LOCAL MANAGEMENT PRACTICES IN WATERSHEDS OF NORTHERN CHILOÉ ISLAND. INTEGRATING EFFECTS ON SOIL PHYSICAL PROPERTIES RELATED TO WATER STORAGE.

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A mis padres, por siempre apoyarme en mis travesías (locuras) sin condiciones.

A Belén y Bárbara, por ser el comité editorial de mi vida.

A Valentina, por ser mi cable a tierra.

Matías Guerrero Gatica es Biólogo de la P. Universidad Católica de Chile. Su afición por la naturaleza comienza desde niño, a través de su espíritu eminentemente libre. La pasión por la montaña, el mar o los bosques junto a la motivación entregada por su Profesor de Biología del colegio Raimapu conllevan a que inicie sus estudios en Biología y posteriormente Ecología.

Entre sus intereses está el entender el impacto humano en la naturaleza cómo el ser humano se relaciona con los ecosistemas locales. Mediante la investigación científica interdisciplinaria, pretende abordar estos problemas para superar la actual crisis ambiental que vive el planeta.

Su sueño: volver a reconectar a las personas y la naturaleza.

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RESUMEN

Una consecuencia importante del cambio global antropogénico es la modificación de la cobertura del suelo, impactando a la biodiversidad y la provisión de servicios ecosistémicos, como el suministro de agua dulce para consumo humano. Recientemente, la literatura científica que investiga las consecuencias del cambio global antropogénico se ha centrado en la relación entre los humanos y los ecosistemas. La incorporación de factores sociales en el estudio de las funciones ecológicas permite comprender mejor cómo los patrones de modificación de la tierra están influyendo en la provisión agua para los seres humanos en paisajes antropogénicos. Particularmente en el sur de Chile, la escasez de agua ejerció presión sobre las medidas para superar un problema extendido por más de 10 años. Aquí, examiné un subconjunto crítico de variables relacionadas con la tasa de infiltración del agua en el suelo, a fin de vincular el almacenamiento y suministro de agua, a escala local, con actividades antropogénicas en el paisaje. Para hacerlo, primero identifiqué el conjunto de prácticas de manejo realizadas en dos cuencas hidrográficas del norte de la isla de Chiloé que proporcionan agua a la ciudad de Ancud. Luego, analicé cómo afectan un conjunto de propiedades físicas del suelo relacionadas con el almacenamiento de agua del suelo. Se identificaron trece prácticas de manejo y cuatro de ellas fueron analizadas en términos de propiedades del suelo relacionadas con el almacenamiento de agua del suelo. Los análisis mostraron diferencias significativas entre las prácticas con respecto a las propiedades relacionadas con el almacenamiento de agua del suelo. Aquí, propongo un enfoque para mejorar nuestra comprensión del impacto de las prácticas de gestión en el paisaje a escala local de cuenca para mejorar el almacenamiento de agua en el suelo y la posterior provisión de agua.

ABSTRACT

A major consequence of anthropogenic global change is the modification of land cover, affecting biodiversity and the provision of ecosystem services, such as the supply of freshwater for human use. Recently, the scientific literature on the consequences of anthropogenic global change has focused on the relation between humans and ecosystems. The incorporation of social factors into the study of ecological functions makes it possible to better understand how patterns of land modification are influencing the regular provision of water for humans in anthropogenic landscapes. Particularly in southern Chile, water scarcity puts pressure on stakeholders to find measures to overcome a problem that has continued for over 10 years. Here, I examined a critical subset of the variables related to water infiltration rate in the soil, in order to link water storage and supply, at the local scale, with anthropogenic activities in the landscape. To do this, I first identified the set of management practices done in two catchments of northern Chiloé Island that provides water to the city of Ancud. Then, I analyzed how they affect a set of soil physical properties related to soil water storage. Thirteen management practices were identified and four of them were analyzed in terms of soil properties related to soil water storage. Analyses showed significant differences among the practices regarding properties related to soil water storage. Here, I propose an approach in order to improve our understanding of the impact of management practices on the landscape at catchment and local scales to improve soil water storage and subsequent water provision.

INTRODUCTION

A major consequence of anthropogenic global change is the modification of land cover caused by agriculture, forestry, cattle grazing, and other economic activities (Vitousek et al. 1986; Vitousek et al. 1997; Foley et al. 2005). The anthropogenic modification of land cover has captured between one-third and one-half of the earth's surface and productivity, modifying regional and global climate (Vitousek et al. 1997; Chase et al. 2000; Borrelli et al. 2017) and affecting biodiversity and the provision of ecosystem services, such as the supply of freshwater for human use (Meyer and Turner 1992; Defries et al. 2004; Foley et al. 2005). The effects of land cover change on water provision have complex physical and social-ecological drivers. Moreover, from the perspective of human well-being and the supply of ecosystem services, the reliable provision of water for human consumption is critical, because of projected increases in the number and distribution of human population, greater consumption rates, and land cover changes (Vorosmarty 2000; Foley et al. 2005).

In recent decades, the scientific literature on the consequences of anthropogenic global change has focused on the relation between humans and ecosystems (Berkes et al. 1998; Millennium Ecosystem Assessment 2005; Delgado et al. 2009; Hobbs et al. 2009; Díaz et al. 2015; Folke et al. 2016; Bennett et al. 2017; Pascual et al. 2017). Social-ecological factors such as local income, land ownership, expansion of urban areas, rural migrations, and cultural land use patterns and management actions have important consequences for water supply, which is the product of an ecological function that has been primarily understood from an ecological or climatic perspective (Crane 2010; Olabisi 2012). The incorporation of social factors into the study of ecological functions makes it possible to better understand how patterns of land modification are influencing the regular provision of water for humans in anthropogenic landscapes (Vitousek et al. 1997; Liu et al. 2007). In this study, I examined a critical subset of the variables related to water infiltration rate in the soil, in order to link water storage and supply, at the local scale, with anthropogenic activities in the landscape (Figure 1; modified from Ward and Trimble 2003).

Land modification, soil physical properties and water provision

Global change processes induced by human actions influence patterns of resource availability, particularly water. While some studies have documented how water supply has been affected by regional decreases in precipitation (Minetti and Vargas 1997; Curtis et al. 1998; Minetti et al. 2003), others have integrated the relative importance of soil processes and land use changes into their analysis (Bosch and Hewlett 1982; Calder et al. 1997; Chapin et al. 2002; Iroumé and Huber 2002; Brown et al. 2005; Farley et al. 2005; Buytaert et al. 2006; Huber et al. 2008; Dörner et al. 2010). Soil is the major water reservoir of terrestrial ecosystems. Soil changes affect the capacity of ecosystems to provide water because soil functions like a bucket that overflows when filled with rainwater. Precipitation is the major water input to terrestrial ecosystems, which can be stored in soil until it is saturated, becoming available for plant use. The evaporation of water from soils and the transpiration of water by plants (i.e. evapotranspiration) represent the most important outputs of water from ecosystems to the atmosphere (Chapin et al. 2002; Ward and Trimble, 2003). Once the soil becomes saturated, water can move below ground or, when the soil storage capacity is exceeded, water runs off over the soil surface, representing the second most important output of water from ecosystems (Chapin et al. 2002; Ward and Trimble, 2003). Run-off represents the amount of water that was not transferred to the atmosphere through evapotranspiration (Chapin et al. 2002). The modification of land cover by humans has long-term effects on these ecosystem processes. For example, watersheds that lose forest cover show an increase in run-off and a decrease in water provision due to their lower capacity to store water. The storage of water by soils can act as a buffer, providing water to streams and rivers even when precipitation is low or absent (Trimble and Weirich 1987; Chapin et al. 2002). Thus, regions that lose forest cover are subjected to greater water run-off and, by contrast, regions that gain forest cover have lower run-off due to water infiltration in the soil (Trimble and Weirich 1987).

Evidence indicates that timber plantations in south-central Chile can have negative effects on the provision of water to rural communities because of large transpiration losses (Little et al. 2009). Ecosystems, such as wetlands and forests contribute to hydrological regulation, by providing a relatively constant supply of good-quality water (Trimble and Weirich 1987). Rivers and streams are the receptors of these fluxes, which are especially relevant during the dry seasons or periods of declining rainfall (Buytaert et al. 2006; Díaz et al. 2008; Lara et al. 2009).

Soil water storage is a critical ecosystem property that regulates water provision. The overall amount of soil water storage represents a small quantity compared to other earth's reservoirs. Only 0.1% of the total pool of freshwater is stored in terrestrial ecosystems (Lal and Shukla 2004), where storage is dominated by snow and ice. However, soil water is the main source of freshwater for people in areas where snowmelt does not directly influence watershed drainage. In magnitude, water stored in soils globally accounts for 67,000 km^3, which is approximately 50 times the water transported by all rivers and streams (Lal and Shukla 2004). Understanding key physical properties of soils is essential to better understand how anthropogenic activities affect soil water storage.

One of the first processes regulating soil water storage is water infiltration into the soil**.** Infiltration is the incorporation of water derived from the air-soil interface into the soil, via pores or open spaces between soil particles (Chapin et al. 2002; Lal and Shukla 2004; Weil and Brady 2016). Thus, infiltration is an essential process to begin to understand soil water storage. Maintaining high infiltration rates is usually encouraged in soil and water management practices. Infiltration rate is strongly dependent on vegetation cover. Plant cover creates channels in the soil due to root growth, directly beneath the plant, encourages earthworm activity, enhances organic matter accumulation, and protects soil surface structure (Chapin et al. 2002; Ward and Trimble 2003; Weil and Brady 2016), all of which enhance water infiltration. At the watershed scale, vegetation cover is a critical variable related to water storage and supply (Oyarzún et al. 2011). In my study, I assessed how the infiltration rate is affected by management practices, expressed in the modification of other critical soil factors related to soil water storage (Figure 1).

