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A field, laboratory, and literature review evaluation of the water retention curve of volcanic ash soils: How well do standard laboratory methods reflect field conditions?

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Abstract

Accurate determination of the water retention curve (WRC) of a soil is essential for the understanding and modelling of the subsurface hydrological, ecological, and biogeochemical processes. Volcanic ash soils with andic properties (Andosols) are recognized as important providers of ecological and hydrological services in mountainous regions worldwide due to their large fraction of small size particles (clay, silt, and organic matter) that gives them an outstanding water holding capacity. Previous comparative analyses of in situ (field) and standard laboratory methods for the determination of the WRC of Andosols showed contrasting results. Based on an extensive analysis of laboratory, experimental, and field measured WRCs of Andosols in combination with data extracted from the published literature we show that standard laboratory methods using small soil sample volumes (≤300 cm^3) mimic the WRC of these soils only partially. The results obtained by the latter resemble only a small portion of the wet range of the Andosols' WRC (from saturation up to −5 kPa, or pF 1.7), but overestimate substantially their water content for higher matric potentials. This discrepancy occurs irrespective of site-specific land use and cover, soil properties, and applied method. The disagreement limits our capacity to infer correctly subsurface hydrological behaviour, as illustrated through the analysis of long-term soil moisture and matric potential data from an experimental site in the tropical Andes. These findings imply that results reported in past research should be used with caution and that future research should focus on determining laboratory methods that allow obtaining a correct characterization of the WRC of Andosols. For the latter, a set of recommendations and future directions to solve the identified methodological issues is proposed.

KEYWORDS
Andosol/Andisol, matric potential, moisture release curve, pF curve, soil moisture, subsurface flow, tropical alpine (Páramo), volcanic ash

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1 | INTRODUCTION

Soils originating from volcanic ash, known as Andosols (IUSS Working Group WRB, 2015) or Andisols (Soil Survey Staff, 1999), possess distinctive mineralogical, chemical, and physical properties (Nanzyo, 2002; Wada, 1985). These soils have an atypical mineralogy composed of allophane with subordinate imogolite and ferrihydrite for allophanic Andosols or Al- and Fe-humus complexes for non-allophanic Andosols (McDaniel, Lowe, Arnalds, & Ping, 2012; Shoji, Nanzyo, & Dahlgren, 1993). Andosols also present a high affinity for phosphate retention combined with high organic matter accumulation (Dahlgren, Saigusa, & Ugolini, 2004). The mineralogical and chemical features of these soils provide them with andic properties (Soil Survey Staff, 2010), which in turn explain their unique physical characteristics. The latter include low bulk density, high porosity, and large surface area that gives them an outstanding water holding capacity (McDaniel et al., 2012). Andosols are found worldwide, in humid montane regions with past and present volcanic activity (Shoji, Dahlgren, & Nanzyo, 1993), providing important hydrological and ecological services (Terribile et al., 2018). Because of this, even though Andosols cover only 1% of the Earth's crust, they represent an important resource supporting the water supply of approximately 10% of world's population (Neall, 2006; Ping, 2000; Shoji, Nanzyo, & Dahlgren, 1993), including the densely populated tropics, where half of the world population is projected to live by 2050 (Wright et al., 2017).

Given the increasing recognition of the hydrological services produced by Andosols such as water storage and flow regulation (Buytaert, Célleri, et al., 2006; Buytaert, Wyseure, De Bièvre, & Deckers, 2005; Mosquera et al., 2016; Mosquera, Lazo, Célleri, Wilcox, & Crespo, 2015), investigations about their hydraulic properties increased during the last decades. The correct determination of these properties, and of the water retention characteristics in particular, is fundamental to improve the understanding of subsurface hydrological, ecological, and biogeochemical processes (Selker, Keller, & McCord, 1999) and to increase the predictive capability of numerical models to accurately represent these processes (Vereecken et al., 2016). As such, the water retention capacity of Andosols is one of the most investigated features (81 publications with ≈3200 citations in the period 1982–2019; Figure 1a, see Appendix A for details). The published literature regarding this topic focused predominantly on the determination of the Andosols' physical and hydraulic properties (35%) and the assessment of the impacts of land use and land cover change on these properties (25%; Figure 1b). Other authors investigated the subsurface flow dynamics (6%), the hillslope stability (6%), the derivation and use of pedotransfer functions (5%), the testing of soil moisture sensors (5%), and the hydrological behaviour of catchments using hydrological models (4%), among others (Figure 1b).

The soil water retention curve (WRC, also known as the moisture release curve, moisture characteristic curve, or pF curve) represents the change in the soil matric potential (tension) during drying and/or wetting cycles (Hillel, 1998). A variety of methods that enable the determination of the WRC were developed in the last 50 years, ranging from laboratory to field approaches (Selker et al., 1999). The WRC

is typically measured on small undisturbed soil samples (usually 100 cm^3 volume) in the laboratory (hereafter referred to as standard laboratory methods), while the field methods consist of the simultaneous measurement of the soil water content and matric potential in the soil profile (Hillel, 2004). The improvement of sensor technology during the last few decades have resulted in a more accurate and faster determination of the WRC of the soil. Despite these advances, the assessment of the extent to which the samples used in laboratory methods correctly mimic the hydraulic behaviour of the soils under field conditions has been rarely addressed until now. Depending on the soil type, it might be possible that standard laboratory methods prohibit a correct estimation of the soil WRC (e.g., Bittelli & Flury, 2009; Solone, Bittelli, Tomei, & Morari, 2012; van Lier, EAR, & Inforsato, 2019). Therefore, we decided to conduct a comparative analysis of the WRC of volcanic ash soils using laboratory and field methods, and to compare the findings with the Andosols WRC data published worldwide.

For Andosols, the sandbox (Stakman, Valk, & Van Der Harst, 1969) and pressure plate extractor (FAO, 2002) methods are the most widely used laboratory methods (49% and 18%, respectively; Figure 1c) to measure the water content of the soil at matric potentials below field capacity (i.e., the amount of water that a soil retains against gravity; Kirkham (2014)). To determine the soil water content around field capacity, the pressure plate extractor and the multistep (van Dam, Stricker, & Droogers, 1992) method are commonly used (65% and 13%, respectively; Figure 1d). The pressure plate extractor and the pressure membrane apparatus (Richards, 1941) are applied (68% and 23%, respectively; Figure 1e) to measure the water content at potentials above field capacity up to the permanent wilting point (i.e., the matric potential that prevents plant roots to extract water from the soil causing wilting; Kirkham (2014)). Despite the usefulness of these hydrostatic equilibrium based methods, it is known that they can yield an inaccurate representation of the water retention capacity of the soils as compared to field conditions (Hillel, 1998), particularly for fine-textured soils (i.e., soils composed mainly of clay and silt; Bittelli & Flury, 2009; Solone et al., 2012). This issue results from an inadequate soil–plate contact and a lack of hydrostatic equilibrium (Bittelli & Flury, 2009; Solone et al., 2012; van Lier et al., 2019). The magnitude of the discrepancy, however, depends on the specific properties of the soil (Solone et al., 2012). For instance, the magnitude tends to be small in the absence of soil micro- and macrostructure (e.g., sandy soils), whereas it can be substantial for structured soils (Nimmo, 1997). Notwithstanding the variety of laboratory methods used to determine the Andosols' WRCs (Figure 1c-e), knowledge about whether these methods reflect correctly the hydraulic behaviour of these soils under field conditions, as well as the magnitude of the potential discrepancy, is limited.

