south of the Los Lagos Region (39 S – Dörner *et al*., 2015), despite their widespread significance in soil formation and their status as a dominant soil order in southern Chile.

Our study site is small, zero-order watershed of 5900 m2 within the Estero el Alto (el Alto Creek) basin, a tributary of the Ibañez River in Chilean Patagonia. The site is on a gentle hillslope (average 21°) at an elevation 1020 masl (46° 15’ 26” S, 72° 23’ 43” W). The climate is cool temperate, with 1500 mm annual precipitation and moderate seasonality. The site is 58 km SE of the Hudson Volcano, and is directly on the longitudinal axis of the second and more explosive eruption of the winter of 1991 (Scasso *et al*., 1994; Wilson *et al*., 2011). Soils in this plume are a coarse, gray, ashy pumice (5-10 mm) overlying older, finer Andosols (Andic Oxyaquic Dystrudepts - Stolpe *et al*., 2014; Images available in Flores, 2016)

The descriptions in the available literature for southern Chile all suggest that the older, thicker ash deposit originated from previous late-Glacial and Holocene eruptions of Hudson, most significantly from a major eruption approximately 3500 years BP (Stern, 1991; Haberle and Lumley, 1998; Bertrand and Fagel, 2008; Bertín and Amigo, 2013; Gardeweg and Sellés, 2013; Fontijn *et al*., 2014; Stern *et al*., 2015; Stern *et al*., 2016). Average distance to bedrock is 145 cm (range: 53 to 251 cm). Vegetation is characterized by mature, monospecific forests (100 - 200+ year old) of southern beech (*Nothofagus pumilio*) (Flores, 2016). Forest stands here, and elsewhere in the recent plume, appear to have been minimally impacted by the rain of pyroclastic material.

2.2 Field Methods

Nineteen soil pits were excavated to the bedrock with a 4” diameter bucket auger, recording depth of horizons and slope. Subsamples (100 cm^3) from three representative profiles were taken approximately every 25 cm for grain size analysis (30 total samples)

Undisturbed profiles for hydrologic parameter estimation were cored taken from a gentle slope (< 5°) just outside the watershed boundary. Five replicate cores of 29.5 ± 2.5 cm length were taken from both the overlying pyroclastic material or lapilli (hereinafter referred to as “recent”) and the underlying fine-textured Andosol (“paleosol”), removing any overlying organic horizons. Open spaces on top of the cores were filled with pre-cut pieces of expanded polystyrene foam, and the cores were then wrapped in film and duct tape, carefully packaged and transported to the laboratory. (Process images available in Flores, 2016)

2.3 Laboratory Procedures

Samples from the soil pits analyzed for grain size distribution were oven dried at 105°C until constant weight, dry sieved on a mechanical sieve shaker (2, 1, 0.5, 0.25, 0.125, 0.064 µm fractions), and the fractions were weighed (±1 g). Core samples processed for bulk density (ρ_t), porosity (η), field capacity (Θ_{fc}) and saturated hydraulic conductivity (Ks) for both recent and paleosol horizons (10 total cores). Cores were subject to three sequential treatments: (1)

undisturbed samples at natural moisture content; (2) air-dried (45°C) remolded samples, followed by (3) oven-dried (105°C) remolded samples.

Treatment 1 temperature was considered a reasonable approximation of maximum air temperature for hot summer days at the respective latitude (30 - 40º range for much of the southern cone according to NASA Global Observatory land surface temperatures; https://earthobservatory.nasa.gov). Treatment 2 was determined by standard methods (e.g. ASTM 2010, 2015, 2016), but may also delimit maximum surface temperature for exposed soils (Garratt, 1992).

On arrival to the laboratory, the undisturbed cores were weighed and core length was measured to the nearest millimeter. A fine nylon mesh was glued to the bottom of the tubes to avoid loss of material during the subsequent analyses. The bottoms were capped, and water was added to the upper surface of the samples slowly and carefully over a three-day period until saturation. The saturated samples were then uncapped at the bottom and left to drain, and were weighed over 30 minute intervals until reaching constant weight (which happened after 6 to 7 hours for recent horizons, and about 24 hours for paleosols). The samples were re-wetted to saturation and placed in a modified constant-head upward flow permeameter for estimating hydraulic conductivity (Carter, 1993): the head loss Δh was maintained at a constant value of 11.3 ± 0.2 cm, with the five cores of each treatment evaluated simultaneously. Each core was tested between 3 and 5 times depending on variability of replicates, and we report the average of all conductivity tests.

