Original Research Paper

Formation of Post-Fire Water Repellent Layers on *Nothofagus glauca* (Hualo) Forests, After the Historical "Las Máquinas" Wildfire in South-Central Chile

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Abstract: The Chilean summer of 2017 was the worst wildfire season by far. Hundreds of wildfires burned a total of more than half a million hectares of forested land (native forests and forest plantations). A significant portion of the burned area was occupied by Hualo (*Nothofagus glauca* (Phil.) Krasser), a native forest species widely distributed in central Chile. Using the water-drop-penetration-time method, post-fire water repellency was evaluated at different depths (on the mineral soil surface and 5 mm below it) for a Hualo stand. Comparative data were obtained from a neighboring 11-year-old Monterrey pine (*Pinus radiata* D. Don) plantation. Both stands were located near Santa Olga, one of the towns that were totally consumed by the wildfire. A Chi-Square statistical analysis was used to determine significant differences among stands and soil depths. Results suggested that the abundant Hualo native forest species exhibited strong potentials to form fire-induced water repellent layers. Differences were mainly in depth between the two species. As wildfires in Chile are expected to increase in frequency and intensity, the authors strongly recommend post-fire flood control practices on Hualo-burned drainage areas located upstream from human settlements, as well as erosion and sediment control techniques to avoid post-fire desertification processes.

Keywords: Mediterranean Environments, Erosion Risk, Forest Firehidrofobicity, *Pinus radiata*

Introduction

Chile witnessed the worst wildfire season on record during the 2017's summer season. This catastrophic event originated from multiple ignitions at different locations within the south-central portion of the country. The origins of the wildfires were mostly intentional arson ignitions. All the ignitions had an area extent bigger than ever before, totaling a burned area of more than 600,000 ha. Such fire behavior was explained by the convergence of high wind speeds, extremely high temperatures (after several heat waves), low relative humidity in the air, topography difficult to access (mostly mountainous terrains) and an unusual pre-summer rainfall event that produced abundant fine fuels (Urrutia-Jalabert *et al.*, 2018). As a consequence, a total of 11 people died and thousands lost their homes, not to mention the millions of dollars cost of economic losses.

Considering all burnt areas, the "Las Máquinas" wildfire, which affected the Empedrado, Constitución and Cauquenes municipal districts (Maule Region) is considered the largest wildfire ever documented in

Chile's history, consuming 183,946 ha of Monterrey pine (*Pinus radiata* D. Don) commercial plantations and untouched Hualo (*Nothofagus glauca* (Phil.) Krasser) forests. Hualo is a native forest species very common in the region. These forests are distributed between latitudes 34°S and 37°S and can reach up to 30 m in height. The species seems to have some fire-resistance adaptations, such as self-pruning and exfoliating bark, similar to Ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) in North America (Fitzgerald, 2005). Located in Mediterranean climates (wet winters and dry summers), this *Nothofagus* species has the ability to resist long periods of draughts, which are the periods where wildfires could naturally occur, mainly from volcanic eruptions.

Chile is a country strongly affected by global warming (Quintana and Aceituno, 2011; Stolpe and Undurraga, 2016). As annual precipitation is expected to continue decreasing, becoming also more intense and concentrated in fewer storm events within a given year (Valdés-Pineda *et al.*, 2014), wildfire episodes in south-central Chile are expected to occur more often and with higher severities. As a consequence, it is important to understand the post-fire flood and desertification potential of Chilean ecosystems after the passage of wildfires. Post-fire water repellency (hydrophobicity) is the most relevant variable determining the hydrological effects of a burnt area (DeBan *et al.*, 1998; Garcia-Chevesich, 2005; Neary, 2009).

Water repellency is a physical property of soils that can be altered by fire, by which a soil infiltrates water slower than normal (DeBano, 1981; DeBan *et al.*, 1998; Letey *et al.*, 2000). Water repellent soils have been studied by many researchers and land managers around the world because of their potential negative impacts on the hydrologic cycle, especially on infiltration processes (DeBano, 2003), as previously mentioned. This discreet, invisible layer is created as a result of the accumulation of certain types of organic compounds that have not been decomposed into humus (Doerr and Cerda, 2005). In addition, heat produced during wildfires volatilizes organic compounds that either combust or migrate into the soil profile, resulting on a water-repellent layer at some depth parallel to the soil surface, or at the mineral soil surface (DeBano, 1981).