An important element in the accurateness of the determination of the hydraulic properties of soils using standard laboratory methods, including the WRCs, is the representativeness of the used soil sample volume. What is the smallest representative elementary volume (REV) of the soil to assure that laboratory measurements give a correct representation of the properties in the field (Bear, 1972; Kutilek & Nielsen, 1994)? The determination of the REV for a given soil depends
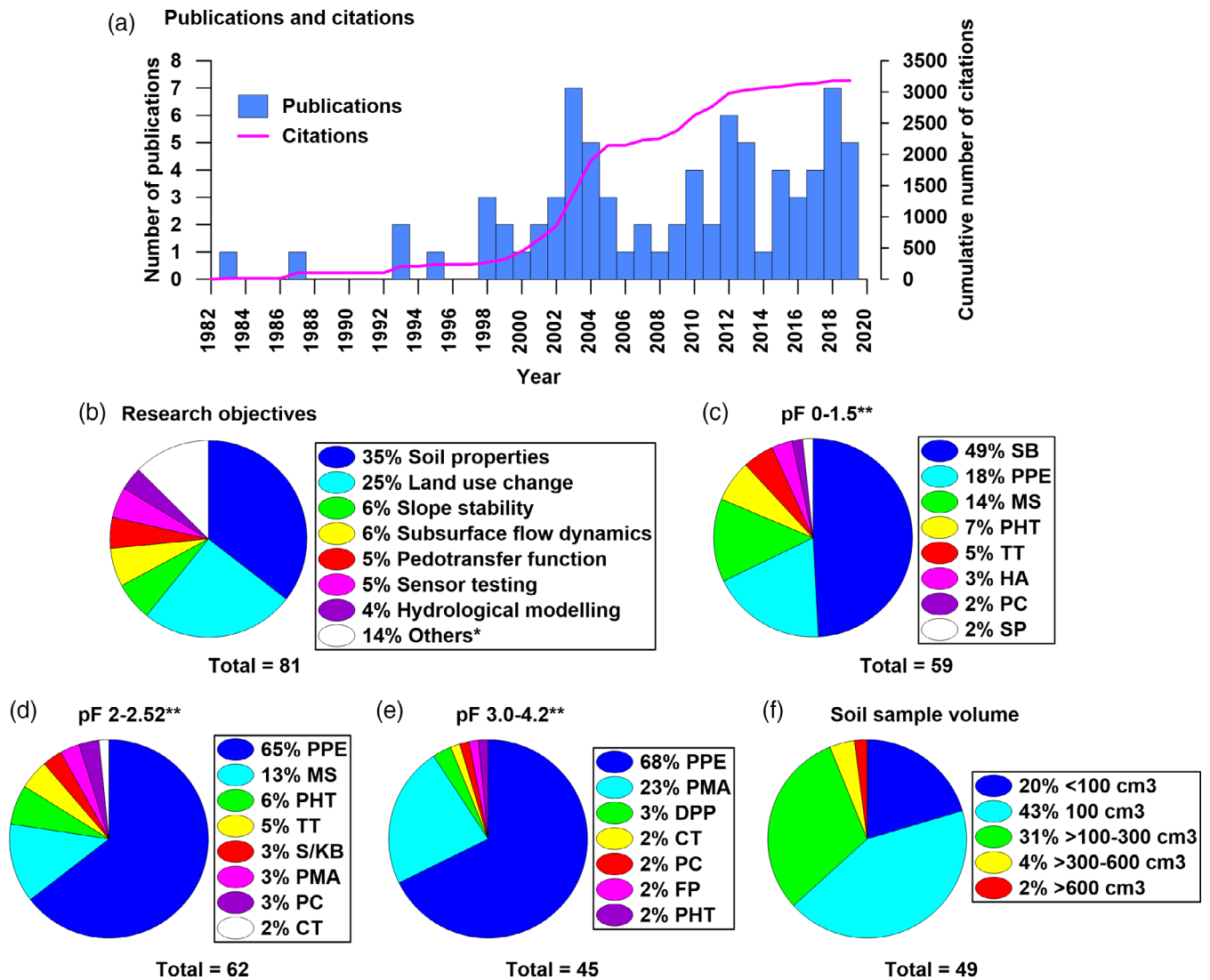
FIGURE 1 Synthesis of published literature presenting data on the water retention curves (WRCs) of Andosols. (a) Evolution of the number of publications and cumulative number of citations of the consulted studies (81 in total). The pie charts summarize the research objectives of the consulted studies (b), the applied laboratory methods (c-e), and the volume of the soil samples used for the determination of the WRCs (f) in the consulted studies. The laboratory methods are classified according to different matric potential ranges (pF = logarithm of the matric potential in cm H₂O). Total = number of studies reporting results for each pie chart category. *others in subplot b) include carbon stocks, soil genesis, biosolid application, ecological services, estimation of soil hydraulic parameters, soil description, spatial variability and spatial prediction of soil properties, water conservation practices, and biogeochemical modelling. **acronyms of the laboratory methods in subplots c)-e) are as follows: SB=sandbox, S/KB=sand/kaolin box, PPE = pressure plate extractors, HA = Haines apparatus, MS = multistep, PHT = pressure heads by tensiometers, TT = mini-tensiometers, PC=pressure cells, SP=suction plate, PMA = pressure membrane apparatus, CT = centrifuge, FP=filter paper, DPP=dew-point potentiometer

largely on how well the sample volume captures the micro- and macrostructure that controls the water movement. Based on measurements of bulk density and water content in Japanese volcanic ash soils, Sato and Tokunaga (1976) reported that the REV of Andosols is 100 cm³. That is, a cylindrical sample with a cross-sectional area of 20 cm² (Ø = 5 cm, h = 5.1 cm). On the basis of saturated hydraulic conductivity measurements using different laboratory methods only, Buytaert, Wyseure, et al. (2005) confirmed that the REV to determine the hydraulic properties of Andosols is 100 cm³. Regarding the water retention capacity of these soils, the majority of laboratory analyses have been conducted using soil samples with a volume ≤ 100 cm³

(63%; Figure 1f), with only 6% of the studies using volume samples >300 cm³. Despite the general application of standard laboratory methods using small sample volumes to determine the WRC of Andosols, only a few studies compared laboratory results with field measurements (e.g., Eguchi & Hasegawa, 2008; Fontes, Gonçalves, & Pereira, 2004).

To investigate the hydrological behaviour of Andosols in the Island of Terceira (Azores), Fontes et al. (2004) compared WRCs measured in the laboratory and in the field for allophanic Andosols under grazed pasture. In the laboratory, they used the sand/kaolin box method (Stakman et al., 1969) to measure the water content of

100 cm^3 undisturbed soil samples for potentials below field capacity. For potentials above field capacity, they used the pressure membrane apparatus and determined the water content of disturbed soil samples with a volume of 25 cm^3. In parallel, they used neutron probes and mercury tensiometers to measure soil moisture and matric potential in large soil monoliths (2.5 m × 1.5 m × 1.20 m) to determine the WRC under field conditions. These authors reported that the laboratory measurements accurately described the field soil water retention for potentials lower than field capacity, but overestimated significantly the soil moisture content for potentials above field capacity. To improve the understanding of preferential flow in unsaturated soil, Eguchi and Hasegawa (2008) also compared the WRCs obtained via laboratory analyses and field measurements for Hydric Hapludand Andosols in a cropping field in Ibaraki, Japan. They applied the suction plate method to 314 cm^3 soil samples and used time domain reflectometers and ceramic porous cups in the field to measure the WRC of the soils for matric potentials below field capacity. These authors found no difference between both methods. Despite these findings, it is yet unknown if these differences/similarities are due to local land use and/or management (i.e., both sites were impacted by different land use), the laboratory method used, the volume of the soil sample; and/or more importantly, if they are valid for all Andosols or only for some specific subclasses/subgroups. Considering the variety of purposes for which laboratory-obtained WRCs of Andosols have been and are used (Figure 1a), the contrasting findings reported in past investigations demand a thorough analysis of whether standard laboratory analyses using small soil samples reflect field conditions correctly.

How well do standard laboratory methods represent the field water retention curve of volcanic ash soils? To address this important question, we analysed the WRC of Andosols obtained through standard laboratory methods and direct field measurements. The soil samples were collected from and the in-situ measurements were conducted at experimental sites in the Ecuadorian Andes. In parallel, we reviewed the literature on this topic and compared our results with published WRC data. Our findings will assist in the setting-up of more efficient and cost-effective monitoring strategies of the soil water relation in regions where Andosols are found. This information is essential for the assessment of how changes in climate and land use will affect the water storage and flow regulation in environments dominated by Andosols.

2 | MATERIALS AND METHODS

2.1 | Description of the experimental sites

The field measurements and the soil sampling collection were conducted at two experimental sites in the tropical alpine (Páramo) ecosystem in south Ecuador. The first site was the Zhurucay Ecohydrological Observatory located on the west slope of the western Andean mountain range (3°04′S, 79°14′W). This site covers an area of 7.53 km^2 and is situated between 3400 to 3900 m a.s.l. The second site is an experimental hillslope (3900–4000 m a.s.l.) located at the Quinuas Ecohydrological Observatory on the east slope of the western Andean Cordillera (2°47′S, 79°13′W), approximately 35 km north of Zhurucay. The landscape in the region is of glacial origin, resulting in the formation of a U-shaped geomorphology. The study region is dominated by non-allophanic Andosols rich in Al- and Fe-humus complexes (Buytaert, Sevink, De Leeuw, & Deckers, 2005). These soils are typically found on the Páramo hillslopes, covering nearly 75% to 80% of the extent of both observatories (Mosquera et al., 2015; Pesántez, Mosquera, Crespo, Breuer, & Windhorst, 2018), and are the result from the accumulation of ash originated during Quaternary volcanic activity in combination with the humid and cold local climate. The latter limits the microbial activity and thus favours the accumulation of organic matter in the soil. As a result, the little developed (0.4–0.65 m thickness) andic horizon of the soil is humic and acidic (pH 4.4–5.6), has a typically low bulk density ($<0.9 \text{ g cm}^{-3}$), and presents a porous and open soil structure with high water holding capacity (Buytaert, Deckers, & Wyseure, 2006). Andosols at both sites are mainly covered by tussock grass, commonly in the genera *Calamagrostis* and *Festuca*, whose roots are found up to around 10–15 cm depth (Mosquera, Célleri, et al., 2016; Mosquera, Crespo, Breuer, Feyen, & Windhorst, 2020). The anthropogenic disturbance in the Zhurucay Observatory is limited to light cattle grazing in its lower part; whereas there is no disturbance at the Quinuas experimental hillslope as it is located in a protected national park. Detailed descriptions of the Zhurucay and Quinuas observatories are available in Mosquera et al. (2015) and Pesántez et al. (2018).