Following the testing of the undisturbed samples, the cores were dismantled in ordered 3-cm layers, in order to maintain any possible trends with depth when reconstituting them. The layers were dried in aluminum trays in a convection oven at 45°C, until reaching constant weight. The respective cores were then reassembled, carefully remolded taking care not to break aggregates of the fine horizon or fragment the coarse particles, and maintaining the original order of the layers. Core dimensions were recorded before repeating the measurements of field capacity and saturated hydraulic conductivity, as described above. Finally, the cores were again disassembled in ordered 3-cm layers, dried at 105°C for 24 hours, reassembled, and field capacity and hydraulic conductivity measurements were repeated. (Process images available in Flores, 2016)

2.4 Calculations and Statistical Analysis

Core volume at saturation together with water volume estimated from the change in mass of the core (saturated mass minus final dry mass at 105 ºC,) were used to calculate porosity. Final dry mass together with core dimensions for each treatment were used to calculate bulk density (Carter *et al*., 1993). Water content at field capacity was calculated as the difference in mass between drained and final dry mass; values for field capacity are reported as a percentage of total water content at saturation (Vanapalli *et al*., 1998).

Saturated hydraulic conductivity (Ks) values were computed assuming Darcian flow (Carter *et al*., 1993). Because the samples were remolded and repacked for the air-dried and oven-dried treatments, there should occur expected changes in Ks due to changing porosity, unrelated to the drying. To account for such effects we compared the Ks values obtained for these two treatments against the expected values for Ks that might result solely from changes in the samples porosity, based on the Kozeny-Carman equation (Eq. 2.1; Carman, 1937), as follows:

$$Ks' = C * {d_{10}}^2 * \left(\frac{\eta 3}{(1-\eta)^2}\right) \tag{2.1}$$

where C is the Kozeny-Carman constant (C), η is the porosity, and d10 is the characteristic diameter of the sediments (90% of the material by weight - considered uniform with each of the two soil types). C was initially computed for each sample, solving Eq. 2.1 with Ks and porosity for the unaltered core (treatment 1). For treatments 2 and 3, the constant C was applied to Eq. 2.1, thereby adjusting Ks' for the measured changes in porosity specific to each treatment. We then compared measured Ks values for the different treatments vs. the expected Ks' values, for each one of the treatments, thus isolating the changes due to drying. Theoretical Ks' vs. observed Ks were compared based on general comparison tracking with successive treatments.

The effect of the treatments on bulk density, porosity and field capacity was tested by repeated measures ANOVA followed by Tukey's post hoc tests. For Ks the H statistic was calculated using non-parametric Kruskal-Wallis ANOVA..

CHAPTER 3 RESULTS

3.1 Spatial distribution and granulometry

Median thickness of the recent 1991 horizon was 39 cm (range 32-59 cm), while the paleosol median thickness was 124 cm (range 118-161 cm). Figure 3.1 shows core sites (n=20) and basin morphology for the model watershed (left); also relationship between soil depth and slope for recent coarse grained lapilli (1991 eruption) and underlying finer volcanic paleosol (right) where dashed lines show approximate range of hill-slope effects on depth of both horizons The thicknesses for both horizons were consistent across soil pits for shallow hillslopes (Fig. 3.1), but significant departures from median values were observed for slopes greater than 23 - 27°. At this threshold the recent horizon was significantly deeper, while the paleo horizons were significantly shallower.

