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Cambios en las propiedades físicas y químicas de un suelo después de 3 temporadas de aplicaciones de efluente proveniente de la producción de celulosa.

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A Mónica y a todos mis Hijos, Paulina; Rodrigo; Manuel, Coté y Emilio

Dedicado a mi Madre.

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Changes in some forest soil properties after three years' irrigations with industrial paper mill treated effluent

Key words: chemical and physical soil properties, sodium adsorption ratio, exchangeable sodium percentage, soil structure

RESUMEN

La reutilización de aguas residuales en la agricultura es una práctica a pesar de los riesgos involucrados. Pero debido a la escasez de agua para consumo humano y riego, se ha resuelto utilizarla. El objetivo de este estudio fue determinar el impacto en las propiedades físicas y químicas de un suelo forestal después de tres años de aplicación de efluentes tratados industriales provenientes de la fabricación de papel. Se realizaron experimentos en la región semiárida del centro-sur de Chile conocida como Secano Interior. Suelo T1 con y T0 sin riego con efluentes de la fabricación de pulpa de papel. Tratamientos replicados cuatro veces en un diseño de bloques aleatorios. Las muestras de suelo se tomaron para análisis químicos y físicos de 0-20 cm de profundidad inmediatamente después del final de la temporada de riego y después del período de invierno antes del siguiente ciclo de riego. Los datos fueron analizados usando un ANOVA de una vía. El riego con efluente industrial no causó cambios significativos en las propiedades químicas del suelo como pH, materia orgánica, K, Ca y Mg. excepto para Na con altas concentraciones en el suelo, y como resultado de las altas concentraciones de este elemento en los efluentes provenientes de la fabricación del papel que fueron aplicados vía riego. El contenido de Na^{+} aumentó la capacidad de intercambio catiónico (CIC) al final del estudio (3er año), dando lugar a un porcentaje de sodio intercambiable (ESP) del 8,5%. Otro efecto fue el aumento de los valores de la relación de adsorción de sodio (SAR) al final del período de estudio (6,2 meq L^{-1}), ambos parámetros directamente asociados a las propiedades químicas del efluente. No se observaron diferencias en la estructura del suelo en T1 en comparación con parcelas sin aplicaciones de efluentes (T0), representadas por los valores de densidad aparente, porosidad, tasas de infiltración y conductividad hidráulica. Nuestros resultados revelan la

importancia de monitorear las propiedades del suelo a corto plazo cuando se aplica efluente industrial tratado del proceso de fabricación de papel.

ABSTRACT

Reuse of wastewater in agriculture is an applied management despite the risks involved. But due to the scarcity of water for human consumption and irrigation, it has been resolved to use it. The aim of this study was to determine the impact on physical and chemical properties in a forest soil after three years of paper mill industrial treated effluent application. Experiments were conducted in the semi-arid region of south-central Chile known as the Secano Interior. T1 soil with and T0 without irrigation with paper mill effluents. Treatments that were replicated four times in a random block design. Soil samples were taken for chemical and physical analyses from 0-20 cm depth, immediately after the end of the irrigation period and after the winter season before the next irrigation cycle. Data were analyzed using one-way ANOVA. The irrigation with industrial effluent did not cause significant changes in soil chemical properties as pH, organic matter, K, Ca and Mg, except for Na with high concentrations in soil, as a result of the high concentrations of this element in the paper mill effluents applied. The Na^+ content increased the cation exchange capacity (CEC) at the end of the study (3rd year), leading to an exchangeable sodium percentage (ESP) of 8.5%. Another effect was the increase in sodium adsorption ratio (SAR) values at the end of the study period (6.2 meq L^{-1}), both parameters directly associated with effluent chemical properties. No difference was observed in soil structure when T1 was compared to plots without effluent applications (T0), as represented by the values of bulk density, porosity, infiltration rates and hydraulic conductivity. Our results reveal the importance of monitoring soil properties in the short run when paper mill industrial treated effluent is applied.

CAPITULO 1.

INTRODUCCION GENERAL

INTRODUCCION

El agua es un componente clave en los procesos de sistemas biológicos, tales como la estabilización de la actividad biológica y metabólica (Chen et al, 2012). Del total de agua del planeta, solo un 3% corresponde a agua dulce y de esta, el 1% es agua disponible para el uso de la humanidad. Siendo la disponibilidad del recurso para la agricultura, dependiente de condiciones de suelo, tipo de cultivo y la temperatura (Chen et al, 2012)

Varios estudios han abordado los efectos del cambio climático en los recursos hídricos (Vorosmarty et al. 2000, Arnell y Lloyd-Hughes 2014, Gosling y Arnell 2016). El aumento de las temperaturas puede tener un efecto directo en la evapotranspiración, lo que lleva a un aumento de la demanda de agua para la agricultura y la silvicultura (Johnson y Sharma 2010). A escala nacional y dadas las condiciones actuales, Chile se encuentra en un camino que podría resultar en una escasez de agua significativa, especialmente en las zonas centrales del país, donde se encuentra alrededor del 75% de la población total (Fuentes et al, 2021). La escasez hídrica en Chile no es exclusiva de climas áridos, como en las regiones del norte del país, y afecta regiones del centro sur (33°-45° S), lo cual ha sido de manifiesto por los científicos como “Megasequía”, presente en esta zona del Cono-Sur de América desde el año 2010 (Garreaud et al. 2017). Aunque no está totalmente claro qué efecto tiene el cambio climático en la variabilidad interanual del clima, Boisier et al. (2016), estudiando series temporales de pluviómetros y modelos climáticos globales, estimaron que alrededor del 25% de la sequía y el déficit de precipitación relacionado es causado por el cambio climático.