Among the main factors influencing infiltration rates, soil water absorption depends on the previous soil moisture content (i.e. the moisture content stored in the soil profile before the rainfall or irrigation event; Weil and Brady 2016). Low soil moisture content will tend to attract water into the soil. However, when the soil is saturated with rainfall, fewer pore spaces will be available for absorption, resulting in the loss of water via runoff (Blanco and Lal 2008). Another relevant factor is soil compaction, a condition produced by human activities on the soil surface, which determines how much water can enter the subsoil. For example, in a compacted soil, water infiltration and its subsequent movement downward in the soil profile will be restricted, leading to greater runoff (Blanco and Lal 2008). Non-compacted and unstructured soils stimulate infiltration rate and water storage in the soil profile (Chapin et al. 2002).

Once water enters the soil, properties of the soil profile will determine its lateral or vertical movement. Anthropogenic actions in the landscape can generate effects in the capacity of soils to store water. For example, fire impact tends to eliminate organic matter, affecting soil physical properties such as porosity and hydraulic conductivity. As a consequence of the loss of the surface layer of soil, soil depth (Certini 2005) and the capacity of soils to store water is reduced (Boyer and Miller 1994; Fayos 1997), therefore increasing both runoff and erosion (Martin and Moody 2001). In southern Chile, the large-scale use of fire by humans (indigenous people and European settlers) resulted in the significant loss of surface soil layers (Holz and Veblen 2011). Consequently, soil depth is a key soil property related to water storage and provides evidence of the recent history of land use impacts.

Human impact on soil water storage through the analysis of management practices

With the aim of integrating the human-nature relationship into the analysis of water supply and soil water storage in this area of Chile, I addressed the management practices and how they affect functions related to water storage (Berkes et al. 2003; Mascia et al. 2003; Newing et al. 2011; Mace 2014; Bennett et al. 2016; Bennett et al. 2017; Spalding et al. 2017; Sutherland et al. 2018; Teel et al. 2018). Emphasis must be placed on anthropogenic actions that ultimately determine water storage in soils (Mace 2014; Bennett et al. 2017; Spalding et al. 2017; Sutherland et al. 2018).

The first step in the analysis presented here was to identify the set of actions by the local community that have potential impacts on soil water infiltration and storage. I used the concept of management practices as a tool to integrate ecosystem properties and land modifications due to human actions (Fischer et al. 2015; Bennett et al. 2017; Spalding et al. 2017).

The concept of management practices expands on the biophysical aspects comprised by land use and land cover (LULC) analysis, adding the anthropogenic component to the study of soil-water connections. Di Gregorio (2016) defines land cover as the biophysical coverage of the earth’s surface. Land use is defined as the particular way in which people or societies use and administer the land (FAO 2000). Generally, LULC changes are addressed at large spatial scales through the inspection of satellite images, defined by categories of photosynthetic reflectance, or other properties, to then use informatics tools related to geographic information systems (GIS) to produce a spatial classifications (Lambin et al. 2001; Echeverría et al. 2006; Zhao et al. 2016). LULC approaches do not consider the specific human actions done within a LULC type and their local-scale impacts on ecological processes such as soil water storage (Newing et al. 2011; Mace 2014; Bennett et al. 2016; Spalding et al. 2017).

The management practices concept generally refers to human actions done with the specific objective of changing the landscape, regardless of whether they are originated from engineering, urban or agricultural management. The US Clean Water Act of 1972 is one of the documents that introduced a related concept, the “Best Management Practices” (BMP) as a response to the need to control pollutants in water (Weightmann 1996; D’Arcy and Frost 2001).-Feather and Amacher (1994), in the context of a program developed by the United States Department of Agriculture (USDA), extended the concept of BMPs to farming. Then, BMPs are defined (Feather and Amacher, 1994) as “an agronomically sound practice that protects or enhances water quality and are at least as profitable as existing practices”. Feather and Amacher (1994) propose in their study BMPs such as split application of nitrogen, irrigation scheduling or deep soil nitrate nesting. The original categories of BMPs do not emerge from direct perceptions of local people.

I propose that management practices in the context of the research question of this thesis should consider the views and perceptions of rural people about their use of the landscape. The analysis should contemplate perspectives emerged from land users, through mixed-methods approaches.

I define management practice as an activity done by rural landowners in the landscape with a specific temporal and spatial dynamic and with a specific method or technique determined by the local culture or local economy. The management practices developed by rural communities will affect biophysical factors that ultimately could change soil water storage and availability. A management practice results from rational and non-rational decisions by land users. In this study, I analyzed how particular management practices influence factors related to soil water storage in rural Chiloé. To understand the impacts of management practices on soil water storage will add information at local-scale that is not evident from the classical perspective of LULC. Generally, studies using the LULC perspective are based on satellite images with limited or no information about on-the-ground aspects such as social-ecological dynamics. Here, through interviews with local landowners, I analyzed how they identify and describe their activities in the field as a way of assessing their impact on variables influencing soil water storage.

One approach used by ecosystem scientists to assess human impacts on the water cycle at the landscape scale, is the watershed approach (Likens 2001; Chapin et al. 2002; Neary et al. 2009; Likens 2013). A watershed is defined as the area drained by a stream, river or lake that goes to a unique exit for runoff (Chapin et al. 2002). The area of a watershed can be easily delimited, using topographic measurements, and the watershed unit provides a spatially-explicit and useful model to assess the internal flows of matter and energy in an ecosystem and the exchanges with its surroundings (e.g. (Delgado et al. 2013). In this way, changes in land cover, and past and current management practices, within the target area could be spatially integrated and their consequences evaluated.

Regional and local context for water provision and soil water storage in northern Chiloé

Because of its climatic heterogeneity, Chile presents contrasting scenarios of freshwater inputs, outputs, storage and human use. The Región de los Lagos has an average rainfall of around 2 thousand mm per year. Despite abundant rainfall, water scarcity affects large areas of south-central Chile, particularly rural areas of northern Chiloé Island (Frene et al, 2014). It is projected that, under climate change, this condition of water scarcity will become more intense over most of south-central Chile (CR2 2015) due in part to declining precipitation. However, precipitation trends for the city of Puerto Montt, directly north of Chiloé Island, showed no change since 1977 and the city of Ancud (Chiloé) shows no change since 1993 (data extracted from DGA, 2018; Figure 2 and Table 1).

Another possible explanation for the current water scarcity in rural areas has emerged through the analysis of LULC changes and reductions in areas of native forest in south-central Chile, especially over the past 30 years due to institutional stimuli such as the D.L. 701, a state forest subvention (Huber et al. 1998; Echeverría et al. 2006; Huber et al. 2008; Lara et al. 2009; Little et al. 2009; Huber et al. 2010; Miranda et al. 2015; Miranda et al. 2016). The LULC scenario is critical in island regions, such as Chiloé, where the only reservoirs of water are the soils of native forests and peatlands, because there is no water storage in the form of ice or snow. Water scarcity in rural areas of central and northern Chiloé island have been documented for more than 10 years (Frene et al. 2014). The Municipality of Ancud has implemented a network for water delivery to rural places affected by water shortage, primarily during the summer. Annual expenses to provide access to clean water using cistern trucks has increased from USD 30,000 in 2013 to more than USD 250,000 in 2015 (Norambuena 2015).

In the Municipality of Ancud, Chiloé, where water availability is seasonally limited, one of the strategic areas to assess water supply for human use is the locality of Lajas Blancas. Lajas Blancas includes the catchments of Quilahuilque (246 hectares) and Mechaico (1,448 hectares), both of which provide water to the city of Ancud from local dams (Figure 3). The locality of Lajas Blancas has gained greater attention from the local community and has been the site of several interventions that aim to enhance agricultural production, and more recently, to regulate water provision. Previous work has considered the possible application of the concept of Payment for Ecosystem Services (PES; Cabrera and Rojas 2009), an initiative led by the Forest Institute (INFOR). The study cited above concluded that it could be feasible to implement a PES and suggested better land managements in the Mechaico catchment to improve water provision. There is a lack of quantitative data about management practices in use by local inhabitants of these two strategic catchments and their relationship with soil water supply and storage.

Objectives

Considering the need for better understanding the relation between local management practices and factors affecting soil water storage and availability in these two catchments, which can become models for northern Chiloé Island, the objectives of the present thesis were:

- To identify and quantify the frequency of different management practices currently used by people in the catchments of Quilahuilque and Mechaico, which are locally important for determining the water supply for human use.
- To assess the anthropogenic effect on soil water availability through the analysis of the relationship between current management practices and the factors that influence water infiltration and storage. Specifically, I measured soil moisture content, soil compaction and soil depth as factors affecting infiltration rate, which was also measured.
- To explore a conceptual model integrating the different local management practices and their impacts on water infiltration rates in soils, and use this model to make recommendations to enhance soil water storage capacity and water delivery for human use.

My study assumes that the local community has developed a clear set of recognizable or simply defined management practices through their socio-economic activities on the land that could be identified from interviews in the field. Additionally, I expect that the local management practices would have different implications for the factors related to soil water storage

METHODOLOGY

Research site

The study area includes two catchments: Mechaico (41º55’21’’S-73º50’27’’W) and Quilahuilque (41º55’03’’S-73º50’27’’W), which are located in the rural sector of Lajas Blancas, municipality of Ancud, Chiloé Island (Figure 3). The larger Mechaico catchment has a total area of 14,48 km^2, while the smaller Quilahuilque catchment has a total area of 2,46 Km^2. Lajas Blancas currently maintains two water catchment pumps, controlled by the local private sanitary provider ESSAL that supplies drinking water to the city of Ancud: one in Mechaico and the other one in Quilahuilque (Figure 3). Further, a third water catchment pump was installed in the higher part of the Mechaico catchment in 2013. The purpose of this water pump is to supply of drinking water to the rural community of Lajas Blancas (Figure 3). Unlike the water supplied to the city of Ancud, which receives a cleaning and filtering treatment, no water cleaning and filtering treatment of drinking water is applied in the catchment that supply water for local people.