Though soil water repellency has been studied in Chile in the past (Ellies *et al.*, 2005; Cuevas, 2006), the only study in the country that considered fire as a formation factor for soil hydrophobicity was, to the extend of our knowledge, the one by Garcia-Chevesich *et al.* (2010) on Monterrey pine plantations near the town of Yungay. However, fire-induced water repellency potentials of Chilean native forest species are mostly unknown. The post-fire water repellency of Hualo, the most commonly found tree species in the region, was evaluated in this study.

Materials and Methods

The study area was located in the Justo Pastor León Experimental Station (Fig. 1), property of the University of Chile (Faculty of Forest Sciences and Nature Conservancy). The property is located one kilometer west of Santa Olga, one of the towns that were totally consumed by the wildfire, leaving more than 1,000 people homeless. The experimental station has an area of 392 ha and there are two main land uses in the area: Monterrey pine plantations and Hualo native forests. Severely burned stands of each species (Monterrey pine, site designation PINE; and Hualo, site designated HUALO) were randomly selected and an area of about 2,500 m^2 on each site was tested for water repellency, for each species. The two stands were located next to each other, belonging to the same geomorphological unit (one above a dirt road and the other one below it): North aspect, deep soils and metamorphic (schists) parent material. However, the Hualo stand was steeper (45% slope) than the Monterrey pine stand (15% slope). Five soil samples (down to 10 cm below the soil surface) were collected from each site and taken to the laboratory to determine the textural characteristics according to Bouyoucos hydrometer method (Day, 1965). Additional soil variables such as bulk Electric Conductivity (EC$_b$) and soil moisture content were evaluated by using a GS3 sensor connected to a Procheck portable recorder (Decagon Devices Inc., Pullman, WA).

The water-drop-penetration-time method (Wallis *et al.*, 1991; DeBan *et al.*, 1998; Letey *et al.*, 2000) was used to determine the degree of water repellency at the mineral soil surface (0 mm) and 5 mm below it. A drop of water was placed on the mineral soil surface (manually removing the remaining ashes, if any), documenting how long it took for the drop to infiltrate into the soil. The same criteria used by Garcia-Chevesich *et al.* (2010), was applied to determine the degree of water repellency (originally from the US National Wildfire Coordinating Group), i.e., *slight or null repellency* (the drop of water takes 10 sec or less to infiltrate), *moderate repellency* (between 10 and 40 sec) and *strong repellency* (more than 40 sec).