2.2 | WRC determination from in situ (field) measurements

An experimental plot (17 m × 23 m) was constructed at the upper, conserved part (3770 m a.s.l.) of the Zhurucay Observatory to monitor the subsurface flow dynamics. This plot was selected because the Andosol soil was covered by tussock grass and unaffected by cattle grazing (Figure 2a). To further ensure the latter, the plot was surrounded by a barbed wire fence during the monitoring period. The slope of the plot, 20% on average, was similar to the average gradient of the observatory. The plot was instrumented with water content reflectometers (WCR; Campbell Scientific CS616, accuracy ±2.5%, measurement range 0% to 100% moisture content) and tensiometers (UMS T8; accuracy ±0.5 kPa, measurement range ∼−85 to 0 kPa; or pF 0 to pF ∼2.9). The WCR probes were calibrated to the local soil conditions by Ochoa-Sánchez, Crespo, and Célleri (2018). The temporal variation of soil moisture and matric potential was monitored at the middle of the slope (position C in Figure 2b). Two sets of WCR probes and tensiometers, separated horizontally 12.8 m from each other, were installed in the organic (andic) horizon of the Andosols (the Ah horizon in Figure 2b, the black soil layer in Figure 2c). The probes were placed within the hydrologically active layer of this soil horizon below the root zone. That is, 2 cm below the lower boundary of the latter (Mosquera et al., 2020). The WCRs were placed horizontally
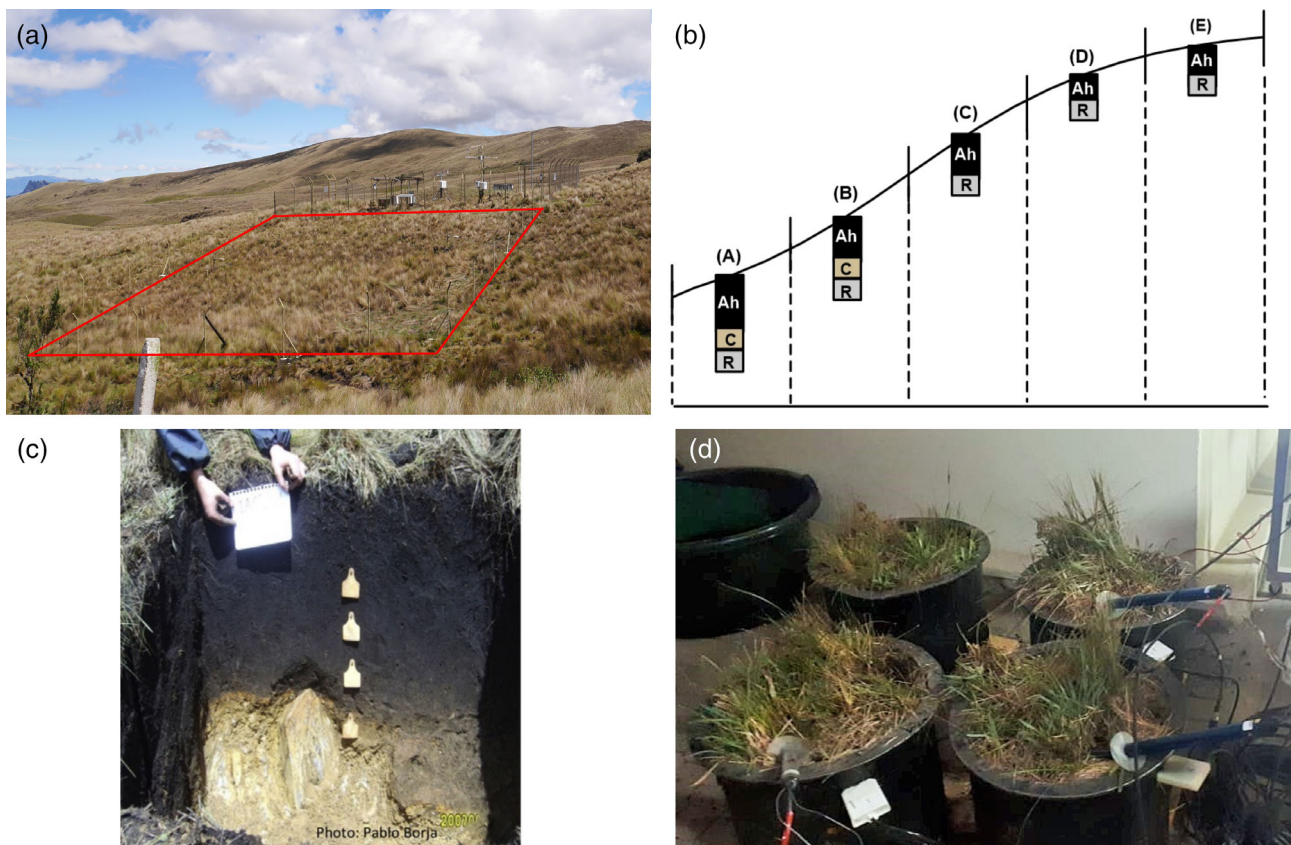
FIGURE 2 Study site and monitoring setup for determining the water retention curves of Andosols. (a) View of the experimental plot (marked in red) located in the Zhurucay Ecohydrological observatory in South Ecuador; (b) conceptual diagram of the spatial distribution of Andosols in the Zhurucay observatory hillslopes (Ah = andic horizon, C = mineral horizon, R = bedrock); (c) profile of an Andosol in the observatory; and d) experimental setup for monitoring the soil water content and matric potential in the Ah horizon of undisturbed Andosol soil cores (Ø = 40 cm, h = 32 cm) covered by tussock grass. Positions along the hillslope in subplot (b) correspond to: (A) = toe slope, (B) = lower slope, (C) = middle slope, (D) = upper slope, and (E) = hilltop. (photo credits: (a) Galo Carrillo, (c) Pablo Borja, and (d) Giovanny M. Mosquera)

so that the measurements represented the soil water content at a single depth of interest. The tensiometer probes were installed vertically from the top, with the ceramic cup located at the same depth as the corresponding WCR. A correction factor was applied to the matric potential measurements due to the tensiometer installation position as recommended by the manufatrurer (UMS, 2011). The soil moisture content and matric potential data were continuously recorded at 5-min intervals during the period January 2011–June 2018. The average soil moisture and matric potential values of the two sets of measurements were used to construct the in situ WRC of the Andosols within the range of measurement of the tensiometers (i.e., from pF 0 or saturation to pF $\sim$2.9). Given the high accuracy of the probes used for measuring the soil water content and matric potential at high-temporal frequency, the correct installation and calibration of the instruments, and the fact that they were exposed to "real world" environmental conditions during an 8-year period, the relation between those measurements was considered in our study as the correct representation of the water retention capacity of the soils under field conditions (hereafter referred to as the field WRC). Precipitation was also recorded every 5-min during the same period using a tipping-bucket rain gauge (Texas TE525MM; resolution 0.1 mm)

located approximately 10 m away from the experimental plot at 3780 m a.s.l.

2.3 | Collection of soil samples

Although field measurements were only conducted in the Zhurucay Observatory, soil samples to determine the WRC of the Andosols experimentally and in the laboratory were collected at both the Zhurucay and Quinuas Observatories.