The vegetation in the study area is dominated by southern temperate, broad-leaved, evergreen forests (Armesto et al. 1996; Smith-Ramírez 2004, Martínez-Tileria et al. 2017). These forests are included in the Valdivian forest ecoregion, recognized as a global biodiversity hotspot (Arroyo et al. 2004). The rural locality of Lajas Blancas, where the two catchments are located, is inhabited by 74 people, while the city of Ancud is inhabited by 28,123 people (Instituto Nacional de Estadistica 2017). The main land-based socio-economic activities of Lajas Blancas include non-irrigated agriculture (mainly potatoes, peas, broad beans, carrots, raspberries, lettuces, coriander), cattle and sheep raising, and the extraction of timber and firewood. There is a limited area occupied by plantations of exotic timber trees (mainly *Eucalyptus sp.;* Appendix 1).

The proportion of the main types of land cover in Mechaico and Quilahuilque watersheds are summarized in Appendix 1. The land cover in these two catchments was dominated by mature broad-leaved evergreen forests (34.4% in Mechaico and 47.5% for Quilahuilque), followed by secondary native forest (33,8% for Mechaico and 29,1% for Quilahuilque) and anthropogenic grazing pastures (21,4% for Mechaico and 18,3% for Quilahuilque).

Based on the soil series described at the study site (CIREN 2003), I examined broad differences in soil physical conditions over which anthropogenic activities are overlaid. According to the data from CIREN (2003) I discarded potential differences in soil types and conditions related to soil water storage due to geological substrate.

Mechaico soil was the only soil series described for the entire study area. The Mechaico soil series is part of the family of Andsol soils (nomenclature used by the United States Department of Agriculture, USDA), thus derived from volcanic ejecta (such as ash, pumish, cinders and lava) and/or volcanistic materials. The dominant processes in most andisols are weathering and mineral transformation (USDA 1999).

Mechaico soils series are moderately deep, (average 90 cm) subjected to light erosion. This geological process gives the appearance of soft rolling hills and flat terraces with abrupt slopes towards streams and ravines of hills, generally, between 30% and 50%. These terraces are presented between 100 m and 180 m high and are derived probably from fluvioglacial processes (Hinojosa and Villagrán, 1997). Nevertheless, their Soil drainage is good and only flat areas have a moderate to imperfect drainage (CIREN 2003).

Identification of management practices

The first approach to understand basic social configuration of the study site was based on interviews of members of the Association of Forest Engineers for the Native Forest (AIFBN).Two in-depth interviews were conducted with two officials of AIFBN in order to understand the main initiatives of territorial planning related to alleviate water shortage issues, understand the social and local institutional arrangement, and to obtain the names of some key informants from the local community.

The first set of preliminary unstructured interviews supported the elaboration of semi-structured open-ended interviews following the free-listing method (Ryan et al. 2000; Newing et al. 2011; details of the interviews described in Appendix 2). Fieldwork was conducted in August 2016 (two weeks) and January, 2017 (two weeks), implying approximately four weeks of presence in the community of Lajas Blancas and a total of 12 field visits, which included between 1-3 house visits to interview participants. Snowballing or respondent-driven sampling was used to contact and interview local inhabitants, obtaining their recommendations for additional persons to be interviewed (Goodman 1961).

The goal of the semi-structured interviews was to identify and obtain a better description of direct management practices currently applied in the two catchments by the rural community and potentially affecting soil physical state. Consequently, the types of management practices analyzed in this study were compiled from the perceptions and actions of local inhabitants described in the interviews. The questionnaire included four groups of questions: (1) personal data and information on property size and ownership; (2) economic or subsistence activities based on the land in the catchments, including spatial and temporal dynamics of landowners' activities; (3) frequency or recurrence of management practices to carry out economic or subsistence activities across the years, and changes in land management practices over the past 10 years, and; (4) landowners' understanding of the implications of direct management practices for water availability in the two catchments. The number of people interviewed followed the principle of saturation, which limited the interviews when new data did not provide additional information relevant to the research question (Glaser and Strauss 1967; Newing et al. 2011; Bryman 2016).

In the round of semi-structured interviews, a total of 20 household heads were surveyed (15 men and 5 women). Their ages ranged from 24 to 98 years old, with an average of 59. They were residents of the rural locality of Lajas Blancas. Interviews lasted between 17 minutes and 1 hour 19 minutes (average = 30 minutes). Considering an average of 2,2 persons per household (Instituto Nacional de Estadística, 2017), and the 74 people that live in Lajas Blancas (Instituto Nacional de Estadistica 2017), interviews covered 59,5% of the people of Lajas Blancas. To analyze the semi-structured interviews and identify the main land management practices that could potentially affect soils and water infiltration rates that were described by local inhabitants, I used the Deedose program of discourse analysis (Lieber and Weisner 2013).

Analysis of soil physical factors related to soil water storage within management units

According to the land management practices within the watersheds defined through the interviews, I selected the rural management units, i.e. subjected to the same practices, where the soil physical factors related to soil water storage were measured: infiltration rate, soil moisture, soil depth and compaction. I used the following criteria to define the management practice units where the soil physical properties were measured:

1. The same management practices were applied to the land by 25% or more of people interviewed and,

2. The management practices were applied in the three main land cover/land uses: mature forest, secondary forest and prairies (Appendix 1)

Given these criteria, four different management practice units were sampled in both catchments (Table 2). Within each land unit defined by the application of a given management practice, I sampled six sites and three sub-samples per site. First, the six sites were selected with the supervision of the landowner to restrict the analysis to representative sites with specific management practices. Within the same managed land unit, three random subsites were selected (Figure 3). In each subsite, three subsamples were taken (separated by less than 2 m), and three critical factors related to soil water storage were measured: (1) soil compaction, measured with a soil compaction meter (Hand penetrometer, Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) at 10 cm and 20 cm of soil depth, as deep soils could be affected by management practices aboveground (Bachmann et al. 2006). The soil compaction meter was introduced in two points: in the first point it was introduced at a depth of 10 cm; in the second point, 10 cm apart from the first point, the same instrument was introduced at a depth of 20 cm; (2) soil depth, measured with a soil gouge auger (Eijkelkamp) with 100 cm of operational length and 30 mm of diameter and (3) water infiltration rate measured with a mini-disk portable infiltrometer (Mini-disk Infiltrometer DECAGON Devices). Additionally, soil moisture content (%) was measured using a digital soil moisture meter model EXTECH MO750. The measures were made at a soil depth of 10 cm. Data were obtained between 18 and 24 April 2017. Each of the six sampling sites was georeferenced (Figure 3). All the points sampled were on flat terrains with =<1% of slope.

Statistical Analyses

Factors related to soil water storage in each management practices unit defined were primarily analyzed through Principal Component Analysis (PCA) using the Past Program (v. 2.17c; Hammer et al. 2001). The PCA was conducted to analyze general patterns of the factors related to soil water storage according to the different management practices where soils were extracted as well to summarize information emerged from the factors related to soil water storage (Quinn and Keough 2002). To analyze variables that could explain differences in infiltration rate, a linear model was conducted through the R Studio statistical program (R studio v. 1.0.143) with the factors related to soil water storage and management practices as explanatory variables. Further, one-way ANOVA was performed through the R Studio statistical program (R studio v. 1.0.143) to analyze how each of the soil physical properties measured related to soil water storage is affected by the four management practices analyzed.

RESULTS

Identification of local management practices in the two catchments

A total of 13 management practices currently in use were identified by the people interviewed in the two catchments of Mechaico and Quilahuilque (Table 2). Accumulation curve of management practices per interviewee was saturated at the interview number 8 (Figure 4). Additionally, the percentage of the 13 management practices used by the people interviewed varied from 85% to 5% (Table 2). The most common management practice was “extraction of native firewood and timber for self-consumption”, practiced by 85% of the households (17 people) which includes the use of native forest for firewood and timber for building among other uses. “Managed livestock farming” was the second most frequent practice, applied by 60% of the households (12 people), a practice of raising livestock in enclosed pastures. The “forest conservation” management practice, which consists of conservation of remnant forest in a no-take area,which yields no direct economic income, was cited by 10 landowners, occupying the third place in overall frequency.

The main management practices that were most frequent among the households interviewed (recorded 37 times, Table 2) in the two watersheds of Lajas Blancas were forest and timber harvest practices (extraction of native firewood and timber for self-consumption, forest conservation, exotic plantations and plantation of native trees),. Raising livestock (the categories of managed and unmanaged livestock farming) was the second most frequent practices conducted by this rural community (recorded 18 times; Table 2). Agricultural practices (the categories of farm products for self-consumption, farm products for sale, and permaculture and organic agriculture) was third most frequent (recorded 14 times). It is important to note that four out of the 12 people who practiced managed livestock farming reported switching to unmanaged livestock farming in winter.

A special case of management practice was extraction of native firewood and timber for sale. Preliminary evidence was gathered about the presence of this practice, reported to be carried out without a formal management plan approved by CONAF. In other words, this practice is carried out illegally, making it difficult to gather evidence of its frequency due to the disincentives to landowners to indicate where it is practiced.

Past information for the study area

Concerning changes in management practices 10 years ago, past management practices cited by the interviews were the use of fire to open forested areas for farming (a practice used since the arrival of the first settlers in 1898), wood extraction for the production of coal, and clearing forests for planting potato crops. These practices are not used today by any of landowners according to the interviews. Current management practices are not different from those used 10 years ago, except for permaculture and organic agriculture, and low-impact tourism, which have been recently introduced to the study site.