Data collected in the water repellency field tests were analyzed using the Chi-Square statistical test to identify significant differences among species and soil depths, considering a 10% level of significance. In addition to the above, a mini-disk infiltrometer was used to evaluate infiltration rates over the reminding ashes.
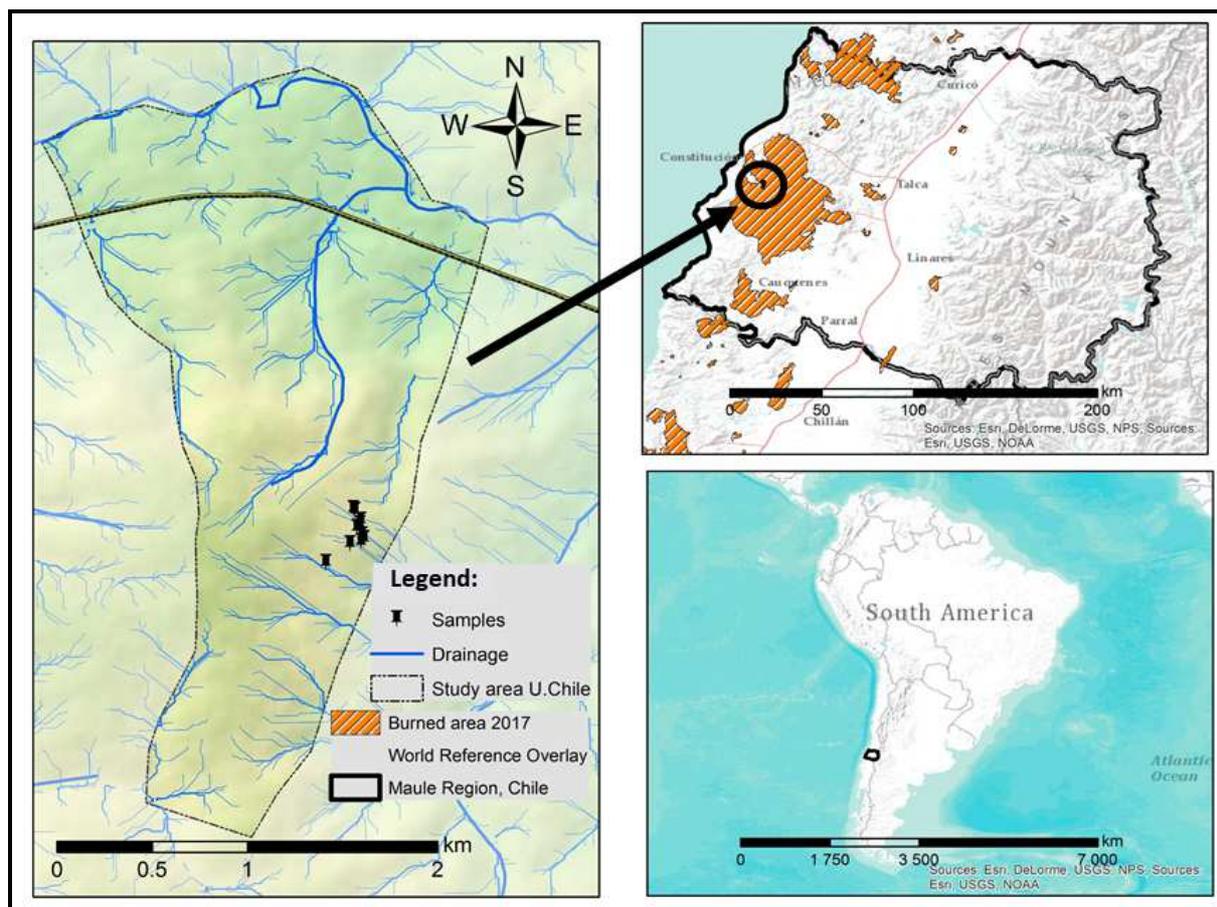
Fig. 1: Location of the study sites in the Justo Pastor León Research Station

Discussion

Soil textural analyses indicated the presence of clay-rich soils on both sites (Fig. 2). Though no significant differences were found on soil moisture (Fig. 3), The result obtained for bulk electrical conductivity were the same for both sites, near 0.0 dS m^{-1}, this is expected when soil water content is under $0.1 m^3 m^{-3}$ (Thring *et al.*, 2014) and reflects the limitations to assess the EC_b when the soil is closer to dry through dielectric methods like GS3 sensor.

Significant differences in post-fire water repellency were detected among stands and soil depths (Fig. 4). Results indicate that surface water repellency was evident on the Pine site, a layer over 5 mm deep at 50% of the study site, distributed over the terrain and not following any apparent pattern. However, the fire-induced hydrophobic layer was located below the soil surface on the Hualo site, with the presence of some permeable spots.

Steeper slopes (Hualo site) should result in the erosion of finer soil particles located on the surface, leading to a slightly coarser material on the soil-fire interacting range, compared to those from flatter areas

(Pine site). Similar to what Garcia-Chevesich *et al.* (2010) found on Chilean soils near Yungay (VIII Region), fine-textured surface soils from the PINE site probably prevented much of its volatilized water repellent substances from migrating very far below the surface during the fire (DeBano, 1981; Letey *et al.*, 2000). This was, not the case for the possible surface (first two millimeters) coarser soils of the Hualo site, if that was the case before the fire occurred. Since the HUALO site the one with the steepest terrain, it makes sense to assume that surface finer particles migrated downslope leaving the soil surface much coarser textured (Garcia-Chevesich, 2015).

Hydrologically, on the other hand, the position within the soil surface at both sites has different effects on a given drainage area. The presence of a surface water repellent layer (Pine site) has tremendous implications on runoff production. Considering the same return period for a storm occurring over an area, the magnitude of peak-flow rates after a wildfire can be hundreds of times higher than the ones generated before the burn, when vegetation covered the site (*e.g.*, DeBan *et al.*, 1998; Neary, 2009; Neary *et al.*, 2012). In

other words, a surface water repellent layer increases the risk of flooding events, putting in danger human lives and infrastructure.