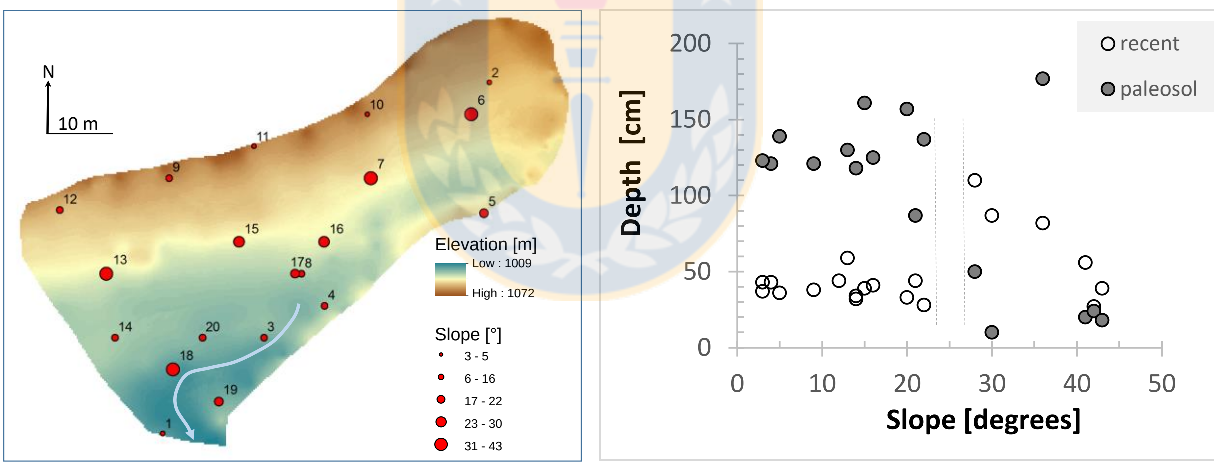

Figure 3.1 Core sites and basin morphology (a); Relationship between soil depth and slope (b).

Figure 3.2 present the granulometry for andosol (red) versus recent (gray) lapilli in the general vicinity of the cores. Solid lines show respective median values, % finer than sequence, for various sampling stations and representative depths (paleosol: n=5 sites, 19 total samples, and recent: n= 6 sites and 11 total respectively). Shaded area represents 1st to 3rd quartiles, dashed lines maximum and minimum values.

The recent and paleo horizons showed very clear separation for average grain size (Fig. 3.2), with d50 of 1 mm and 0.3 mm, respectively, maintaining strong separation (±1 s.d.) for all grain sizes over 0.08 mm. The recent horizon also had a much narrower distribution in variance across all samples compared to the paleo horizons. One paleo deposit of coarse sand dimensions (1-2 mm, approx. 5 cm deposit at 90 cm depth) contributed to overlap of the full range in grain size distributions between paleo-andosols and recent lapilli horizons

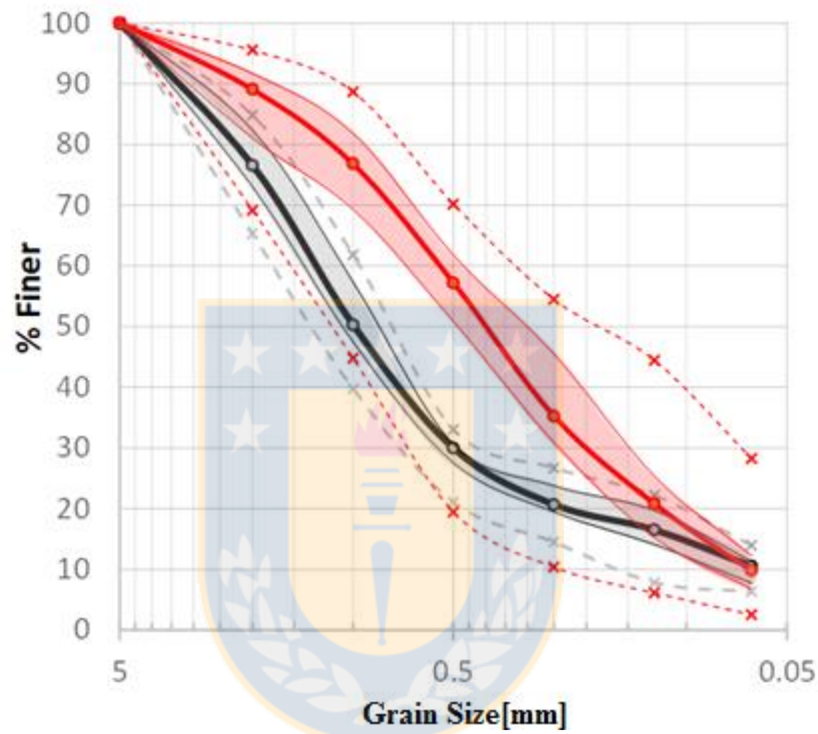

Figure 3.2 Granulometry for andosol (red) and recent (gray) lapilli in the vicinity of the cores.