Una de las soluciones posibles a la escasez de agua en procesos productivos, ha sido la búsqueda de nuevas tecnologías que permitan por una parte aumentar la eficiencia y por otro lado, nuevas fuentes de agua, que permitan a la población y a procesos productivos y de servicio (agricultores, industria, minería, sanitarías, entre otros) abastecerse conforme a sus necesidades.

En tal escenario, se plantea la reutilización de aguas residuales, las cuales pueden ser de distintas procedencias: urbanas, o industriales. Esta tendencia de carácter global responde al incremento de la demanda por los recursos hídricos, como consecuencia, por ejemplo, del incremento sostenido de los rendimientos de cultivos agrícolas, que demandan mayores volúmenes de agua de riego.

Los efluentes, definidos por el Servicio agrícola y Ganadero (SAG) como líquidos residuales generados en procesos productivos o de servicios, sean éstos industriales, mineros, agroindustrias, ganadería (purines), pesca, o de otras actividades, que son aplicados al suelo, están siendo usados como agua de riego en muchos países, donde varios de ellos han desarrollado lineamientos y marcos legales para su uso, que aplican el criterio de calidad y regulan la forma de aprovechamiento de los efluentes para propósitos de riego. Ejemplos de estos lineamientos se encuentran resumidos en la guía para el reúso del agua de la agencia para la protección ambiental de EEUU (U.S. EPA, 2004).

El agua residual reciclada utilizada para riego en zonas áridas y semi áridas, es considerada una solución plausible económicamente, ya que permite paliar los efectos de la escasez hídrica (Valipour y Singh, 2016; Yannopoulos et al., 2015). En muchos países se utiliza aguas residuales urbanas para riego, especialmente en zonas semiáridas (Costa et al., 2016; Angelakis y Gikas, 2014). Incluso se puede considerar el uso de agua residual como parte de una estrategia para un manejo sustentable del agua (Qadir et al., 2003). En Australia, el uso de aguas residuales es una práctica común en sectores agrícolas, considerándose una alternativa plausible para el riego de cultivos (Angelakis y Gikas, 2014).

Aguas residuales de la industria de la celulosa

En términos de consumo de agua, la producción de celulosa es una de las mayores consumidoras de agua fresca (100-250 m^3 t^{-1} papel), donde prácticamente toda el agua residual conforma los efluentes (72-225 m^3 t^{-1} papel), por lo que se requiere tratarla previo a su disposición final (Tester et al., 1987). La liberación de estos residuos en fuentes de agua naturales causa una serie de efectos sobre organismos acuáticos, entre los cuales están los clastogénicos, carcinogénicos, endocrinos y mutagénicos (Ali y Sreekrishnan, 2001; Karrasch et al., 2006). La aplicación o uso de estas fuentes de aguas residuales en riego de cultivos, puede constituir una alternativa viable y atractiva (por su contenido de nutrientes), comparado con su descarga en fuentes de agua naturales.

Implicancias del uso de aguas residuales de la industria de la celulosa

Los suelos irrigados con agua residual, cruda o tratada, tienden a modificar sus propiedades fisicoquímicas por la constante adición de materia orgánica, sales y agua a un determinado pH. Dependiendo del pH del suelo y su capacidad amortiguadora, es posible que se presente un desplazamiento del pH del suelo hacia los valores del agua de riego (Mapanda et al., 2005; Xu et al., 2010), lo cual puede presentar distintas ventajas o problemas complejos, según la interacción de los diferentes componentes del suelo y del agua residual. Por ejemplo, al disminuir el pH del suelo, la adsorción de diversos iones metálicos, como Cu^{++}, Cd^{++} y Pb^{++}, en la superficie de las arcillas disminuye por la protonación de los grupos funcionales presentes en el microambiente edáfico, si bien esto es más evidente a valores de pH por debajo de 5 (Abollino et al., 2003).

La pulpa celulósica presente en efluentes de estos procesos industriales contiene una serie de elementos de importancia nutrimental para las plantas, tales como el nitrógeno (N), fósforo (P) y potasio (K), que pueden contribuir a paliar los efectos de la deficiencia de nutrientes en el suelo y mejorar los rendimientos de cultivos por su aplicación en el suelo (Becerra-Castro et al, 2015). Otros elementos, como el magnesio, sodio, cloruros, azufre; y compuestos orgánicos como la lignina clorada y derivados fenólicos, son comunes tanto en la pulpa como en los efluentes, los cuales pueden causar efectos fitotóxicos y desbalances nutricionales en las plantas.