In contrast to the above, having a fire-induced hydrophobic layer below-the-ground surface (Hualo site) has more implications for at least some runoff retention, though there is higher risk for the removal (erosion) of the surface soil horizon (Neary *et al.*, 2012). Loss of the surface "A" horizon that holds most of the nutrients in a form chemically available for plants has long-term implications for future site productivity (Garcia-Chevesich, 2015). Thus, eroding the surface portion of a soil can aggravate post-fire desertification processes, since the lack of nutrients and surface protection normally results from less vegetation cover, leading to more soil erosion later on.
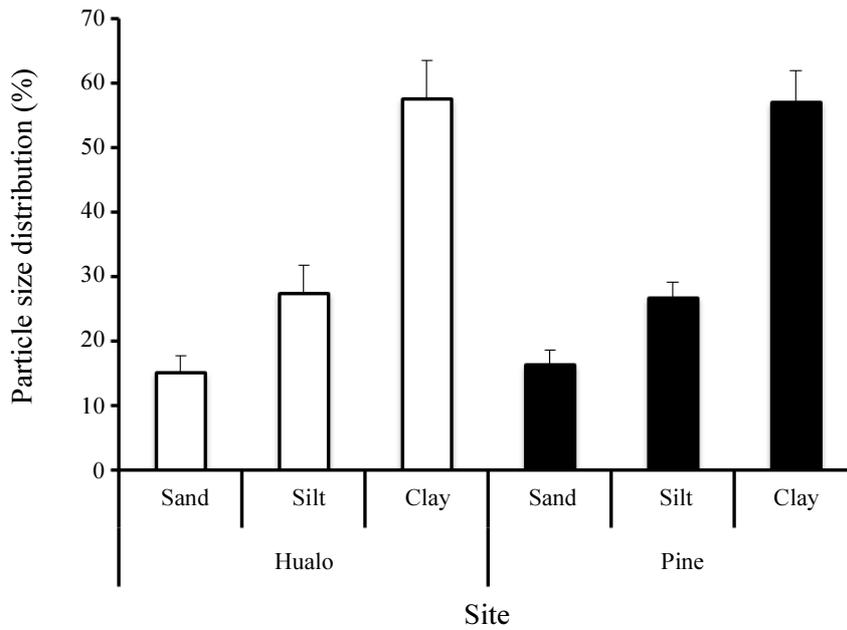
Fig. 2: Average and 90% confidence intervals of soil particle size distribution on both sites, in the first 10 cm depth
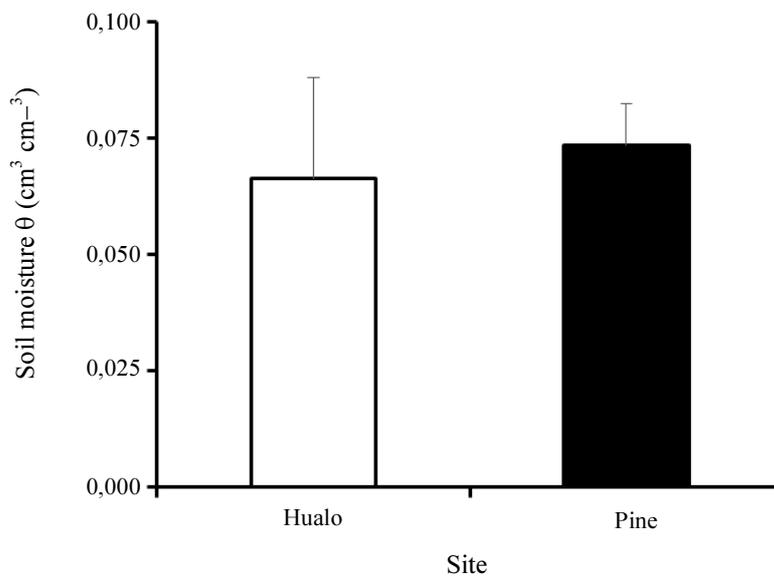
Fig. 3: Averages and 90% confidence intervals for volumetric soil water content (θ), on both sites
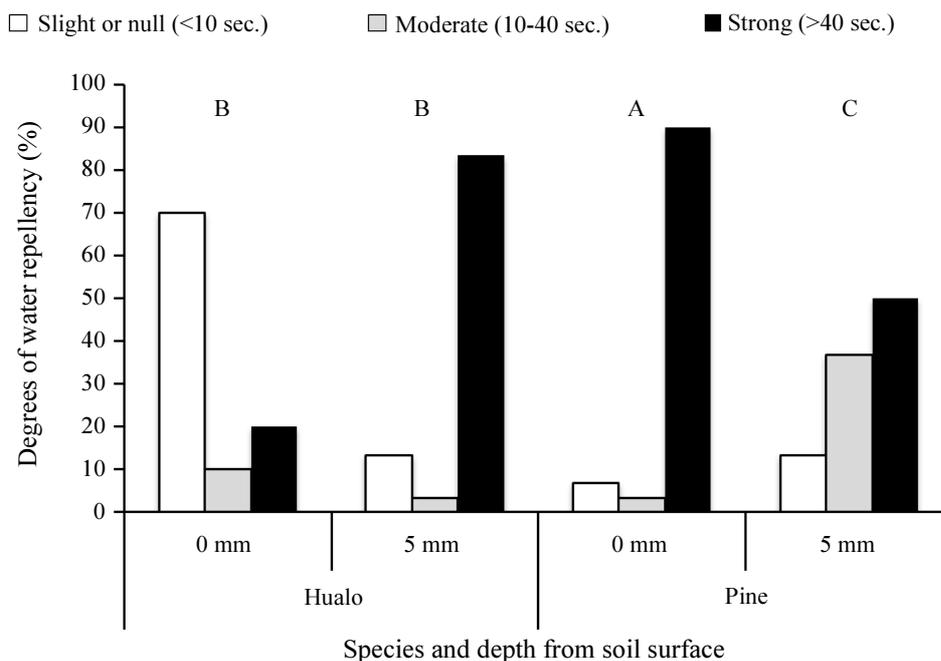
Fig. 4: Post-fire water repellency in the soil (%) relative to the depth of measurement and species, measured using the Water Drop Penetration Time (WDPT) method. Proportions within the graph followed by the same letter are not significantly different at the 0.10 level, evaluated using a Chi-square analysis