3.2 Soil Hydrologic Parameter Estimation

Table 3.1 compares the effect of sample processing on the estimation of dry bulk density (ρ_t), porosity (η), field capacity (Θ_{fc}) and saturated hydraulic conductivity (Ks) for old and new tephra layers. Also shown are mean values (+/- s.d.); F statistic from ANOVA followed by Tukey's post hoc tests (bulk density, porosity and field capacity) and H statistic for non-parametric Kruskal-Wallis ANOVA for Ks. Significance levels are indicated by * p< .05, ** p< .01 and n.s. = not significant (p> .05).

Coarse and fine tephra bulk density (0.78 ±0.03 and 0.53 ±0.04 g cm-3, respectively, Table 3.1) were least affected by the manipulation, with a 17% decrease for fine material following only the

45º C treatment. Coarse and fine porosity (60 ±1.1%; 75 ±1.2%) and field capacity (32 ±0.8%; 60 ±1%) decreased progressively with each treatment, with 2x stronger effect on coarse material (-32% porosity, -34% field capacity) compared to fine (-19% and -17%, respectively). Ks (coarse 20.6 ±14.8 cm h-1; fine 3.8 ±4.4 cm h-1) was substantially affected by experimental manipulation, with an overall increase by 1.5x and 3.1x for recent coarse and fine paleo horizons respectively (considering only the 45º C treatment as significant, owing to high variance from the 105º C treatment, Table 3.1).

Shrinkage occurred following both experimental treatments compared to intact cores, contributing directly to some of the changes in parameters above. For the 45° C treatment, core volume decreased by 7.2% and 13.6% for recent and paleo soils. Treatment 3 at 105° C produced an additional shrinkage of 1.8% and 8.1% for recent and paleo soils, respectively.

Tabla 3.1 Comparison of the effect of sample processing on the estimation of soil parameters

Parameter	**Hor.**	**Undisturbed** (1)	**Air-Dried** (2)	**Oven-Dried** (3)	$F_{2,12}$	p_{12}	p_{13}	p_{23}
ρ_t [g cm^{-3}]	New	0.78 (0.03)	0.81 (0.022)	0.83 (0.031)	2.93	n.s	n.s	n.s.
	Old	0.53 (0.04)	0.62 (0.036)	0.67 (0.033)	100.8	**	**	n.s.
η [%]	New	60 (1.1)	52 (2.4)	41 (2)	147.5	**	**	**
	Old	75 (1.2)	71 (0.8)	61 (2)	19.91	**	**	**
Θ_{fc} [%]	New	32 (0.8)	30 (0.4)	21 (1.6)	170.9	*	**	**
	Old	60 (1)	57 (1.4)	50 (1)	84.55	**	**	**
					H_2			
Ks [cm h^{-1}]	New	20.6 (14.8)	50.7 (28.3)	319.5 (360.6)	6.54	*	*	n.s.
	Old	3.8 (4.4)	15.6 (15.3)	21.6 (11.7)	7.46	*	*	n.s.

Changes effected to Ks were much greater than, and of opposing trajectory to, those expected simply from a change in porosity. Expected change in Ks following Eq. 2.1 should show a gradual decreasing trend together with the decreases in porosity observed with the subsequent treatments. Instead, average Ks increased by a factor of 4.5x and 70x for recent coarse material, while paleosol Ks increased by 7x and 20x (considering the full range of treatments 2 and 3, respectively).