Selection of management practices influencing soil water storage

Out of the 13 management practices identified by landowners, only four were selected by applying the criteria established earlier, that is, practices carried out by 25% of people or more and practices carried out in both of the catchments.

- Extraction of native firewood and timber for self-consumption
- Managed livestock farming
- Unmanaged livestock farming

- Forest conservation

The criteria separating the practices of managed livestock farming (reported 13 times, 65% of interviewees) and unmanaged livestock farming free roaming in the woods (reported 5 times, 25% of interviewees) was that people interviewed declared the use of enclosures for controlling the movement of managed livestock. Concerning managed livestock farming, for example, interviewee 20 stated:

"Algunos potreros son más grandes y otros son más chicos. Eh… en la noche les voy dando a las vacas más controladas. En el día andan más sueltas (…) algunos potreros son de 4-5 hectáreas. En la noche ya se los mermo, es un cuarto de hectárea (Some enclosures are big and others are smaller. In the night I give the cows (grass) [in a] more regulated [way]. In the day they move around freely (…) some pastures are of 4-5 hectares. In the night, I reduce the space to a quarter of a hectare)".

The interviewee 8 stated along the same lines that:

"Los potreros son del día no más. Lo ideal pa' lechear es de todos los días… las vacas les gusta comer pastito fresco (…) entonces ojalá tener unos 20 potreros entonces 20 días atrás pasó y ya en el primero está el pasto verde ya. (The enclosures are only for one day. The ideal for milking is to move the cows each day. The cows like the fresh grass (…), so ideally you must have a 20 enclosures, so 20 days later the cows are in the first one where the grass is green again)".

Unmanaged livestock farming is based on an extensive use of land, without rotation of grazing areas. This management practice uses pastures, forest and scrubland cover. Enclosures for management are not used. In the winter, several farmers used the nearby forest as a “barn” to protect livestock from cold and provide them with food from the forest understory, mainly native bamboo (*Chusquea sp*.). For example, interviewee 16 stated that:

“las vacas… duermen ahí, acampan ahí. Si no hubiera monte las vacas en el invierno andan todas cucurrucas (the cows in the woodland sleep there, camp out there. If I would have not have woodland, the cows in the winter would be weak)”

Extraction of native firewood and timber for self-consumption was cited by the majority of people (85% of the number interviewed) and household use this as a source of energy for cooking and heating and for building fences, among others. People declared that timber and firewood extraction were mainly through the collection of fallen branches and trunks. For example, interviewed 1 stated:

“Cuando hay palos que se cayeron, se quebraron o están demasiado picados arriba, secos, que no tienen ningún valor se botan para hacerlo leña para la casa. (When there are fallen branches on the ground, broken or damaged at the top, dry, that have no value, they are thrown together to make firewood for the house.)”

Finally, the management practice called forest conservation refers to landowners leaving a specific portion of their surrounding native forest as a non-harvest zone. Landowners explained why they wish to maintain a portion of their forestland relatively undisturbed. The reasons range from conservation ideals, topographic or access reasons and fear of inspections against unregulated management by the forest service. For example, interviewee 2 expressed:

“Algún día puede ser [cortar el monte que no se ha talado] pero serán los renuevos, nosotros quedaremos ya... Quedará pa’ los que vienen de atrás (*Someday it may happen [cutting the* *woodlands that have not been cut down], but it will be the new trees, we will have passed away. It will be for the people that comes behind)*”

The interviewee 6 stated geographical reasons to avoid extracting wood from its forest. To the question “Do you extract native wood from your fields?” the interviewee stated:

“Un poco como, un poco laderazo el campo, entonces uno no puede traer madera hacia acá, porque hay justo una, muy quebrao’ acá, así el campo, es muy quebrao” (Some… my land has a lot of slope, so one cannot get the wood over here, because it is just… there are lots of ravines, the country is that way, with lots of ravines.)”.

Other landowners expressed especial concern for the maintenance of forest cover near rivers, as logging in riparian areas is specifically prohibited by the current native forest law (CONAF 2016).

The frequency of native wood extraction for sale could not be quantified due to the difficulty in gathering this information. Some landowners that conducted these harvesting practices did not declare them because of the risk of being fined by the authority. Consequently, the impacts on soil water storage of this management practice generally remained underestimated.

Analysis of factors influencing soil water storage within management units

The factors related to soil water storage sampled in this thesis were infiltration rate, soil moisture contents, soil depth, and soil compaction at 10 and 20 cm deep. Data from each management practice for all the variables were analyzed through a PCA. The analysis includes the soil physical variables (soil compaction, soil moisture, soil depth and infiltration rate) separated by management practices (Figure 5). The two main principal components explained 66,8% of data variability for the four soil physical properties analyzed, confirmed by the eigenvalues (Table 3). The analysis inside the PC1 through the loadings components showed that the group structure is explained by soil compaction at 10 and at 20 cm and by infiltration rate while the differences in the PC2 were explained by soil depth and soil moisture (Table 4).

In the PCA, the sampling points corresponding to the forest conservation practice (enclosed by the green line), and the sites used for unmanaged livestock (enclosed by the red line) are separated along the principal component 1 (45,13% of variance; Table 3 and Figure 5). The first axis (PC1) did not clearly separate the two management practices of extraction of native firewood and timber for self-consumption (yellow line) and managed livestock within grazing pastures (blue line). Concerning the principal component 2, the management practices formed only one group.

Additionally, a linear model was conducted to explore how the infiltration rate is affected by soil compaction, soil depth, soil moisture and management practices (Table 1). Analyses showed that water infiltration rate varied significantly in relation to two variables: the management practice of forest conservation and the soil depth. The best model (highest overall R^2, lowest p value) is shown in Table 5.

To clarify the differences among management practices, ANOVA were carried out on each of the five soil factors measured related to soil water storage. Concerning the Infiltration rate, significant differences were found ($p = 0,002$; $F = 7,2$; DF: 3). An *a posteriori* Tukey's test demonstrated a significant difference between the forest conservation practice (land covered by no-take forest) versus all the other management practices ($p < 0,05$; Figure 6A). Soil depth had no significant differences among management practices ($p = 0,634$; $F = 0,581$;DF: 3 Figure 6B). When comparing current soil moisture among management practices there were no significant differences (p = 0,19; F = 1,744; DF: 3; Figure 6C). In contrast, there were significant differences among management practices regarding the condition of soil compaction at 10 cm (p = 0,02; F = 4,118; DF:3; Figure 6D), and at 20 cm of soil depth (p = 0,019; F= 4,185; DF: 3; Figure 6E). In both cases, the Tukey's test revealed statistical differences between unmanaged livestock (areas with free-ranging livestock) and forest conservation (no-take forest conservation areas; Figure 6D and 6E).

DISCUSSION

Identification of management practices in the two catchments

In this study, the first objective was to identify management practices currently in use by landowners in the two catchments, Mechaico and Quilahuilque, as a means of subsistence and benefiting from the land. These practices could potentially affect the delivery of clean water by the ecological systems in the watersheds (Nuñez et al, 2006).

Before identifying the management practices, a necessary step was to define management practice as a working concept. In this thesis, I included the perspectives of local inhabitants regarding their use of the land through personal interviews. The approach goes in line with the novel proposal to explore human-nature relations about water availability (Folke et al. 2002; Neary et al. 2009; Newing et al. 2011; Mace 2014). There is a potential to complement the information emerged from other analyses, such as LULC data (Overmars and Verburg 2005). Additionally, although the dominant land cover type for both Mechaico (34,4%) and Quilahuilque catchments (47,5%) was mature native forest (CONAF and UACH 2014 and Appendix 1), the condition of the native forest has been changed or degraded by past land uses in the zone, which highlights the importance of analyzing management practices at local scale within the land cover types to gain a better understanding of the land condition.

According to the interviews, the main management practices used by the rural community in the area are related mainly to: 1) the forest cover (extraction of native firewood and timber for self-consumption, forest conservation or no-take areas, exotic plantations and plantation of native trees) and 2) livestock raising, including cattle and sheep (managed livestock within grazing pastures, unmanaged free-ranging livestock). These two major areas of economic activity are essential to address questions about soil water storage at the local and watershed scales. While the present thesis did not analyze the relation between soil water storage and LULC patterns, the extraction of native firewood and timber for self-consumption and the potential replacement of native forest by exotic plantations as a new management practice and economic activity are relevant in terms of their different consequences for soil water storage in the two catchments. While both can have consequences on soil water storage, the replacement of primary or secondary forest in favor of fast-growing exotic plantations has shown the more serious consequences for soil water storage and subsequent provision (Lara and Veblen, 1993; Nuñez et al, 2006; Oyarzún et al, 2011). The practice of leaving no-take areas devoted to forest conservation can have direct positive effects to soil water storage since it maintains soil physical properties and tree cover (Oyarzún et al, 2011).

One limitation of the present thesis is that I did not inquire about the reasons of landowners for using different practices, such as why they would leave a no-take area for forest conservation. The high frequency of the forest conservation practice among the land owners opens up an opportunity to maintain or improve the state of soil properties related to soil water storage at watershed scale. Regarding extraction of native firewood and timber for sale, the preliminary evidence collected in the period of fieldwork about the actions taken by some landowners highlighted its illegal character. While selling firewood is not illegal *per se*, two conditions may lead this to being carried out illegally: i) the high costs of implementing a formal and legal management plan approved by CONAF is a pre-requisite to extract and sell timber, and is often limiting; ii) the requirement to have property titles in rule, a necessary condition CONAF imposes to approve a management plan, is often not met. As a consequence, there is a lack of appropriate estimates regarding the frequency of this management practice in the study area. Thus, it is critical to assess the basic characteristics and the frequency of use of extraction of native firewood and timber for sale, as well as how this practice affects soil water storage in the two catchments. Several methods, such as the randomized response technique (RRT) should be employed in the near future to assess the relevance of activities that generate conflicts for respondents (Greenberg et al. 1971; Conteh et al. 2014; Oyanedel et al. 2018).