Results

The above analysis reflects the relevance and importance of post-fire mitigation activities, especially those related to the prevention of floods (Pine site) and desertification (Hualo site). In the United States, for example, there is the Burned Area Emergency Rehabilitation (BAER) Team, a branch of the US Forest Service that specializes in post-fire flood and erosion prevention. Immediately after a wildfire, or at least before the rains begin, the BAER Team analyzes the severity of a wildfire and tests, among other things, for hydrophobicity. Thus, flood control measures such as gabions or sand bags can be recommended for placement in strategic places, commonly near human settlements. Similarly, whenever necessary, mulching, hydroseeding, bioblankets, straw wattles, or any bioengineering or structural techniques are applied after wildfires to prevent excess of soil erosion. Normally, water repellency is eliminated either mechanically or by the use of wetting agents and the area is seeded (Robichaud *et al.*, 2000). Unfortunately, this is not the case for Chile's post-fire activities, which are more focused on labor-intense sediment traps such as check-dams and terracing, resulting on less effective and more expensive practices.

Conclusion

For the first time a Chilean forest species (*Nothofagus glauca*) is characterized in terms of its potential to form fire-induced water repellency. These results indicate that, just like *Pinus radiata*, the species has a high potential to form soil water repellency during wildfires. As wildfires in Chile are expected to increase in both, frequency and intensity, the authors strongly recommend the implementation of flood and desertification prevention measures after wildfires severely burn large drainage areas.

Acknowledgement

Dedication

To the 11 victims and thousands of people that lost their homes during the wildfires occurred on summer of 2017 in central Chile.

Author's Contributions

Pablo García-Chevesich conceived the acquisition of data in the field, designed and performed experiments analysed data and wrote the paper, discussed the results and implications and commented on the manuscript at all stages, approved the document and changes proposed by

pair reviewers. All authors contributed equally to this work in the acquisition of data, drafting the article for significant intellectual content and review and approval of the version to be submitted.

Ethics

There are no ethical issues associated with this research.

References

Cuevas, J., 2006. Efectos de la materia orgánica y el manejo sobre la hidrofobicidad de suelos volcánicos. R.C. Suelo y Nutrición Vegetal., 6: 13-27.

Day, P.R., 1965. Particle fractionation and Particle-Size Analysis. In: Methods of Soil Analysis, Black C.A. (Ed.), American Society of Agronomy, Madison, pp: 545-567.