In the Zhurucay Observatory, three large undisturbed soil cores (Ø = 40 cm, h = 32 cm; Figure 2d) were collected at the middle position of the slope (C in Figure 2b) for the determination of the WRC during a desiccation experiment. For direct comparison with the field WRC, the large-size cores were randomly collected from a 5 m × 5 m area centered around the site were the field measurements were conducted within the plot shown in Figure 2a. The vegetation in the cores was conserved to maintain field conditions during the desiccation of the samples. We also collected samples from the andic horizon of the Andosols across the Zhurucay Observatory. Small, undisturbed soil samples with a volume of 100 cm³ were collected using standard steel

rings (Ø = 5 cm, h = 5.1 cm; which at the start of the research was considered as the REV of the Andosols) and approximately 500 gr of disturbed soil for measuring the WRCs in the laboratory. Those samples were collected at approximately 14 sampling locations roughly separated 150 m from each other along three transects across the Zhurucay Observatory (41 sampling locations in total). The sampling strategy was designed such that the soil samples were collected at different positions along the hillslopes (Lazo, Mosquera, McDonnell, & Crespo, 2019). Samples were collected accordingly at the toe, the lower, the middle, and the upper sections of the hillslopes, as well as at the hilltops (i.e., the positions A–E in Figure 2b). The physiographic characteristics and the properties of the soils collected at each sampling position are described in Table 1. The samples collected at the middle slope position (C in Figure 2b) were used for direct comparison with the field and experimental WRCs of the Andosols in the Zhurucay Observatory. Given that we also conducted a comparison of the WRCs of the Andosols obtained via laboratory analysis with available data from the literature (Section 2.6), the samples collected at different physiographic positions were used to account for the potential variability in specific terrain conditions (e.g., physiographic position and/or gradient) found in the compiled literature dataset. At each sampling site, undisturbed and disturbed soil samples were collected in triplicate at the same depth in which the field and experimental measurements in the large soil cores were made; that is, within the hydrologically active layer of the Ah horizon below the root zone.

A similar soil sampling strategy was carried out in the experimental hillslope of the Quinuas Observatory. In the experimental hillslope, however, the large soil cores and small undisturbed and disturbed soil samples were only collected at the middle slope position.

2.4 | WRC determination on large soil cores via a desiccation experiment

The large undisturbed soil cores were wetted by capillary rise from the bottom for a period of two months to secure saturation before the start of the desiccation cycle. Subsequently, a WCR probe (Campbell Scientific CS616) and a tensiometer (UMS T8) were placed in each soil core at the same depth where the field measurements were conducted and the small soil samples collected (Figure 2d). The WCR probes were placed horizontally through holes on the sides of the cores and the tensiometer probes were installed from the top at an angle of 35° from the vertical line. A correction for the inclination angle was applied according to the manufacturer's recommendations (UMS, 2011). Positive matric potential measurements from the tensiometers in each of the samples indicated saturation. After this check, we let the samples drain and recorded the soil moisture content and matric potential at 5-min intervals throughout the entire desiccation process. During this process, duplicate small soil samples (Ø = 2.5, cm h = 5 cm) were collected from each soil core to determine the "real" moisture content of the soil in the laboratory. The small samples were collected every 1 to 4 days during the first 3 weeks of the experiment, and every 10 to 15 days subsequently. These data were used to construct the calibration curve for each of the WCR probes used in the experiment. The experiment was carried out for about 50 days, until

the tensiometers' measurement range was reached. Thus, the soil water content and matric potential values recorded during the desiccation process represent the WRC of the Andosols (hereafter referred to as the experimental WRC) from saturation to pF 2.9 (−85 kPa).

2.5 | WRC determination on small soil cores using standard laboratory methods

The 100 cm^3 undisturbed samples were used to determine the soils' bulk density and soil water retention at matric potentials (or pF, defined as logarithms of the matric potentials in cm water column) below field capacity. The moisture contents were measured at pF 0 (saturation, −1 cm H_2O or −0.1 kPa), pF 0.5 (−3.2 cm H_2O or −0.31 kPa), pF 1.5 (−32 cm H_2O or −3.1 kPa), and pF 2.52 (field capacity, −330 cm H_2O or −33 kPa). Sieved, disturbed soil samples (Ø = 4 cm, h = 1 cm) were used to determine the water retention capacity at pF 3.4 (−2500 cm H_2O or −245 kPa) and pF 4.2 (permanent wilting point, −15 500 cm H_2O or −1550 kPa). The WRCs were determined using the sandbox apparatus (for pF-values 0.5–1.5) and the low (pF 2.52) and high (pF 3.4 and 4.2) pressure plate extractors (FAO, 2002) (Soil Moisture Equipment Corp., Goleta, CA, USA). We selected these methods to determine the WRC of the Andosols (hereafter referred to as the laboratory WRC) because they are the most frequently used in the analysed literature (Figure 1c-e). Although a direct comparison between the laboratory WRC using the presently considered REV of the Andosols (undisturbed soil samples of 100 cm^3) and the field and experimental WRCs is possible up to pF ∼2.9 due to the measurement range of the tensiometer probes, we also present the results of the laboratory WRC for higher matric potentials (applying the standard laboratory method to the disturbed soil samples) for reference.

2.6 | Compilation of WRC data from the published literature

We identified 81 studies that reported quantitative information (in figures or tables) on the WRCs of Andosols or volcanic ash soils with andic properties (i.e., pumice soils were excluded; see Appendix A for a detailed description of the applied literature search procedure, and the list of selected documents in Supplementary Material). From this database, we selected the papers reporting the WRC for: (i) the organic (andic) horizon of Andosols (up to a depth of 50 cm), (ii) Andosols covered by grassland vegetation, and (iii) Andosols situated in conserved areas unaffected by changes in land use and cover. That is, for conditions comparable to the Zhurucay Observatory. Sixteen papers that fulfilled these criteria were selected for further analysis. Information from these publications provided the data from which we reconstructed 71 WRCs. The main details about the locations, features, the physical, chemical, and mineralogical soil characteristics, and the methods and soil sample volumes used to determine these WRCs are summarized in Table 2. Information on the specific terrain conditions (e.g., physiographic position and/or gradient) are not included in the table since the majority of

TABLE 1 Hydraulic properties of the Ah (andic) horizon of the Andosols monitored at different positions along the hillslopes (as shown in Figure 2b) in the Zhurucay Ecohydrological observatory. The values presented in the table are the average and the standard deviation (in parenthesis) of the properties measured in the laboratory

Position code[a]	n[b]	Slope (%)	Horizon type	Horizon depth (cm)	BD[c] (g cm^{-3})	pF[c] 0 (cm^3 cm^{-3})	pF[c] 0.5 (cm^3 cm^{-3})	pF[c] 1.5 (cm^3 cm^{-3})	pF[c] 2.52 (cm^3 cm^{-3})	pF[c] 3.4 (cm^3 cm^{-3})	pF[c] 4.2 (cm^3 cm^{-3})
A	10	7 (5)	Ah	41 (2)	0.38 (0.25)	0.80 (0.10)	0.78 (0.09)	0.71 (0.06)	0.63 (0.04)	0.41 (0.14)	0.31 (0.03)
B	5	17 (14)	Ah	33 (6)	0.36 (0.10)	0.81 (0.04)	0.81 (0.04)	0.80 (0.04)	0.67 (0.002)	0.51 (0.10)	0.49 (0.10)
C	10	21 (16)	Ah	34 (7)	0.40 (0.04)	0.77 (0.03)	0.76 (0.03)	0.75 (0.04)	0.70 (0.02)	0.60 (0.08)	0.53 (0.07)
D	9	11 (9)	Ah	38 (3)	0.47 (0.16)	0.72 (0.08)	0.72 (0.08)	0.71 (0.08)	0.63 (0.05)	0.52 (0.11)	0.54 (0.06)
E	7	4 (3)	Ah	35 (11)	0.49 (0.14)	0.73 (0.06)	0.73 (0.06)	0.72 (0.06)	0.65 (0.04)	0.58 (0.06)	0.51 (0.04)

[a]A, Toe slope; B, Lower slope; C, Middle slope; D, Upper slope; E, Summit.

[b]n, number of locations where triplicate samples were collected and analysed at each of the hillslope positions across the Zhurucay Ecohydrological Observatory.

[c]BD, bulk density; pF, log$_{10}$ matric potential in cm H$_2$O.