The practice of extraction of native firewood and timber for self-consumption turned out to be the most important activity of the rural landowners in the two catchments. This practice uses wood for multiple purposes. One of them is for firewood, recognizing the superior quality in terms of heat generation of native wood, (mainly Ulmo (*Eucryphia cordifolia*), Tepú (*Tepualia stipularis*) and Luma (*Amomyrtus luma)*; but not restricted to these species) compared to exotic wood, mainly *Eucalyptus* (INFOR 2010). Other uses included construction, mainly for fences and house building. The species used include the ones mentioned before and Canelo (*Drimys winteri*), Mañío (*Podocarpus nubigena*), Arrayán (*Luma apiculata*) among others (personal interviews). There is a potential of further studies to measure quantitatively the structure of the forest included within this management practice, incorporating the variability inside this practice and developing finer categories in order to improve the management of the practice and the subsequent soil water storage. For example, measuring tree density and diversity, and the abundance and impact of cattle (in the case of livestock raising) may differentiate how the landowners manage areas that are relevant for supplying firewood or timber for self-consumption (e.g. Zamorano-Elgueta et al, 2012; Zamorano-Elgueta 2014).

Concerning the livestock management practices, differences were found in the way people manage the livestock (sheep, cows or goats) depending on the season of the year. The use of rotations and fencing is restricted mainly to summer and other times of the year; many landowners managed free-ranging livestock in their land. While there is a difference in summer regarding the management of livestock as either free-ranging or enclosed, the management is similar in winter. This seasonal practice may worsen the state of soil water storage in winter, in places that may recover some properties that enhance water storage during summer, such as soil compaction or infiltration rates. There is abundant evidence of the negative effects of livestock on the ecological condition of forest and soils, especially their effects on the understory of temperate forests in southern Chile and Argentina (Veblen et al, 1992; Carmona et al. 2002; Vazquez 2002; Zamorano-Elgueta et al. 2012; Zamorano-Elgueta et al, 2014). Additionally, evidence is emerging about the effects of livestock in the soil physical properties of temperate forests (Dörner et al, 2011). In the present study, some landowners reported managing livestock within areas with secondary forest. This information suggests that there is a greater complexity in the use of landscape, with mixed uses in the same area, which provides information that complements an analysis based on LULC. At local scale and in terms of soil water storage properties, areas that are seen as secondary forest for example, can be subject to different livestock and forest extraction management practices.

Identification of the management practices in the present study opens up the possibility to understand linkages at the local scale between forest and livestock management practices. Local rules, local to global economic trends, geographic position of lands or the cultural background are factors that can explain local-scale tradeoffs of landowners choosing different management practices (Nagendra, 2007; Olabisi, 2012; Nguyen et al, 2018). The goal of such an analysis would be to stimulate better management practices to improve the water storage and provision of the two catchments.

Regarding the less frequent management practices (beekeeping, low-impact tourism, permaculture or organic agriculture, plantation of native trees, farm products for sale), they may have low or null effects on water storage due to the limited amount of land used and low intensity of use. These forest-use practices may even have a positive effect on water storage because they are based on products related to old-growth forests. Such management practices can provide alternative income to reduce the intensity of other practices that are detrimental for soil water storage properties. However, economic revenues from these management practices do not always support people's livelihoods or may have marginal effects on their overall income (Bookbinder et al. 1998; Addinsall et al. 2017). Further research is required to understand the economic viability of these management practices.

In the present study, the concept of management practices provides complementary information at the local scale to supplement studies based on LULC, which provide an overview of the landscape. The concept proved to be a useful approach for identifying local factors influencing LULC dynamics. Among these are specific dynamics used to manage (or not) livestock that will impact soil water storage or the presence of practices that positively impact soil water storage (forest conservation or low-impact tourism as an emergent practice) in two catchments of Northern Chiloé Island: Mechaico and Quilahuilque. The management practices approach adds more relevance to local scale processes as determinants of soil water storage potential. Normally, at larger scales, studies using satellite images that reveal changes in LULC, hide local dynamics (such as different management practices done in a same land cover) that are actually generating impacts on soil physical properties (Olabisi 2012). Adding this new "layer" of information to better explain LULC changes will improve future initiatives to ameliorate local soil water shortages and enhance water provision. The challenge is how to link local processes to those occurring at larger scales since they represent an important driver to understand global change (Wilbanks and Kates 1999)

Analysis of factors related to soil water storage within management units

In terms of soil physical properties related to soil water storage, the large difference between unmanaged livestock raising and forest conservation practice was expected since they have important differences. First of all, the goal of these management practices differ: the unmanaged livestock practice is conducted in prairies without management of enclosures and with an extensive use of the landscapes for cattle grazing (most often without input of fertilizers). In the case of forest conservation practice, the landowners did not extract firewood or timber and no cattle grazing is allowed, due to the presence of fences or because abrupt topography limits access.

Through the PC1, we observe similarities of soil water storage properties under two management practices: managed livestock farming and the extraction of native firewood and timber for self-consumption (Figure 5). The extraction of native firewood and timber for self-consumption is done in an area of secondary forest, qualitatively different from fenced prairies. Because of this, it was expected that these two practices conducted in different areas show disparities in terms of their influence on soil water storage. Nevertheless, the PC1 revealed similarities, which imply a poor management of forested areas, which produces similar soil properties relative to the intensively used prairies, areas which are expected to have low soil water storage capacity (Dörner et al, 2010; Dörner et al, 2011). A possible explanation can be the presence and impact of livestock in areas where the extraction of native firewood and timber for self-consumption is practiced. In temperate forests of southern Chile, there is evidence of the negative effects of cattle grazing on tree regeneration (Zamorano-Elgueta et al. 2012; Zamorano-Elgueta et al. 2014). Other studies also showed the effect of cattle grazing in soil physical properties, such as compaction, affecting infiltration rate (Pietola et al. 2005). Additionally, historical practices of fire for open field done in the locality of Lajas Blancas may affect places such as areas with secondary forest (Bahamonde, 2013), reducing their capacity to storage water.

The linear model analysis (Table 5) showed significant differences in the infiltration rate of areas managed for forest conservation compared to all the other practices. Additionally, this analysis provides evidence of significant differences in terms of soil depth, a soil condition which could be a consequence of past fires set by local people. Again, both the presence of unmanaged livestock, without limitation by fences, and the historical fires occurred in the area may explain the large differences in infiltration rates. Particularly, the practice of forest conservation appears to be critical at the landscape level because we measured higher infiltration rates, as shown by the comparative analysis among management practices (Figure 6A). The preservation of some forested areas within the landscape may contribute to maintain the infiltration rates at levels that allow domestic, productive and industrial water uses. A critical step will be to explore the feasibility of understanding how much land must remain preserved to maintain or enhance water storage and the subsequent water provision for the local community.

The linear model showed significant differences in the effect of soil depth to infiltration rate (Table 3). However, the analysis conducted to see differences among management practices did not show significant differences in soil depth (Figure 6B). Hence, past conditions of sites sampled may determine soil depth instead of current management practices. There is evidence of historical practices of fire at large scales in southern Chile (Schilling et al. 2008; Holz and Veblen 2011). At the local scale, the use of fire since the arrival of the first colonist in 1898 in the current locality of Lajas Blancas was a practice used to open space for agriculture and livestock raising (Turra, 1986; Bahamonde, 2013). The use of fire implies a series of soil physical modifications, such as the increase in soil hydrophobicity (making them less able to infiltrate water), removal of organic matter, and erosion (Certini 2005; Miyata et al. 2010; Oyarzún et al. 2011), and a decrease in soil water storage (Anderson et al. 1976; Weil and Brady, 2016). Another consequence of fire is a reduction in soil depth. As a result, some areas where I measured factors related to soil water storage, may have suffered historical anthropogenic fires with consequent soil loss. Nevertheless, other changes in land use also affect soil depth (Dörner et al. 2015; Dörner et al. 2016). Thus, current practices represent an impact that overlaps with the impacts established by the historic use of fire. Hence the importance of monitoring and stimulating management practices that maintain the soil or, at least, do not cause the complete loss of the first layer of soils.

Concerning soil moisture content, this is a variable related to infiltration rate (Lal and Vandoren 1990; Lal and Shukla 2004; Weil and Brady 2016). Soil moisture and infiltration are also related to soil compaction, as compaction reduces total porosity (Weil and Brady 2016). Despite differences in soil compaction, these differences were not translated into different soil moisture contents. One explanation is that soil moisture is also related to rain episodes. The season in which soil moisture was measured corresponds to autumn. Episodes of rainy days occurred at the time of sampling to measure soil moisture. Consequently, measures of soil moisture content must incorporate seasonal variability as a way to understand behavior of soils on wet and dry seasons (Weil and Brady, 2016).

Results of soil compaction are in accordance with the infiltration rate results since it would be related to the passage of cows inside places where extraction of native firewood and timber for self-consumption is practiced (Carmona et al. 2002; Vazquez 2002; Zamorano-Elgueta et al. 2012). Places where landowners presently maintain livestock would be used for other management practices, such as wood extraction for self-consumption, which compacts the soils. Data from the literature confirms the relationship between soil compaction and soil infiltration (Shafiq et al. 1994; Shukla et al. 2003; Lal and Shukla 2004; Castellano and Valone 2007; Blanco and Lal 2008).

The information obtained in this work, following a pragmatist paradigm (Creswell, 2014), is summarized in a conceptual model (Figure 7). The conceptual model synthesizes the effect of management practices used in the two catchments on water infiltration rate and water storage factors in the soil. This conceptual model summarizes the beneficial or the detrimental effect of different local management practices used in these catchments on the capacity of soils to infiltrate water during the process of water storage. The conceptual model includes the effects of management practices that were not sampled, in terms of water infiltration rates. Human actions are related to the management practices, in the biophysical unit delimited by the catchment boundaries, and will have direct effects on water infiltration rates. Further, the conceptualization suggests other soil physical properties and measures that are necessary to understand how the management practices identified affect the capacity of soils to store water. Among these are the extension of soil moisture samples across seasons and years, and the measurement of soil organic matter.