DeBano, L.F., 1981. Water repellent soils: A state-of-the art. USDA Forest Service, General Technical Report PSW-46.

DeBano, L.F., 2003. The Role of Fire and Soil Heating on Water Repellency. In: Soil Water Repellency: Occurrence, Consequences and Amelioration, Ritsema, C.J. and L.W. Dekker (Eds.), Elsevier Science B. V. Amsterdam, The Netherlands, pp: 193-202.

DeBan, L.F., D.G. Neary and P.F. Ffolliott, 1998. Fire's Effects on Ecosystems. 1st Edn., John Wiley and Sons, New York, pp: 333.

Doerr, S.H. and A. Cerda, 2005. Fire effects on soil system functioning: New insights and future challenges. Int. J. Wildland Fire, 14: 339-342. DOI: 10.1071/WF05094

Ellies, A., C. Ramirez and R. MacDonald, 2005. Organic matter and wetting capacity distribution in aggregates of Chilean Soils. Catena, 59: 69-78. DOI: 10.1016/j.catena.2004.05.005

Fitzgerald, S.A., 2005. Fire ecology of ponderosa pine and the rebuilding of fire-resistant ponderosa pine ecosystems. USDA Forest Service, General Technical Report PSW-GTR, 198: 197-225.

Garcia-Chevesich, P., 2005. Changes on soil resources following the historical Rodeo-Chediski wildfire in Arizona. M.Sc. Thesis, University of Arizona.

Garcia-Chevesich, P., 2015. Erosion Control and Land Restoration. 1st Edn., Outskirts Press, Denver, CO., pp: 486.

Garcia-Chevesich, P., R. Pizarro, C.L. Stropki, P. Ramirez de Arellano and P.F. Ffolliott *et al*., 2010. Formation of post-fire water repellent layers in Monterrey pine (*Pinus radiata* D. Don) plantations in central Chile. J. Soil Sci. Plant Nutr., 10: 399-406. DOI: 10.4067/S0718-95162010000200001

Letey, J., M.L.K. Carrillo and X.P. Pang, 2000. Approaches to characterize the degree of water repellency. J. Hydrol. 231-232: 61-65. DOI: 10.1016/S0022-1694(00)00183-9

Neary, D.G., 2009. Post-wildland fire desertification: Can rehabilitation treatments make a difference? Fire Ecol., 5: 129-144. DOI: 10.4996/fireecology.0501129

Neary, D.G., K.A. Koestner, A. Youberg and P.E. Koestner, 2012. Post-fire rill and gully formation, Schultz Fire 2010, Arizona, USA. Geoderma, 191: 97-104. DOI: 10.1016/j.geoderma.2012.01.016

Quintana, J.M. and P. Aceituno, 2011. Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43° S. Atmósfera, 25: 1-22.

Robichaud, P., J. Beyers and D. Neary, 2000. Evaluating the effectiveness of post-fire rehabilitation treatments. General Technical Report RMRS-GTR-63. Fort Collins, USDA Forest Service, Rocky Mountain Research Station.

Stolpe, N. and P. Undurraga, 2016. Long term climatic trends in Chile and effects on soil moisture and temperature regimes. Chilean J. Agric. Res., 76: 487-496. DOI: 10.4067/S0718-58392016000400013

Thring, L.M., D. Boddice, N. Metje, G. Curioni and D.N. Chapman *et al*., 2014. Factors affecting soil permittivity and proposals to obtain gravimetric water content from time domain reflectometry measurements. Canad. Geotech. J., 51: 1303-1317. DOI: 10.1139/cgj-2013-0313

Urrutia-Jalabert, R., M.E. González, Á. González-Reyes, A. Lara and R. Garreaud, 2018. Climate variability and forest fires in central and south-central Chile. Ecosphere, 9: e02171-e02171. DOI: 10.1002/ecs2.2171

Valdés-Pineda, R., R. Pizarro, P. Garcia-Chevesich, J.B. Valdés and F. Pérez *et al*., 2014. Water governance in Chile: Availability, management and climate change. J. Hydrol., 519: 2538-2567. DOI: 10.1016/j.jhydrol.2014.04.016

Wallis, M.G., D.R. Scotter and D.J. Horne, 1991. An evaluation of the intrinsic sorptivity water repellent index on a range of New Zealand soils. Austral. J. Soil Res., 29: 353-362. DOI: 10.1071/SR9910353