CHAPTER 4 DISCUSSION AND CONCLUSIONS

4.1 Comparison with other studies

In general, comparable parameter estimates in the scientific literature for andosols, and more generally for tephra, are infrequent (Table 4.1), corresponding with a limited global distribution of the soil type (Driessen *et al*., 2001) and belated recognition at international levels (Takahashi and Shoji, 2002). The paucity of information from the Southern Hemisphere temperate zone is also evident (with exception of Dörner *et al*., 2015; Lowe *et al*., 2010, and this study). The regional particularity of soils of volcanic origin, product of local climate, endemic vegetation, local geography and volcanic activity that drive time of exposure to the weathering (Ugolini and Dahlgren, 2002) has led to the countries such as Japan or New Zealand developing independent systems of classification of volcanic soils (Takahashi and Shoji, 2002). Lizcano and Santamarina (2006) highlight the high variability of the particle size distribution in volcanic soils. Nevertheless, both the recent coarse and paleo fine horizons studied here fall within the range of clast sizes encountered in the literature (Table 4.1). The recent lapilli horizon in our study, representing young material with very limited effects of weathering or pedogenesis, is noteworthy as a less common example (e.g., Alvarado and Forsythe, 2005).

Table 4.1 summarizes previous estimates for the parameters selected for volcanic soils: dry bulk density (ρ_t), porosity (η), field capacity (Θ_{fc}) and saturated hydraulic conductivity (K_{sat}), with comments on respective methodology. Methods include: [1] known volume of unaltered soils, drying at ambient air temperature; [2] known volume, unaltered soils,drying at 105°; [3] drying at 105 C; [4] saturation of unaltered soils, known volume; [5] neutron probe and the hydraulic head with mercury tensiometers, [6]suction table with sand or kaolin [7] gravity drainage via mesh in original sampling container, Unaltered soils; [8] Volumetric water content through suction matric potential [9] lab permeameter upflow, unaltered soils; [10]crust, hot air and two-step methods;[11]Mualem-van Genuchten models; [12] Falling head permeameter; [13] Guelph constant permeameter; [14] disk infiltrometer and [15] water permeameter, Eijkelkamp, model 09.02.02.25, undisturbed soil.

Bulk density, which for andosols is generally low in comparison with others soil orders (Driessen *et al*., 2001), was on the low end of the reported range for both recent coarse lapilli (e.g., as compared to Tejedor *et al*., 2011) and for the finer andosols (Table 4.1). In the case of the recent material, bulk density would be expected to be influenced by inaccessible pore space within larger pumice particles. Consequently, with weathering, bulk density would be expected to increase over time (assuming no further disturbance, discussed below). For the finer paleosols, reductions in bulk density may also occur over time with increasing contribution of allophane (Dörner *et al*., 2009) and organic matter content (Maeda, 1983). Total carbon has been estimated at 7 and 10 g/kg for the recent and paleo horizons, respectively (Hepp *et al*., 2015), which is skewed toward the low end of organic matter effect on bulk density (Nanzyo, 2002). Colder climate, higher elevation, higher precipitation, and lower pH (4.7 to 6.7, Hepp *et al*., 2015) are all characteristics of this site that may favor competing formation of amorphous silica, which in turn was notably higher for samples from within the watershed boundary, based on the regional study of the 1991 Hudson plume by Hepp (2015). Other unidentified factors are more likely responsible for the low bulk density values observed here.

Porosity of the recent material marked the lowest range reported for tephra or andosols (Table 4.1), consistent with the concept of inaccessible pore space mentioned above. The porosity of the finer paleosols was within the high end of the range reported by Fontes *et al*. (2004), although grain size was not mentioned. Note that fewer studies reported this parameter, and most of those that do were based on coarser grain sizes. Field capacity for recent coarse and fine paleo horizons were in line with those reported for similar soils with comparable particle size distributions (e.g. Fiorillo and Wilson, 2004). Note that the treatment of this parameter in the literature is even more limited, possibly due to methodological problems or lack of universal acceptance (Veihmeyer and Hendrickson, 1931; Assouline and Or, 2014).

Results for Ks of recent coarse material were comparable to those reported by Shimizu and Ono (2015), although their study employed a disk infiltrometer in-situ. The finer paleo horizon was well within the range previously reported from Chile (Dörner *et al*., 2015).

4.2 Drying and reworking effects and potential mechanisms

.