The conceptual model can also help us translate the knowledge emerged from this study into policy measures. The context of water scarcity requires the application of policy measures to overcome a current socio-ecological problem. While some steps have been taken to alleviate the problem of water scarcity in the rural areas (Norambuena 2015), there is a recognition that these are short-term solutions that will not solve the problem in the long term (Frene et al, 2014). Current policy measures include the increase of water delivery through cistern trucks or the increase in depth of water wells. Managing the landscape at the watershed scale together with the rural community provides an alternative pathway to solve the problem, which in other places has been shown to be more efficient in financial terms (Dlugolecki 2012). This approach takes advantage of the ecosystem services framework for a given watershed and seeks to manage the elements of the landscape that enhance water delivery for human consumption.

Final remarks

The present study examines the relationship between local management practices and the factors related to soil water infiltration and storage at the catchment scale. In the present study, the concept of 'management practice' is proposed as a useful tool to assess the primary human impacts on the study site. Categories of management practice emerged from the interviews with inhabitants of the two catchments studied.

Subsequently, the effects of four management practices that affect soil physical properties related to soil water storage were analyzed. Results showed significant differences in infiltration rate and in soil compaction, but there were no significant differences in soil depth and soil moisture.

The present study emphasizes the importance of analyzing processes at local scale, which suggests differences in areas that, from the classical LULC perspective, had not been revealed. The identified land mosaic of practices can serve as a basis to analyze other watersheds from Chiloé Island and elsewhere and how are they are affected by these practices in terms of water storage and provision. A future necessary step will be to understand the reasons behind the application of one practice to the detriment of another. Recognizing these motivations would give us tools to improve or discard practices that are harmful in terms of soil physical properties related to soil water storage and stimulate activities that have positive or neutral effects on water infiltration. In addition, more information about tree diversity and density at seasonal scale inside managed areas will explain more variance regarding the management practices analyzed.

Consequently, I propose to understand the impact of management practices on water supplying catchments at local scales through the integration of different sources of information (Overmars and Verburg 2005). The context of water scarcity in Chiloé Island creates a useful scenario to understand how decisions taken by local landowners may affect soil physical properties related to water storage.

Once local landowners impacts on soil physical properties are understood, a further step is to establish minimum measures at landscape scale. Studies like this one can serve as input to stimulate the establishment of local norms to stimulate the landscape to storage and provide water. Additional studies are necessary to see the feasibility to establish norms to prioritize water provision for human consumption and to analyze if actual norms are sufficient to palliate the effects of water scarcity. This analysis must be framed in a context of a country where the constitution set water as a private good.

In the present study, the native forest represent an important element to infiltrate water in soils. At the institutional level, this is also an important argument in favor to protect native forest covers from the water provision perspective.

Thus, the study demonstrate the importance to analyze problems related to water storage and provision not only from the geo-spatial and soil properties perspective but also integrating local uses and perceptions of local landowners, thus, from the social-ecological perspective. This is the main challenge in order to understand and overcome problems of water scarcity, which are generalized in many parts of the country and at planetary scale.

Conclusions

The present study first, inquire about the management practices currently used by the people in the catchments of Quilahilque and Mechaico. Thirteen management practices were identified. Four of them demonstrated to have importance in terms of soil water storage. Then, the second objective was to assess the anthropogenic effect on soil water availability on the four management practices important for soil water storage. I analyzed a set of soil physical properties affecting infiltration rate. Results showed significant differences in infiltration rate and in soil compaction in the four management practices. There were no significant differences in soil depth and soil moisture.

The set of practices recognized in the two catchments demonstrated to have differential effects on soil physical properties related to soil water storage. The approach proposed here through analyzing the effects of practices on soil physical properties related to soil water storage reinforce the interlinked effect between water scarcity and human impact on the landscape. The present study can serve as an example to study other localities affected by water scarcity to analyze and understand local process of water provision and how this watershed capacities are affected by the reduction in native forests covers. Future works must integrate soil properties related to water storage as well as how local landowners use the landscape since they are interlinked processes (Berkes et al. 1998; Foley et al. 2005;

Sutherland et al, 2018). The motifs behind the use of one practice instead of other may be a useful second step to then propose potential solutions to stimulate those that have a positive or neutral effect in soil properties related to soil water storage.

TABLES

Table 1. Results of the Mann-Kendall test for rainfall trend between 1970 and 2015. (Data extracted from DGA, 2018)

Statistician	Result
Kendall's tau	0.015
S'	173.000
Var(S')	117301.000
p-value (Two-tailed)	**0.613**
alpha	0.05

Table 2. Management practices identified in Mechaico and Quilahuilque, frequency of management practices based on 20 interviews, and fulfillment of the criteria 1 and 2 (Methodology section) to measure soil physical properties related to soil water storage. * indicates management practices for which the soil physical properties were measured.

Management practices	Nº People that use	Definition	Criteria 1	Criteria 2	Land cover related
Extraction of native firewood and timber for self-consumption*	**17/85%**	**Timber or firewood extraction for own consumption, mainly for firewood and for construction**	**Yes**	**Yes**	**Primary forest Secondary forest**
Managed livestock farming*	**12/60%**	**Livestock (cows, sheep and/or goats) rotated in a series of pasture plots, mainly in summer**	**Yes**	**Yes**	**Prairies**
Forest conservation*	**10/50%**	**No-take portion of native forest**	**Yes**	**Yes**	**Primary forest Secondary forest**
Farm products for self-consumption	9/45%	Agriculture for own consumption	Yes	No	Agricultural field
Exotic tree plantations	8/40%	Plantations of exotic trees, mainly *Eucalyptus sp.*	Yes	No	Plantation
Farming animals for self-consumption	6/30%	Farm animals (chickens, pigs, ducks, geese) for own consumption	Yes	No	Agricultural field
Unmanaged livestock farming*	**5/25%**	**Free range livestock (cows, sheep and/or goats) in pastures and native forest**	**Yes**	**Yes**	**Prairies Primary forest Secondary forest Shrubs**
Farm products for sale	3/15%	Agriculture that produces vegetables and fruits, mainly lettuce, berries and coriander	No	No	Agricultural field
Plantation of native trees	2/10%	Reforestation using native plants	No	Yes	Prairies Primary forest Secondary forest
Permaculture or organic agriculture	2/10%	Agriculture using a cycling chain of organic wastes	No	No	Prairies
Low-impact tourism	2/10%	Recreational activities addressed to foreign people	No	Yes	Primary forest
Beekeeping	1/5%	Bee raising for the production of honey with native trees	No	No	Primary forest Secondary forest
Extraction of native firewood and timber for sale	?	Wood extraction to sell for different purposes, mainly for timber or firewood	?	?	?

Table 3. Eigenvalues and % of variance of the PCA with a correlation matrix.

PC	Eigenvalue	% variance
1	2,2564	45,129
2	1,0847	21,695
3	0,9877	19,755
4	0,5225	10,451
5	0,1485	2,97

Table 4. PCA loadings of the component 1 and 2.

Variables	PC1	PC2
Infiltration rate	**-0,5096**	0,1615
Compaction at 10 cm	**0,6164**	0,1231
Compaction at 20 cm	**0,5364**	0,4079
Soil depth	-0,2625	**0,6728**
Soil moisture	-0,06136	**0,5829**

Table 5. Effect of soil depth and management practices on infiltration rate

Variables	Estimate	SE	t value	p value
Intercept	-3,00E-4	1,657E-4	-1,81	0,08611
Unmanaged livestock	-9,57E-5	7,361E-5	-1,3	0,20912
Extraction of native firewood and timber for self-consumption	-2,079E-5	7,116E-5	-0,292	0,77326
Forest conservation	2,689E-4	7,143E-5	3,765	**0,00131**
Soil depth	5,594E-6	1,959E-6	2,856	**0,01011**

Note: The adjusted R^2 is 0,5928. The F-statistic is $9{,}371_{4,19}$. The p-value is 0,0002335.

FIGURES

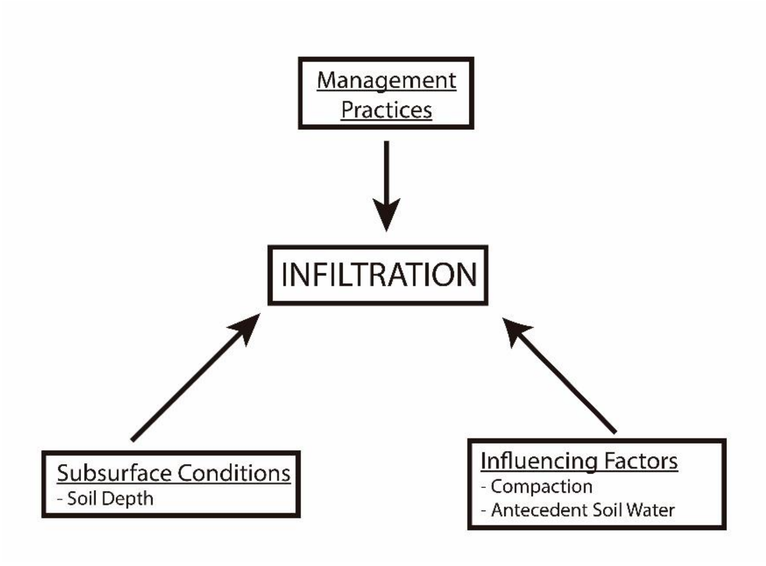

Figure 1. Human impacts and soil variables influencing water infiltration rates in soil (modified from Ward and Trimble, 2003).