TABLE 2 Summary of the published literature presenting soil moisture content versus matric potential data used for the construction of the water retention curves (moisture release curves, moisture characteristic curves, or pF curves) of volcanic ash soils with andic properties (Andosols/Andisols) using standard laboratory methods

Ref[a]	Country[b]	RQ[c]	Elevation (m a.s.l)	Slope (%)	R	N	Soil subclass	Depth (cm)	BD (gr cm^{-3})	φ (%)	pH	OM (%)	Sand (%)	Silt (%)	Clay (%)	Al$_p$/Al$_o$ (%)	Fe$_o$ (g kg^{-1})	Si$_o$ (g kg^{-1})	Allophane (%)	Lab. method[d]	Sample volume (cm^3)
[1]	ECU	LUC	3450	-	12	-	Histic	15	0.3	-	-	33	-	-	-	-	-	-	-	MS + PPE	100
[2]	ECU	SG	3970	-	-	8	-	0–24 / 24–56	0.26	83	4.8	62	29	41	31	0.92	-	-	-	PMA	100
			3850	-				0–12 / 12–44	0.48	73	4.6	46	32	36	32	0.82	-	-	-		
			3830	-				0–15 / 15–41	0.17	82	5.3	62	40	32	29	1.08	-	-	-		
			3550	-				0–17 / 17–60	0.57	71	4.6	26	19	27	55	0.47	-	-	-		
			3425	-				0–16 / 16–62	0.32	82	5	50	26	32	42	0.46	-	-	-		
			3300	-				0–30	0.33	84	5.3	34	24	31	45	0.48	-	-	-		
[3]	ECU	LUC	3400	30	6	-	-	0–10 / 10–25	0.54	-	6	20	-	-	-	-	-	-	-	SB + PPE	100
			3650	22	6	-	-	0–10 / 10–25	0.38	-	5.2	39	-	-	-	-	-	-	-		
			>3650	20	6	-	-	0–10 / 10–25	0.74	-	5.5	12	-	-	-	-	-	-	-		
[4]	ECU	LUC	3650	23	-	36	-	0–50	0.64	-	4.9	29	-	-	-	-	-	-	-	MS + PPE	100
[5]	ECU	HM	3735	-	-	-	-	30	-	-	-	-	-	-	-	-	-	-	-	MS + PPE	-
[6]	JAP	SP	-	-	18	6	-	3–8 / 4–9 / 17–22 / 25–30	-	73	-	-	-	-	-	-	-	-	-	SB + PPE	100
[7]	ECU	LUC	4000	-	4	-	-	0–20 / 20–40	0.85	65	-	11	58	36	7	0.72	-	-	-	PPE	-
			3600					0–30	0.4	80	-	28	9	65	26	0.96	-	-	-		

TABLE 2 (Continued)

Ref[a]	Country[b]	RQ[c]	Elevation (m a.s.l)	Slope (%)	R	N	Soil subclass	Depth (cm)	BD (gr cm⁻³)	φ (%)	pH	OM (%)	Sand (%)	Silt (%)	Clay (%)	Al_p/Al_o (%)	Fe_o (g kg⁻¹)	Si_o (g kg⁻¹)	Allophane (%)	Lab. method[d]	Sample volume (cm³)
[8]	ECU	LUC	4200	0- > 60	5	-	-	0–15 15–30	0.68	-	4.8	11	32	54	9	0.66	0.62	1.71	-	PPE	-
			4000	0- > 60				0–15 15–30	0.84	-	5.2	8	32	45	16	0.58	0.38	0.96	-		-
			3700	0–40				0–15 15–30	0.78	-	5.4	12	30	54	12	0.72	0.43	0.89	-		-
[9]	CHI	LUC	73	1	7	-	Histi-Silandic	5 15 30	0.5	-	5	31	-	-	-	-	-	-	-	SB + PPE	230
[10]	ECU	SD	3500	-	-	3	Melani-Vitric (Pachic)	0–30	0.58	80	-	37	-	-	26	0.97	0.64	0.4	2	PPE + PMA	100
			3700	-			Melani-Vitric (Hydric)	0–30 30–45	0.38	81	-	37	-	-	35	0.99	1.23	2.4	2		
			3250	-			Melani-Vitric (Hydric)	0–7.5 15–50	0.33	83	-	29	-	-	51	0.96	2.07	0.45	2		
[11]	ECU	CS	3860	14	1	-	-	0–10 10–30	0.4	-	4.5	31	-	-	12	0.93	0.85	0.14	0.9	SB + PPE	200
[12]	ECU	LUC	3450	-	-	-	Histic	15	-	-	-	-	-	-	-	-	-	-	-	MS + PPE	100
[13]	JAP	SSF	-	6	5	-	-	7.5 15 30	0.75	-	-	-	-	-	-	-	-	-	-	SB + CT	-
[14]	TAI	SG	970	30	-	3	-	0–27	0.51	81	4.1	11	16	61	23	0.84	2.12	0.31	-	PMA	-
			890	30				0–20	0.55	79	4.5	9	39	48	15	0.88	1.9	0.21	-		
[15]	COG	SD	2290	34	-	9	-	10–50	-	-	-	-	-	-	-	-	-	-	-	SB + PPE	100
[16]	NZL	SG	1000	-	-	5	-	1–10 10–28 33–40	0.9	-	5.5	4	71	22	7	0.17	-	0.43	3.7	PPE	-
			70					0–23	0.69	-	5.5	13	55	30	15	0.4	-	0.09	5	SB + PPE	100

studies did not provide this information. However, the dataset most likely covers a wide range of terrain conditions. We will further refer to these data as the "literature compiled WRC dataset".

3 | RESULTS

3.1 | Comparison of the WRCs using standard laboratory methods

Figure 3 summarizes the laboratory results of the WRCs determined on the 100 cm^3 undisturbed core samples collected across the
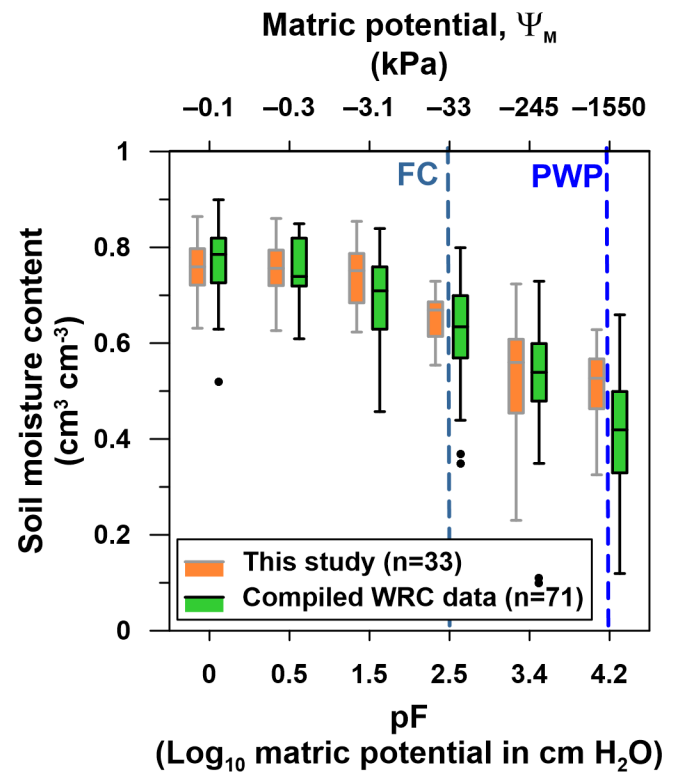

FIGURE 3 Comparison of the water retention curves (WRCs) of Andosols obtained using standard laboratory methods. Soil moisture content versus matric potential relation (i.e., soil WRC, moisture release curve, or pF curve) of the Ah horizon of Andosols at different locations across the Zhurucay Ecohydrological observatory (Figure 2; this study) and the WRCs of 16 published studies summarized in Table 2 (compiled WRC data). All data correspond to the upper horizon (depth < 50 cm) of the Andosol, all covered by pristine grassland (i.e., forest cover and disturbed land use were excluded from the compiled WRC dataset). Data were generated via laboratory analysis using (i) steel rings (100 cm^3 volume) in Zhurucay, and (ii) steel rings of different volume (100–230 cm^3 volume) in the literature compiled WRC dataset (see Table 2 for details). The box plots correspond to the median and the 25 and 75 percentiles, and the whiskers to the maximum and minimum soil moisture values. The dashed vertical lines represent field capacity (FC; pF 2.52, −330 cm H$_2$O, or − 33 kPa) and permanent wilting point (PWP; pF 4.2, −15 500 cm H$_2$O, or − 1550 kPa). N indicates the number of moisture release curves used to construct the boxplots

hillslopes of the Zhurucay Observatory (Table 1), and the 71 reconstructed WRCs from the 16 selected studies summarized in Table 2. The WRCs of the Andosols in Zhurucay depicted that the soil moisture content remained near saturation (0.77 ± 0.04 cm^3 cm^{-3}) up to pF 1.5. A small decrease in soil moisture content was observed at pF 2.52 (0.66 ± 0.03 cm^3 cm^{-3}), indicating that the soils at field capacity lost only 14% of their water content. A continuous reduction of the soils' water content was observed until pF 4.2 (permanent wilting point). At this matric potential, the moisture content of the soils was about 38% lower than at saturation (0.48 ± 0.09 cm^3 cm^{-3}). These findings are in line with those reported for Andosols at nearby sites in the south Ecuadorian Andes for WRCs determined in the laboratory using 100 cm^3 soil samples (Buytaert, Wyseure, et al., 2005; Iñiguez et al., 2016; Marín et al., 2018; Quichimbo et al., 2012). These results suggest that a sufficient number of samples were collected to represent the spatial variability at the study site and the regional soil conditions across the northern Andes (Buytaert, Célleri, et al., 2006; Buytaert, Deckers, & Wyseure, 2006).