The effects of our treatments on reducing bulk density and porosity of the fine andosol horizon are consistent with previous studies on the effects of drying on aggregate properties of these soils (Kubota, 1972; Maeda *et al*., 1977; Basile and De Mascellis, 1999; Bartoli *et al*., 2007). These studies suggest that wet/dry cycles, rather than our drying combined with physical reworking, offer sufficient explanation. Dörner *et al*., (2009) showed evidence that the reduction in porosity upon drying was a combined effect of decrease in fine pores and increase in larger pores. Moreover, the effects appear to be related to the cumulative intensity of exposure to drying, both in the field (Dörner *et al*., 2009), and under laboratory conditions (this study). Our study also demonstrated similar effects on the porosity of recent coarse material, where allophane content is assumed to be negligible. Other mechanisms are therefore likely at play, possibly mediated via fragmentation of the larger pumice, which would affect bulk density and porosity by way of more efficient packing and a reduction in the inaccessible pore space. Further investigations on the effects of mechanical fragmentation and potential exposure of previously inaccessible pore space, especially if combined with treatments on a range of uniform clast sizes, might help elucidate the mechanisms.

The effects of the treatments on field capacity were likely mediated by related mechanisms: reduction of fine pores mentioned earlier (Dörner *et al*., 2009) in addition to temperature driven micro-aggregation of amorphous fine particles. The latter may reduce the specific surface area for attractive forces that retain water (Basile and De Mascellis, 1999; Nanzyo, 2002). Driessen *et al*., (2001) recognized decreases in both soil volume and water holding properties for volcanic soils exposed to air drying, in addition to ion exchange capacity and cohesion of soil particles. In our study, the reduction in field capacity for both fine and also coarse horizons demonstrates that the effects of disturbance on diminished field capacity may be relevant for a wide range of particle sizes.

The effects of the treatments on Ks for both fine and coarse horizons were opposite in response and proportionally greater compared to other parameters (Ks increase by over 200%, compared to

5-35% decrease for other parameters). Superficially this may seem contradictory, that reduced porosity for example would relate to increased permeability.

Tabla 4.1 Summary of previous estimates of soil parameters for volcaic soils

Parameter	Value	Grain Size mm	Est. Age (yrs)	Method	*Author*
ρ_t [g cm^{-3}]	0.78 (± 0.03)	d_{50} 0.6	25	1	This Study
	0.53 (± 0.04)	d_{50} 0.3	>3000	1	This Study
	1.1 - 1.4	Not noted	< 5	2	Alvarado and Forsythe 2005
	0.3 - 0.7	Not noted	<1000	2	Alvarado and Forsythe 2005
	0.7 - 0.9	Not noted	>1000	2	Alvarado and Forsythe 2005
	0.78	% Sand/Silt/Gravel (52/2/46)	<1000	2	Fiorillo and Wilson 2004
	0.87	% Sand/Silt/Clay (60/25/15)	>1000	2	Fiorillo and Wilson 2004
	0.45 - 0.74	Not noted	>1000	3	Fontes *et al.*, 2004
	0.56 – 0.76	% Sand/Silt/clay(12-22/51-60/22-34)	>1000	2	Dörner *et al.*, 2015
	0.6 – 0.62	% Sand/Silt/clay(50-53/37/10-13)	>1000	2	Dörner *et al.*, 2015
	0.8 – 1.1	d_{50} fine (1-2 mm) to medium (2-4 mm)	>1000	2	Tejedor *et al.*, 2011
η [%]	60 (± 1.1)	d_{50} 0.6	25	4	This Study
	75 (± 1.2)	d_{50} 0.3	>3000	4	This Study
	67	% Sand/Silt/Gravel (52/2/46)	<1000	4	Fiorillo and Wilson 2004
	68	% Sand/Silt/Clay (60/25/15)	>1000	4	Fiorillo and Wilson 2004
	60 – 70	d_{50} fine (1-2 mm) to medium (2-4 mm)	>1000	4	Tejedor *et al.*, 2011
	69,6 – 70,9	% Sand/Silt/Clay (16/63/21)	>1000	4	Alarcón *et al.*, (2010)
	66 – 81	Not noted	>1000	5,6	Fontes *et al.*, 2004
Θ_{fc} [%]	32 (± 0.8)	d_{50} 0.6	25	7	This Study
	60 (± 1)	d_{50} 0.3	>3000	7	This Study
	31 – 35	% Sand/Silt/Gravel (52/2/46)	<1000	8	Fiorillo and Wilson 2004
	62	% Sand/Silt/Clay (60/25/15)	>1000	8	Fiorillo and Wilson 2004
Ks[cm h^{-1}]	20.6 (± 14.8)	d_{50} 0.6	25	9	This Study
	3.8 (± 4.42)	d_{50} 0.3	>3000	9	This Study
	0.62 – 10.3	Not noted	>1000	10,11	Fontes *et al* . 2004
	0.58 – 39.6	Sandy/silty	~1000	12	Shinizu and Ono 2015
	0.014 – 1.66	Silty	~3000	12	Shinizu and Ono 2015
	>36	% Sand/Silt/Gravel (52/2/46)	<1000	13	Fiorillo and Wilson 2004
	0.036 – 0.36	% Sand/Silt/Clay (60/25/15)	>1000	13	Fiorillo and Wilson 2004
	10.8 – 97.2	0.25 – 4 mm	<500	14	Craddock *et al.*, 2012
	46.8 – 100	0.25 – 0.75 mm	>2000	14	Craddock *et al.*, 2012
	0.32-56.2	% Sand/Silt/clay(12-22/51-60/22-34)	>1000	15	Dörner *et al.*, 2015
	3.63-33.87	% Sand/Silt/clay(50-53/37/10-13)	>1000	15	Dörner *et al.*, 2015