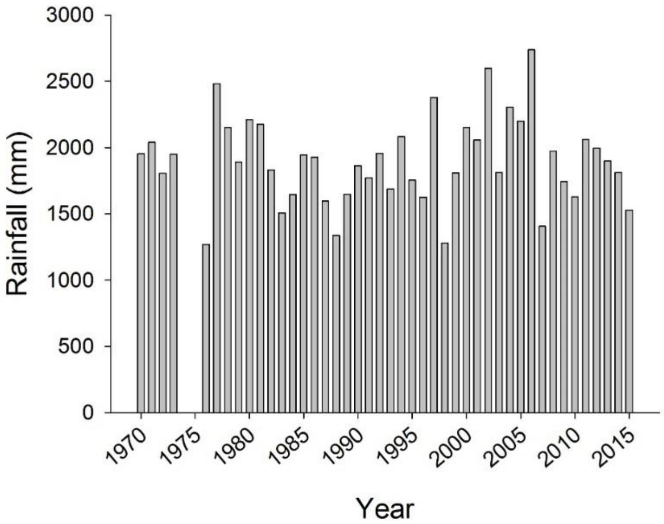

Figure 2. Rainfall records from 1970 to 2015 in the city of Puerto Montt. Missing years are 1974 and 1975.

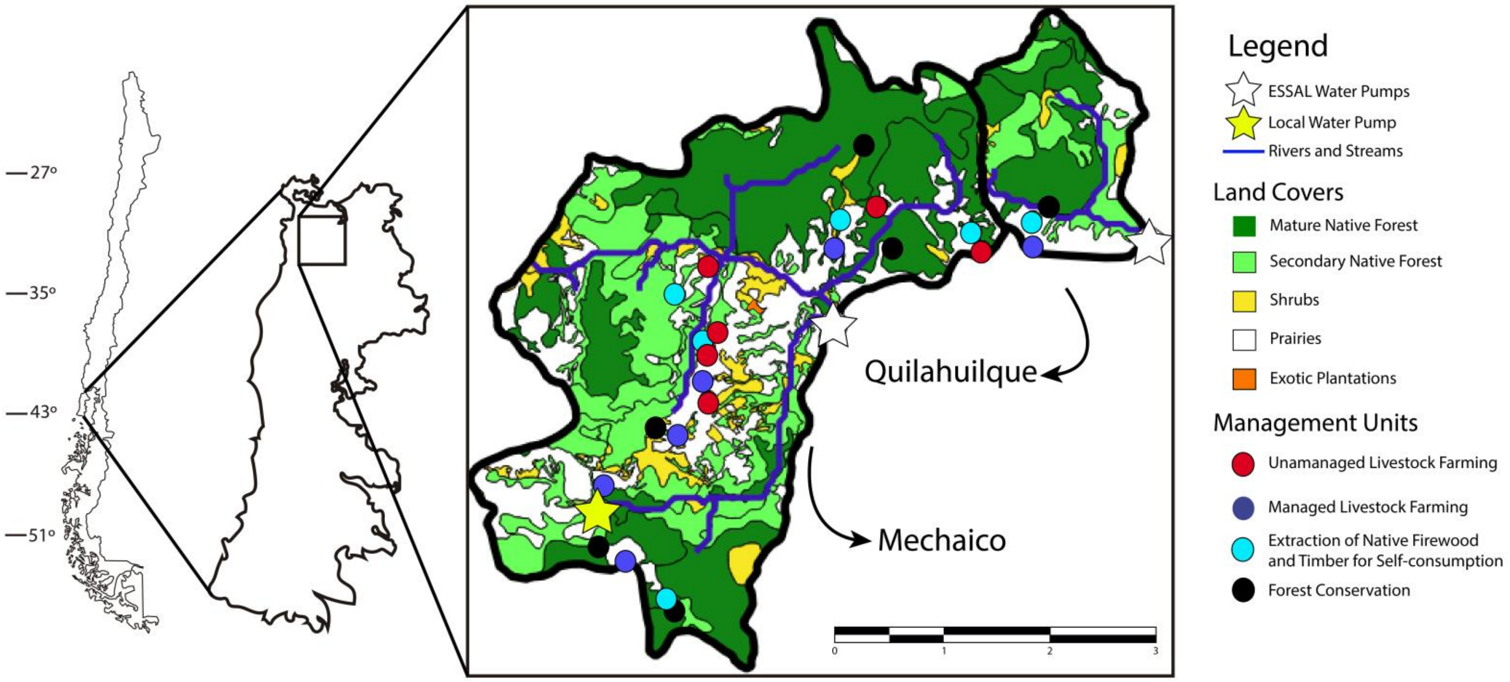

Figure 3. Study site areas in the locality of Lajas Blancas, Municipality of Ancud, Isla Grande de Chiloé and their respective land cover (CONAF and UACH 2014). Mechaico and Quilahuilque are watershed boundaries.

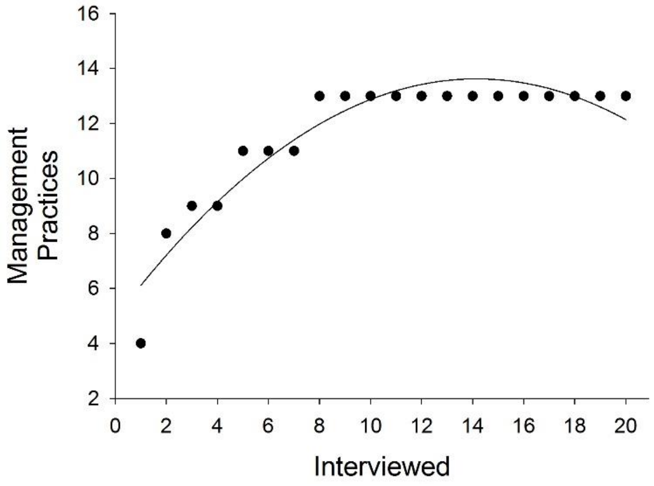

Figure 4. Curve of cumulative management practices identified by the people interviewed (n = 20) in the two catchments.

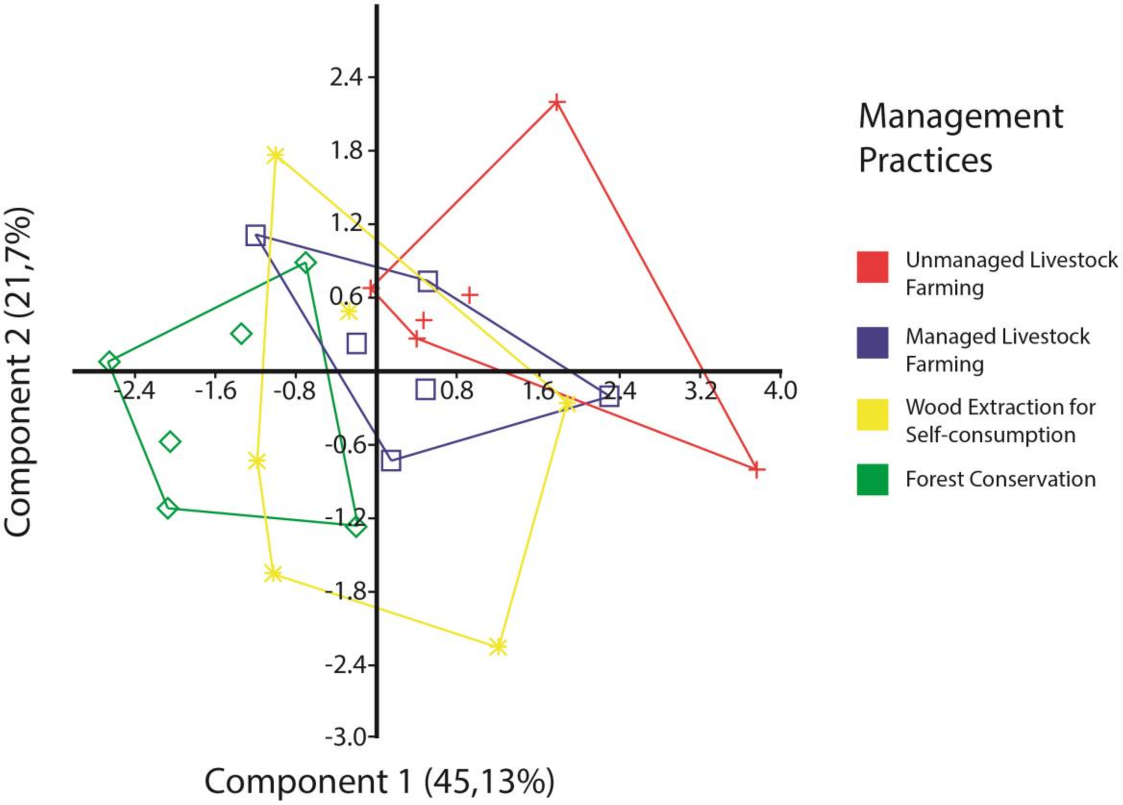

Figure 5. Principal component analysis of the sample points for five factors related to soil water storage. Analyses were conducted separately for each management practice unit measured, separated by colors.