Although the literature compiled WRC data were not in all cases obtained using the same laboratory methods applied in our study, they were remarkably similar to the WRCs of the Andosols in the Zhurucay Observatory (Figure 3). Only a larger variability in moisture content at different matric potentials was observed in the literature compiled WRC dataset. This variability most likely reflects the differences in the site-specific conditions in this dataset (e.g., geographical location; elevation and topographic position; physical, chemical, and mineralogical properties of the Andosols; Table 2). Despite the small differences, the similarity between both datasets depicts that the WRC at the study site, using standard laboratory methods and small soil samples, captured well the general hydraulic behaviour of the soil.

The remarkable similarity between both datasets also suggests that for Andosols different laboratory methods produce similar WRCs irrespective of the method applied. This observation is in line with the findings of Buytaert, Sevink, et al. (2005), who reported that different laboratory methods for the determination of the saturated hydraulic conductivity of non-allophanic Andosols also produced similar results. Furthermore, it is worth noting that although the Andosols in the Zhurucay Observatory are non-allophanic, the literature compiled WRC dataset included both, allophanic and non-allophanic Andosols (Table 2). This indicates that standard laboratory methods yield similar WRCs of Andosols regardless of their specific mineralogical composition. It is also worth highlighting that although the volume of the samples analysed in the majority of studies was 100 cm^3 (Table 2), we did not find differences in the Andosols' WRCs when larger sample volumes were used (up to 230 cm^3). Based on the analysis of the bulk density and water content of the Andosols using soil samples of different volume, Sato and Tokunaga (1976) concluded that the REV of volcanic ash soils with andic properties is 100 cm^3. Our comparative analysis of the different standard laboratory methods for determining the WRC of Andosols supports indirectly this conclusion.

3.2 | Field and experimental WRCs

Our study yielded similar field and experimental (large core samples) WRCs for the Andosols in the Zhurucay Observatory (red and green lines in Figure 4a, respectively). That is, the soil moisture content hardly dropped between saturation (≈ 0.77 cm^3 cm^{-3}) up to pF 1.5. Beyond this point, both curves showed an abrupt and fast reduction in soil moisture content as the matric potential of the soil increased. Similar observations were reported by Ritter, Muñoz-Carpena, Regalado, Vanclooster, and Lambot (2004) for volcanic ash soils in Tenerife (Canary Islands, Spain), who determined the WRC using time domain reflectometer probes and ceramic porous cups to monitor the soil moisture and matric potential directly in large undisturbed soil cores (Ø = 45 cm, h = 85 cm). The field WRC presented larger error bars than the experimental one (Figure 4a). This observation complies with the hysteretic behaviour of the hydraulic properties of the soils when exposed to a succession of wetting and drying cycles under field conditions (Basile, Ciollaro, & Coppola, 2003); differently from the desiccation experiment in which the soil cores were drained only once. The field WRC did not reach field capacity (Figure 4a) as a result of the local environmental conditions. On the one hand, the continuous input of low-intensity precipitation (Padrón, Wilcox, Crespo, & Célleri, 2015) sustains the recharge of soil water (Mosquera et al., 2015, 2016). On the other hand, the high air humidity and the low temperatures year-round (mean annual relative humidity and temperature are 91% and 6.0°C at 3780 m a.s.l.; Córdova, Carrillo-Rojas, Crespo, Wilcox, and Célleri (2015)) restrict soil moisture loss by evapotranspiration. In contrast, the soil cores were dried to a matric potential beyond field capacity during the desiccation experiment (until pF ≈ 2.8). As the experimental WRC resembled well the field WRC in the Zhurucay Observatory, in the following we will refer to the experimental curve as representative of both conditions.

3.3 | Comparison of laboratory, experimental, and field WRCs

The laboratory WRC in Zhurucay approximated closely the experimental observations up to pF 1.5 (i.e., soil moisture contents remained near saturation as shown in Figure 4a). These observations are similar to those reported by Eguchi and Hasegawa (2008) and Fontes et al. (2004) for Andosols in Japan and the Island of Terceira (Azores), respectively. These authors reported that the WRCs obtained via laboratory analysis and field measurements were similar up to pF 1.7. For pF-values >1.5, the laboratory WRC in Zhurucay overestimated the water content of the Andosols in comparison to the experimental WRC. It is important to notice that the moisture content at field capacity was notoriously different between both curves. That is, the laboratory WRC overestimated the water content (0.69 ± 0.03 cm^3 cm^{-3}) by 17% in comparison to the experimental curve (0.59 ± 0.01 cm^3 cm^{-3}). The overestimation for the Andosols in the Quinuas experimental hillslope was even larger than in Zhurucay (33%; Figure 4b). Another significant difference observed for the Andosols at both study sites was that at the soil moisture content in which the laboratory WRCs reached permanent wilting point (0.53 ± 0.10 cm^3 cm^{-3} in Zhurucay and

0.41 ± 0.07 cm³ cm⁻³ in Quinuas), the experimental WRCs only exceeded slightly field capacity (Figure 4a-b). Similar discrepancies between laboratory- and experimental-/field-derived WRCs have been reported for allophanic Andosols under disturbed land use conditions by Fontes et al. (2004). These authors reported that laboratory methods failed to mimic field conditions for pF-values >1.7; and attributed the discrepancy to the presence of allophane in the soil. Our findings for non-allophanic Andosols, however, suggest that the differences in water retention characteristics cannot be attributed solely to the allophane content of the soils. Moreover, the findings of Fontes et al. (2004) at disturbed sites and ours at pristine sites also suggest that the misrepresentation of the laboratory WRCs occurs independently from the land use and/or management of the soils.

4 | DISCUSSION

4.1 | How well do standard laboratory methods represent the field WRC of volcanic ash soils?

On the basis of the extensive comparative analysis we conclude that standard laboratory methods (listed in Figure 1c-e) using soil sample volumes ≤300 cm³ (corresponding to 94% of the sample volumes used for determining the WRCs of Andosols; Figure 1f) do not mimic accurately the water retention of Andosols under field conditions. Our evaluation suggests that the observed differences occur irrespective of site-specific land use and soil properties (e.g., clay mineralogy, organic matter content, texture; Table 2). The observed discrepancies are probably the result of the fact that small-volume soil samples do not represent correctly the soil micro- and macrostructure that controls the water movement of the Andosols (Guzman et al., 2019). In this sense, a recent study demonstrated that the height of the soil sample used in standard laboratory analyses produced substantially different results on the determination of the WRC of a clayey soil with a well- developed structure (Silva, Libardi, & Gimenes, 2018), similar to that of the investigated Andosols. Therefore, a similar assessment for volcanic ash soils could not only help unveil the influence of the soil samples height on their laboratory obtained WRC, but also to illuminate whether the size/height of the soil samples presumably (at least partially) is responsible for the identified discrepancy.