The combined effect of increased aggregation, decreased tension with a change in surface area, and perhaps most importantly the reduction in fine pores and increase in large pores (Dörner *et al*., 2009) may contribute to the disproportionate effect on Ks. We note that container effects together with reworking of the soil cores might contribute to higher Ks measurements, and that the design of this study did not permit independent evaluation of disturbance versus drying effects. However, we note here once again that the effects were significant for the extremes of clast sizes used in our study, lending additional evidence for drying effects beyond those that might occur with physical reworking of soil structure.

The effects of the treatments on Ks for both fine and coarse horizons were opposite in response and proportionally greater compared to other parameters (Ks increase by over 200%, compared to 5-35% decrease for other parameters). Superficially this may seem contradictory, that reduced porosity for example would relate to increased permeability. The combined effect of increased aggregation, decreased tension with a change in surface area, and perhaps most importantly the reduction in fine pores and increase in large pores (Dörner *et al*., 2009) may contribute to the disproportionate effect on Ks. We note that container effects together with reworking of the soil cores might contribute to higher Ks measurements, and that the design of this study did not permit independent evaluation of disturbance versus drying effects. However, we note here once again that the effects were significant for the extremes of clast sizes used in our study, lending additional evidence for drying effects beyond those that might occur with physical reworking of soil structure.

Overall, the effects of drying and disturbance on hydrologic parameters of both recent, coarse lapilli and older, finer andosols were significant for both the 45º C and 105º C treatments. This would imply a relatively low threshold for drying impacts to the hydrology of volcanic ash soils, in accordance with what was presented by Lizcano and Santamanira (2002), who present irreversible effects on soils dried between 40°C and 50°C. This also corresponds with observations of Dörner *et al*. (2009), whose field based observations imply lower natural thresholds imparting significant effects on soil hydrologic parameters.

4.3 Conclusions about significance for laboratory and field studies

The effects of drying and disturbance of volcanic ash deposits, both based on field and laboratory evidence, and for both recent, coarse and older, finer or andosols, call into question some internationally accepted standards for soil analysis of hydrologic parameters (e.g., ASTM D4318, D5084), as recommended Lizcano and Santamaria (2006). It is interesting to note that the standard methods according to Chilean norms (NCh 1515) make reference to similar methodological problems related to sample drying of gypsum and organic soils, but without specific mention to volcanic soils, even when FAO (1972) recommends using non-dried samples when characterizing field capacity in Chilean soils. Another exception includes ASTM D2434, which prescribes the measurement of saturated hydraulic conductivity using only air-dried soils. Our results clearly suggest that in Chile, as elsewhere, hydrologic and physical parameters for fine, but also coarse volcanic materials, should be estimated either from intact cores or in-situ where possible. The potential for drying or disturbance effects even at ambient environmental conditions should be taken into consideration what collecting material in the field, such as at exposed sites or areas with land use legacies (implied by observations of Dörner *et al*., 2009) or local slope effects (Fig. 3.1). The errors incurred in soil processing are significant enough to affect calculations of slope stability, geotechnical risk evaluation, or basic qualities of construction materials (Lizcano and Santamarina, 2006).