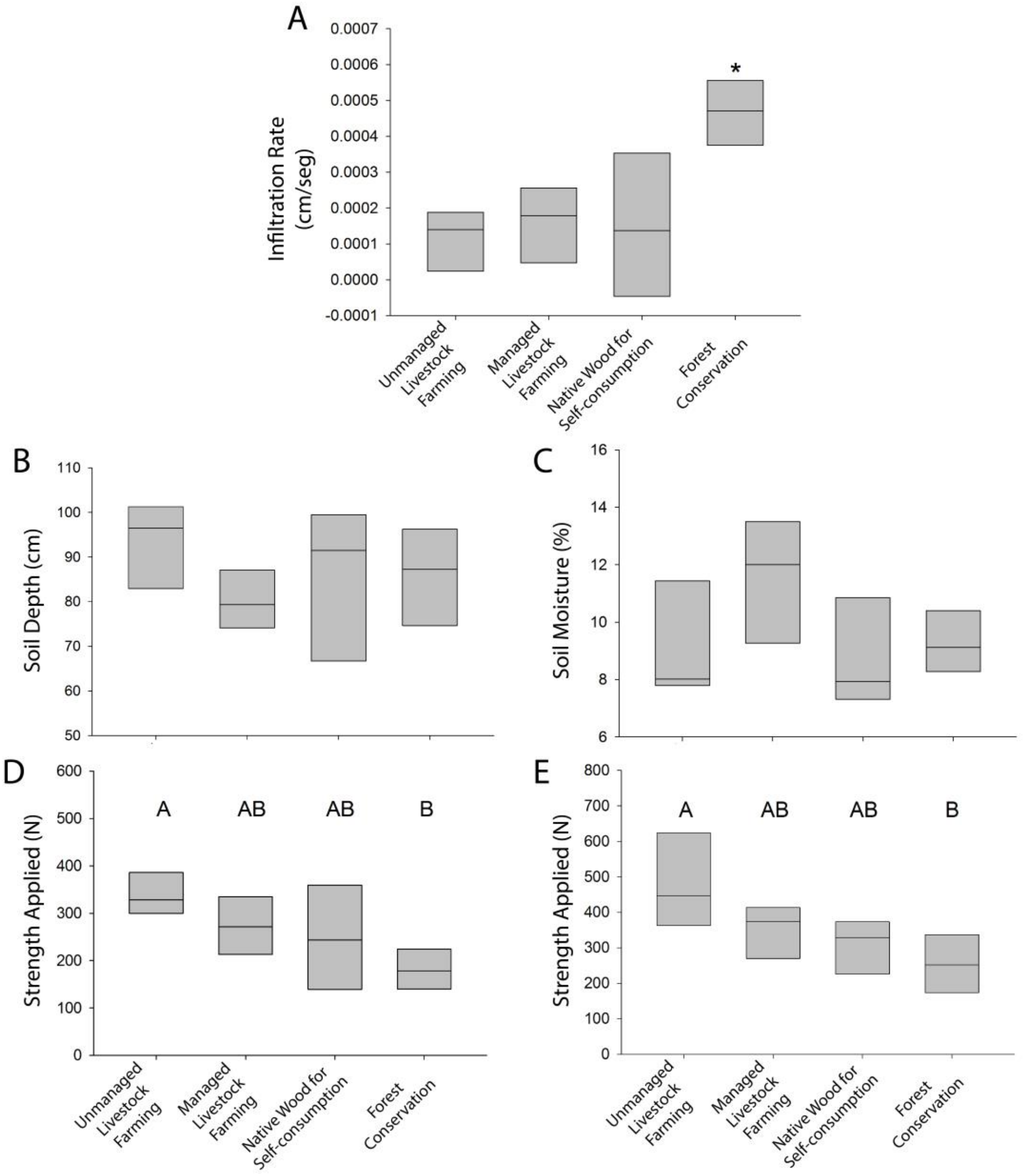

Figure 6. Comparisons of five soil physical variables (A-E) among small scale management units in the two catchments of Mechaico and Quilahuilque. Statistical differences were tested through one-way ANOVA and *a posteriori* Tukey test. A) infiltration rate; B) soil depth; C) soil moisture (%); D) and E) compaction at 10 cm and 20 cm respectively. Asterisks indicate significant differences from all other practices. The horizontal line is the mean of n = 6 records for each management practice unit, the vertical box includes 95% of the data.

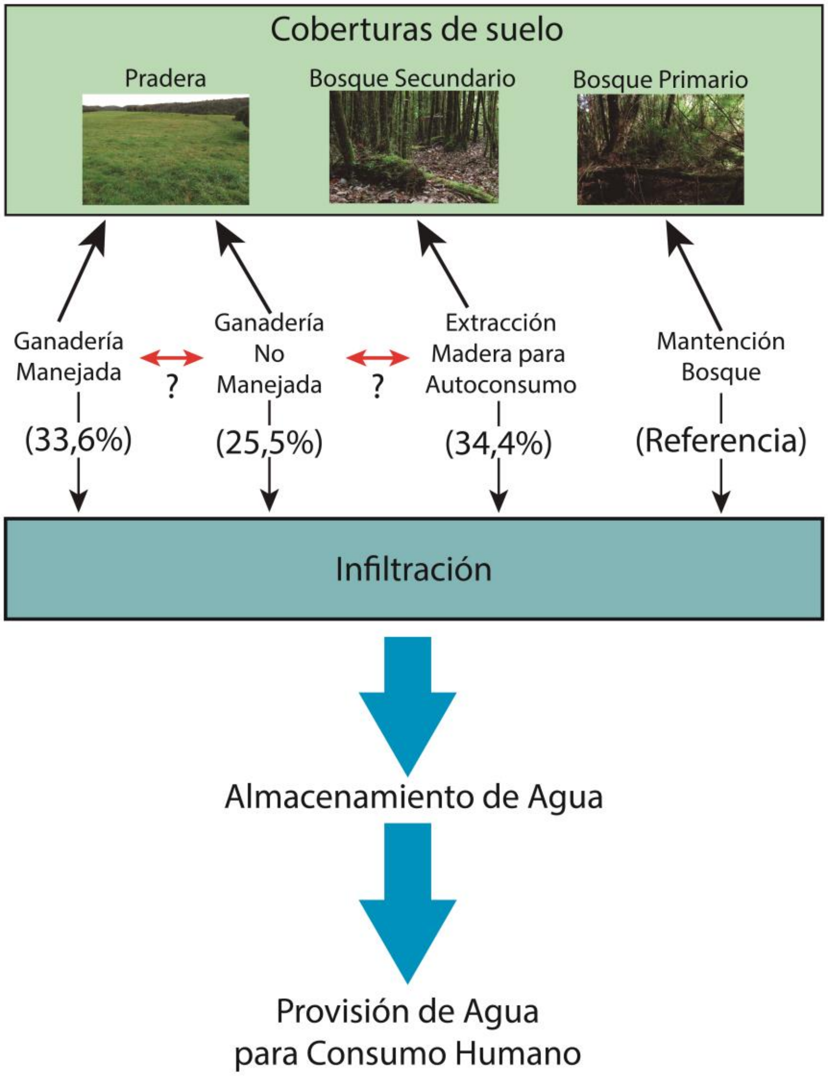

Figure 7. Conceptual model of the effect of management practices on the infiltration rates soils of the two catchments of Mechaico and Quilahuilque.

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APPENDICES

Appendix 1.

Land cover/use units in the two catchments of Mechaico and Quilahuilque according to the 2013 definitions of CONAF national survey (CONAF and UACH 2014)

Land use/cover	**Mechaico (1448 Ha)**		**Quilahuilque (246 Ha)**	
	Area (Ha)	%	Area (Ha)	%
Mature forest	485,9	34,4	124	47,5
Secondary forest	475,8	33,8	76	29,1
Prairies	301,2	21,4	47,8	18,3
Scrublands	139,6	9,9	12,8	4,9
“Mallín”	5,5	0,4	0	0
Exotic plantations	1,4	0,1	0	0
Total	**1.409,3**		**260,6**	

Appendix 2.

List of questions for semi-structured interviews for inhabitants of two catchments, Mechaico and Quilahuilque.

A. Spanish version

Información general

- Fecha de la entrevista
- Nombre
- Edad
- Género
- ¿Vive en Lajas Blancas?
- ¿De qué tamaño es su campo?

Preguntas

1. ¿Qué actividades realiza en su campo? (Si no menciona un uso, preguntar si hace algo ahí) ¿Alguna otra?
2. ¿Cómo desarrolla estas diferentes actividades? (**temporalidad/intensidad/espacialidad**)
3. ¿Cuál de estas actividades es la más importante? (¿Por qué?) ¿Cuál de estas actividades es la que ocupa más espacio/extensión en su campo?

4. ¿Han cambiado (intensificado o disminuido) en los últimos 10 años estas actividades? (Si es así, ¿de qué forma?) ¿Y en los últimos 20 años o más? (Si es así, ¿de qué forma?)
5. ¿Usted cree que alguna o varias de estas actividades afectan la capacidad que tiene el campo/ambiente/ecosistema de guardar o almacenar agua? (¿cuáles?)
6. ¿Cómo ha variado la disponibilidad de agua en la zona?

En caso de que haya disminuido:

7. ¿Cuál cree que es la principal causa de disminución del agua?
8. ¿Cómo podría aumentar o recuperarse la capacidad de guardar agua del campo/ambiente/ecosistema?
9. ¿Podría usted ayudar a que aumente la disponibilidad de agua? (¿Cómo?)

B. English version

General information

- Date of interview
- Age
- Gender
- Do you live in Lajas Blancas

Questions

1. What activities do you develop in your land? (if he/she do not mention one use, as if he/she do anything else there) Any other?

2. How do you develop these activities? Temporality/Intensity/spatiality
3. Which of these activities is the most important? (Why?) Which of these activities is the activitiy that use more space/extension in your land?
4. Have the activities changed (intensified or decreased) in the last ten years? (If they are changed, how did they changed?) And in the last 20 years or more? (If they are changed, how did they changed?)
5. Do you think any of these activities affect the capacity of your land/environment/ecosystem to storage water? (If yes, which activities affect the capacity to storage water?)
6. How have the availability of water changed in the locality?

If water supply for human use has decreased in the past decade:

7. Which cause do you think is the principal cause of water decreasing?
8. How can you increase or recover the capacity of your land/environment/ecosystem to storage water?

Can you help to increase the availability of water? (How?)