Discrepancies can also be due to errors identified when applying the pressure plate laboratory method for determining the WRC of fine textured soils for pF values larger than 2 (e.g., Bittelli & Flury, 2009;
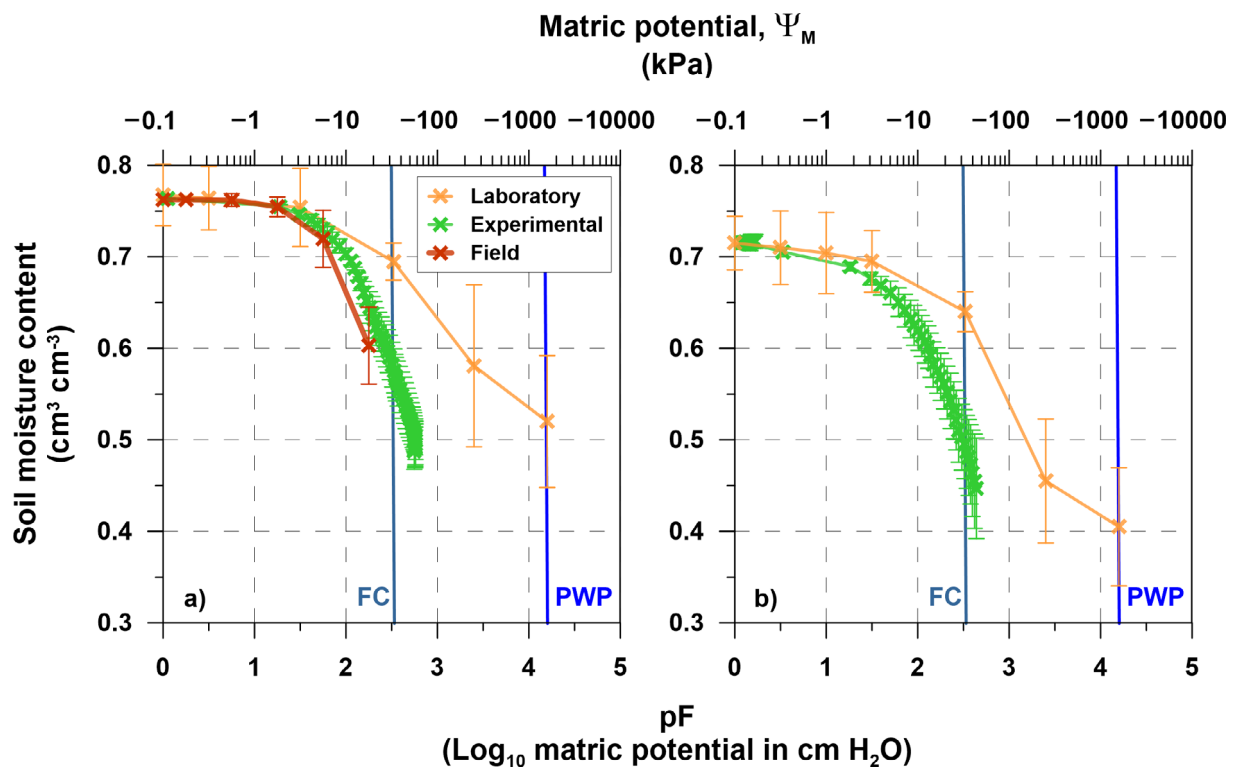

FIGURE 4 Comparison of laboratory, experimental, and in situ (field) water retention curves. (a) Soil moisture content versus matric potential relation of the Ah horizon in the Andosols located in the middle position of the hillslope (position C in Figure 2b) obtained via standard laboratory methods using 100 cm³ steel rings (n = 10), the experimental measurement of the soil moisture content-water potential relation (daily data shown, n = 3) in large undisturbed soil cores (Ø = 40 cm, h = 32 cm), and field measurements of soil moisture content versus matric potential in the experimental plot of the Zhurucay Ecohydrological observatory (data shown in Figure 5, n = 2). Subplot (b) shows the same results for the Ah horizon of Andosol soils in the Quinuas Ecohydrological observatory located 35 km north of Zhurucay measured in the laboratory and experimentally on large soil cores. Data shown are the mean (x symbols connected with a thick line) and standard deviations (vertical error bars) of the measured soil moisture contents. Continuous vertical lines represent the matric potential at field capacity (FC; pF 2.52, −330 cm H₂O, or − 33 kPa) and permanent wilting point (PWP; pF 4.2, −15 500 cm H₂O, or − 1550 kPa)

Solone et al., 2012). Possible errors can be due to an inadequate soil–plate hydraulic conductance, a lack of hydrostatic equilibrium, a lack of soil–plate contact, and/or soil dispersion (Bittelli & Flury, 2009; Solone et al., 2012; van Lier et al., 2019). In other words, methodological limitations can cause that the measured soil moisture content is overestimated. Considering that the Andosols present a moderately fine to fine texture in combination with a high organic matter content and a strong shrinkage during drying (Bartoli, Begin, Burtin, & Schouller, 2007; Dörner, Dec, Peng, & Horn, 2009a), it is likely that the pressure membrane extractor and/or the incorrect use of it could trigger the identified misrepresentation. Lastly, the similarities between the laboratory curves in Zhurucay and the literature compiled WRC dataset (Figure 3) suggest that comparing only different standard laboratory methods is insufficient to determine the cause of the misrepresentation of the WRC of volcanic ash soils with andic properties.

4.2 | Broader implications

Our findings have important implications in soil hydrological research since the WRCs of Andosols obtained via standard laboratory methods are commonly used to investigate water transport and mixing in the subsurface (e.g., Blume, Zehe, & Bronstert, 2009; Dörner et al., 2015). The data collected at the experimental hillslope of the Zhurucay Observatory illustrate this issue when analysing and interpreting the dynamics of soil moisture (Figure 5b). The WRC obtained in the laboratory (yellow line in Figure 4a) indicates that soil moisture at the experimental hillslope decreases rapidly from levels above field

capacity to levels at or near permanent wilting point (blue and purple dashed lines in Figure 5b) shortly after the beginning of dry periods. A similar hydrological behaviour at the hillslope scale was observed by Dörner et al. (2015) for Andosols in southern Chile. These authors attributed this phenomenon to the high unsaturated hydraulic conductivity of the soil. This explanation suggests that water molecules tightly bound to soil particles with the smallest volumes could be emptied as fast as gravitational water moving readily in the macropores of the soil matrix. However, such a behaviour cannot be physically justified, particularly for soils rich in clay minerals with high surface areas such as Andosols (Maeda, Takenaka, & Warkentin, 1977; McDaniel et al., 2012). Our comparative analysis of the Andosols' WRCs provides a more feasible explanation for the observed dynamics. That is, the field capacity of Andosols under field conditions is reached at a much lower water content than that determined through standard laboratory methods (Figure 4a). This explanation is further supported by the matric potential observations in our experimental hillslope, which show that field capacity was never reached during the study period (solid orange line in Figure 5b). In other words, in wet areas where undisturbed Andosols dominate (e.g., in wet regions across the Andean highlands), the physiological activity of the vegetation is not limited by water availability as soil moisture never falls below field capacity. These findings do not only clearly demonstrate the misrepresentation of the WRC of the Andosols using standard laboratory methods, but also the need to determine it accurately for interpreting soil moisture dynamics and inferring subsurface hydrological behaviour.

The WRCs of Andosols obtained via standard laboratory methods have also been used as input for the implementation of physically-
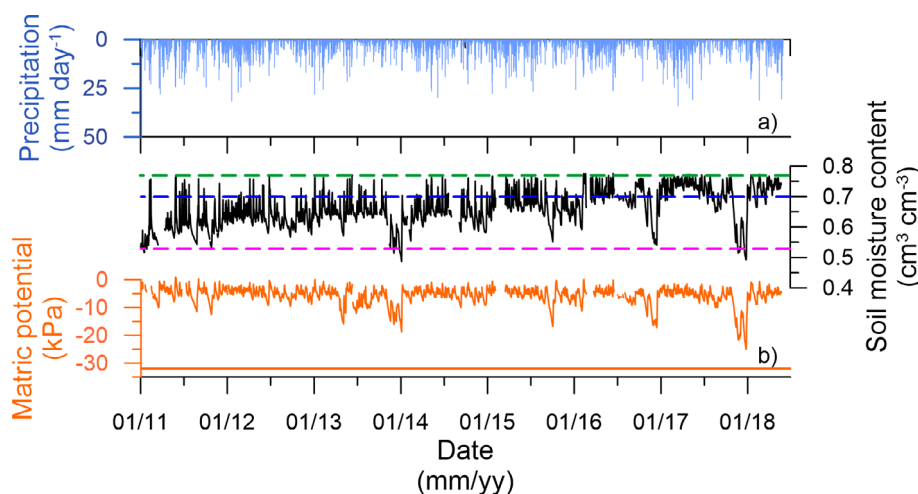

FIGURE 5 In situ measurements of daily precipitation (a), and soil moisture and matric potential within the hydrologically active layer of the Ah horizon of the Andosols at the middle position (b) of the experimental plot of the Zhurucay Ecohydrological observatory (position C in Figure 2b) during the period January 2012–June 2018. The matric potential and soil moisture data correspond to the average of two monitoring stations in the experimental plot and were used to construct the "field" water retention curve (WRC) of the Andosol soil (red line in Figure 4a). The dashed horizontal lines in b) represent the soil moisture values at saturation (green line), field capacity (blue line), and wilting point (purple line) according to the WRC obtained using standard laboratory methods (yellow line in Figure 4a). The solid orange horizontal line in b) represents the matric potential at field capacity (−33 kPa, −330 cm H_2O, or pF = 2.52), which is not reached during the study period according to the field measurements

based numerical models at different spatial scales, from plot to catchment, to simulate water and nutrient fluxes (Alavi & Tomer, 2001; Asada et al., 2018), and to design landslide early warning systems (Ferrari, Eichenberger, Fern, Ebeling, & Laloui, 2012; Frattini, Crosta, Fusi, & Dal Negro, 2004). Alavi and Tomer (2001) reported that simulations yielded by their hydrological model overestimated soil drainage observations by 35–138% and attributed these large errors to the soil WRCs determined in the laboratory on small volume soil samples (68 cm^3). Asada et al. (2018) showed that a modified soil water retention function was needed to improve the simulation of nitrogen loss from soils using a biogeochemical model. These findings further indicate that a correct determination of the WRC of Andosols is required to improve the predictive capability of numerical models used to simulate hydrological, hydraulic, and biogeochemical processes (Fatichi et al., 2016; Köhne, Köhne, & Šimůnek, 2009; Vereecken et al., 2016).