The effects of drying and disturbance from laboratory handling also provide some insight for analogous effects that may occur under natural field conditions, like natural wet/dry cycles (Ugolini and Dahlgren, 2002; Lizcano and Santamarina, 2006; Dörner *et al*., 2009), land use legacies (Alarcon *et al*., 2010, Dörner *et al*., 2009)., landslides (Frattini *et al*., 2004; Papale, 2015) or from moderate to severe disturbances from fires (Alauzis *et al*., 2004, Stoff *et al*., 2010; Ebel and Moody, 2013, 2017), the latter representing potential changes well beyond the existing range of laboratory studies existing. At the scale of our small study watershed, we observed reduced paleosol thicknesses on slopes greater than 25-30°, but increased depths of recent material on the same soil profile (presuming similar slopes). These patterns of final soil depth may reflect erosion and accumulation, respectively, while offering some indirect insight into the potentially low angle of repose and coefficient of static friction. But more importantly, they indicate that, depending on local geography, a large portion of initial volcanic ash deposits may be naturally reworked by gravity, in addition to wind or water erosion (presuming that wind erosion was minimal in a mature forested site). During the 1991 Hudson eruption, deposition of pyroclastic material occurred over a short period of time, with most material falling within a period of several hours. These deposits may be initially unstable, often with significant redistribution within the first several years, according to local residents. Fig. 3.1 suggests that they were subject to natural reworking within the first 20-30 years, and also that these processes may be still ongoing, inferring from the final depth distributions of older soils at the same locations. It is worth noting that the site is on a forested and protected hill slope. Vast areas above tree line (around 1200 m.a.s.l.) would be expected to be even more exposed to drying and reworking of volcanic deposits. Moreover, the massive land-clearing wildfires of the recent colonial period in the region (1920-1970's; Quintanilla, 2008; Bizama *et al*., 2011) might also have affected vast areas of hillslopes that were formerly more protected from the elements. Hence, if drying and erosion of recent volcanic deposits is a widespread effect of natural and anthropogenic processes, corresponding widespread effects on hydrological parameters might be presumed as well. For example this implied spatial variability in the case of bulk density would have implications for general soil structure, vegetation growth and biological activity (Hazelton and Murphy, 2016). Spatial variability for the remaining parameters would not only affect water availability for plants, but also affect hydrologic balance, infiltration vs. runoff, and flux of nutrients and materials from hillslopes and catchments (Hazelton and Murphy, 2016; Assouline and Or, 2014).

The combination of effects of exposure/drying and reworking, together with the probable widespread occurrence of both natural and human mediated reworking of tephra, may have great consequences for soil hydrology at various spatial scales. The increases in bulk density for air and oven dried paleosols, corresponded with decreases in porosity and field capacity, imply a potential reduction in water storage in hillslopes and catchments susceptible to natural reworking or human impacts. Although bulk density of recent coarse material was only slightly affected (increase by ~ 4%), reduced water storage for this horizon might also be significant at these larger scales if one considers the stronger effects on porosity and field capacity. All other things held constant, these changes alone might in turn reduce the amount of precipitation required to generate runoff, with more rapid saturation of soils. However, Ks for both horizons was also affected but with opposite implications, increasing the permeability of tephra upon drying. This presents a more complex scenario in terms of understanding or modeling the hydrologic impacts of alteration of tephra soils or parent material. Increased permeability might counter the effects of reduced porosity, if subsoil drainage rates are sufficient compared to inputs from precipitation. If this is not the case, the implication is for more rapid saturation response to precipitation inputs. As mentioned above, the effects upon Ks (increase by 50 to 200%) outweigh the effects on other parameters (decrease by 5-30%). Clearly, the relative importance of the effects on different hydrologic parameters could be more widely variable than reported here, based just on grain size variability across overlapping plumes (e.g. Vandekerkhove *et al*., 2015), and also since infiltration events are subject to variable antecedent conditions and variability in the overall geology, geomorphology, and soil profile.

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