To facilitate the implementation of numerical models at larger spatial scales, pedotransfer functions (i.e., relations between soil properties with different difficulty in measurement or availability; Pachepsky and van Genuchten (2011)) and spatial predictions of the water retention characteristics of Andosols have also been developed using WRC information obtained from standard laboratory methods (e.g., Guio Blanco, Brito Gomez, Crespo, & Ließ, 2018; Rustanto, Booij, Wösten, & Hoekstra, 2017; Spilling, 2018; Yáñez, Dec, Clunes, & Dörner, 2015). Since these functions are aimed to serve as input data for the implementation of regional to global scale hydrological, ecological, land surface, and earth system models (Fan et al., 2019; Vereecken et al., 2010), the incorrect determination of the water retention characteristics of soils will increase the uncertainty and diminish the accuracy of the produced simulations (Vereecken et al., 2016). Therefore, pedotransfer functions and spatial predictions of the water retention of Andosols should be used with caution and redefined when possible to better represent the hydrological and hydraulic behaviour of these soils in large-scale models. This issue is of particular importance in regions where data are scarce, such as in the tropics where volcanic ash soils are an important resource (Hodnett & Tomasella, 2002; Minasny & Hartemink, 2011).

Past research also focused on the investigation of the impacts of land use change/management on the water retention capacity of Andosols. The land use change or management practices included crop and agroforestry (Abera & Wolde-Meskel, 2013), crop rotation (Duwig et al., 2019), overgrazing (Buytaert, Wyseure, et al., 2005; Podwojewski et al., 2002), forest/wetland conversion to grassland (Dec et al., 2017; Dörner et al., 2016; Roa-García, Brown, Schreier, & Lavkulich, 2011), native forest or grassland conversion to pasture, exotic forest, or crops (Daza Torres, Hernández Flórez, & Triana, 2014; Dörner, Dec, Peng, & Horn, 2009b, 2010; Farley, Kelly, & Hofstede, 2004; Marín et al., 2018; Quichimbo et al., 2012), soil compaction due to tractor traffic (Gómez-Rodríguez, Camacho-Tamayo, & Vélez-Sánchez, 2013), and biosolid application (Salazar et al., 2012). Our findings indicate that although the results from such evaluations are valid for the wetter portion of the WRC (from saturation to pF ∼ 1.7), they should be used with caution for the drier range of the curve. Ideally, the magnitude and direction of the reported impacts should be re-evaluated using an appropriate characterization of the water retention of these soils.

5 | OUTLOOK AND FUTURE DIRECTIONS

The presented comparative analysis among laboratory, experimental, and field WRCs of Andosols revealed that standard laboratory methods using 100 cm^3 soil samples match well with the experimental curve (WRC measured on large soil cores or directly in the field) in the wet range from saturation to a matric potential of 3–5 kPa (pF 1.5–1.7). For higher matric potentials, including the field capacity (pF 2.52), the laboratory-defined curve overestimates considerably the water content of the soil in comparison to the experimental curve. Moreover, the outstanding similarity between our laboratory-obtained WRCs and the 71 WRCs reconstructed from the data extracted from 16 publications in high-ranked journals using small soil samples (≤300 cm^3) reinforces the suspicion that the standard laboratory methods using small soil samples are incapable of mimicking field conditions correctly. However, we cannot conclude whether this is due to the applied laboratory method, the analysed volume of soil sample, or both. Resolving this issue demands the identification of the factors causing the discrepancy and likely an adjustment of the standard laboratory methods.

Given the essential role the water retention of the soil plays in the understanding of subsurface flow processes, appropriate methods to characterize correctly their WRC should be used. Basile et al. (2003) presented an experimental approach that reliably represented the hysteretic behaviour of the water retention capacity of Italian volcanic ash soils in comparison to soil moisture and matric potential measurements in the field. They used a controlled evaporation experiment in combination with matric potential measurements using mini-tensiometers to determine the wet range of the WRCs of the soil. In this approach, a soil sample of 600 cm^3 (Ø = 8.5 cm and h = 11.0 cm) is placed on a load cell, and changes in the weight of the sample during the evaporation process are used to calculate the changes in soil water content. Simultaneously, the matric potential of the soil sample is determined at two heights (3.5 and 6.5 cm from the sample bottom) using mini-tensiometers (3 cm long porous ceramic cups, Ø = 0.6 cm).

The use of mini-tensiometers presents the advantage that the matric potential of the soil can be accurately determined in soil samples larger than the presently considered REV of the Andosols (100 cm^3), but smaller than the soil monoliths used in this study, enabling to characterize simultaneously a larger number of sites/soil profiles in comparison to the soil moisture and matric potential measurements in the field or on large soil monoliths (e.g., Basile et al., 2003; Eguchi & Hasegawa, 2008; Fontes et al., 2004; Ritter et al., 2004; this study). Despite its advantages, the use of mini-tensiometers is only suitable for reconstructing the wet range of the WRC of Andosols. The latter is due to the limited measurement range of the mini-tensiometers (from saturation to pF 2.5–3) and the strong shrinkage of the Andosols during desiccation, which causes a

premature loss of contact between the soil and the tensiometer and thus limits the matric potential measurement range. These limitations make this approach unsuitable for studies that require identifying the soil water available for vegetation (e.g., in agricultural, ecohydrological, eco-physiological, irrigation, and climate change research), which is determined using the soil moisture content at field capacity and permanent wilting point. Other disadvantages are the relatively high cost of the mini-tensiometers and high-precision load cells, and that the described experimental setup can only analyse one sample at a time. Thus, a tradeoff between the cost of the experimental setup and the number of samples to be analysed is an issue to be considered. Even though this method can be momentarily used to determine the wet potion of the Andosols' WRC, its limited measurement range and methodological constraints stress the need to investigate the REV of the Andosols and define laboratory methods capable of determining the WRC from saturation to permanent wilting point.

Preferably, the adaptation of the laboratory methods should be such that after modification they are not only able to accurately mimic field conditions, but also allow analysing multiple soil samples simultaneously in a relatively short time at an acceptable cost. A first step towards addressing this issue will be the re-determination of the REV of the Andosols and the identification of the cause behind the identified deviations. Results from the described evaporation experiment (Basile et al., 2003) provide valuable information about these issues. They suggest that the use of soil samples of 600 cm^3 produce similar hydraulic behaviour than the Andosols in the field. This could be because a larger soil sample represents better the micro- and macro-structure of the soil, shedding light on the REV issue. However, this information is also linked to challenges ahead that must be overcome. For instance, if the REV of Andosols would be several times bigger than the one considered until now (100 cm^3), further investigation should examine whether commonly applied laboratory methods can be accommodated to the analysis of larger soil samples.

Given that the evaporation method is not subject to the hydrostatic equilibrium issues identified for fine texture soils when using the pressure apparatus could be an indication that alternative approaches based on this principle could be considered in future studies. In this sense, options that are not based on the hydrostatic equilibrium principle—e.g., the HYPROP2 instrument (METER Group, 2015) based on the evaporation method (Schindler, 1980) for determining the wet range of the WRC and the WP4C Dewpoint PotentiaMeter device (METER Group, 2017) based on the chilled-mirror dew point technique (Gee, Campbell, Campbell, & Campbell, 1992) for the dry range of the curve—which have been used to determine the WRC of soils with different textural class and organic matter content (e.g., Bechtold et al., 2018; Schelle, Heise, Jänicke, & Durner, 2013; Shokrana & Ghane, 2020)—could also be worth evaluating in future comparative analyses. Lastly, our results clearly depict that for addressing this issue, the comparison between laboratory methods and experimental measurements in large soil cores or in situ (field) measurements is needed, as our extensive evaluation shows that the comparison between laboratory methods alone yields equivocal results.

Resolving the methodological issues is essential to produce reliable information that can be used to enhance the management and conservation of soil and water resources and to develop adaptation strategies in light of changes in climate and land use, so that a sustainable provision of ecosystem services in regions where Andosols are found can be maintained.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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