Uno de los efectos adversos del uso de efluentes de la industria celulósica como fuente de riego en la agricultura, es el contenido de sodio (Na), que junto a otros elementos, puede acumularse en el perfil de suelo, los que eventualmente afectarían su estructura, lo que significa una disminución de la funcionalidad del sistema poroso; incremento de la salinidad del suelo; reducción de la infiltración y conductividad hidráulica; incremento de la resistencia a la expansión radical; y reducción de la aireación a nivel de las raíces (Howe y Wagner, 1996). Otros estudios enfocados en varios tipos de aguas residuales (Valipour y Singh, 2016; Yannopoulos et al., 2015; Singh et al., 2010; Maldonado et al., 2008) y su uso en agricultura, también respaldan el efecto del Na como una condición controversial, ya que requiere un análisis de la sustentabilidad del suelo bajo aplicaciones constantes de este recurso, pese al incremento de rendimientos verificados. Por ejemplo, se observó disminuciones en la estabilidad de agregados; dispersión de suelos arcillosos; sellado superficial; disminución en la conductividad hidráulica; y mayor susceptibilidad a la erosión. Almeida et al. (2017), reportaron estos efectos en un suelo con una plantación de eucaliptos, donde se incrementó la concentración de Na y los valores de pH.

Por otro lado, existe evidencia que el uso de aguas residuales genera aumentos en los tenores de materia orgánica del suelo, permitiendo el incremento de poblaciones de bacterias, actinomicetos, hongos y levaduras (Kannan y Oblisami, 1990). Por la naturaleza de la materia orgánica presente en el agua residual, este incremento en el contenido de materia orgánica le puede conferir una importante alza en la capacidad de intercambio catiónico del suelo, mejorando sus propiedades de filtro y amortiguación química, así como su capacidad de retención de bases intercambiables, incrementando en la fertilidad y la productividad (Xu et al., 2010).

En términos generales, los efluentes de la industria celulósica contienen tanto elementos benéficos (por ejemplo, nutrientes), como polutantes tóxicos, lo cual proporciona tanto oportunidades, como problemas para la producción agrícola, que deben ser considerados (Alghobar y Suresha, 2017). Un problema que deberá ser analizado es la presencia de metales pesados en el agua residual, que se acumula en el suelo y genera contaminación y efectos adversos a la biota edáfica, pudiendo incluso acumularse en algunos órganos de las plantas en estos ambientes (Radwan y Salama, 2006; Khan et al., 2010; Muhammad et al., 2011). Algunos de estos metales, como zinc (Zn), cadmio (Cd), plomo (Pb) y cobre (Cu), pueden encontrarse más fácilmente como contaminantes en plantas (Kachenko y Singh, 2006).

A la luz de los antecedentes presentados, se ha recomendado el uso de aguas residuales como fuente hídrica y de nutrientes de uso agrícola, bajo la consideración de cautelar los efectos adversos potenciales sobre los ecosistemas (Dinesh et al., 2012; Hussain et al., 2001).

HIPOTESIS GENERAL

El uso de efluentes tratados provenientes del proceso de fabricación de papel, aplicados vía riego en un suelo de uso forestal, modifica su sistema poroso y las características químicas del suelo.

OBJETIVO GENERAL

Investigar la magnitud de los cambios en un suelo, tanto en su comportamiento físico como químico, posterior a la adición vía riego tecnificado por un lapso de 3 temporadas, de efluentes cuyo origen es el proceso de obtención de celulosa.

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OBJETIVOS ESPECIFICOS

1. Evaluar el efecto de la composición de estos fluentes tratados, y su uso para riego, en los cambios físicos y químicos del suelo.
2. Determinar los cambios en las características químicas del suelo regado con efluentes tratados.
3. Analizar respuesta de la porosidad y de la funcionalidad del sistema poroso del suelo regado con agua residual al final de la tercera temporada de riego

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CAPITULO 2. CHANGES IN A FOREST SOIL PROPERTIES AFTER THREE YEARS IRRIGATIONS WITH INDUSTRIAL PAPER MILL TREATED EFFLUENT

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Changes in a forest soil properties after three years irrigations with industrial paper mill treated effluent

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ABSTRACT

Reuse of wastewater in agriculture is a practice despite the risks involved. But due to the scarcity of water for human consumption and irrigation, it has been resolved to use it. The aim of this study was to determine impact on physical and chemical properties in a forest soil after three years of paper mill industrial treated effluent application. Experiments were conducted in semi-arid region of south-central Chile known as the Secano Interior. T1 soil with and T0 without irrigation with paper mill effluents. Treatments replicated four times in a random block design. Soil samples was taken to chemical analyses and physical analyses from 0-20 cm depth immediately after the end of irrigation and after the winter period before the next irrigation cycle. Data were analyzed for one-way ANOVA. The irrigation with industrial effluent did not cause significant changes in soil chemical properties as pH, organic matter, K, Ca and Mg. except Na with high concentrations in soil, as a result of the high concentrations of this element in paper mill effluents applied. The Na^+ content increased the CEC at the end of the study (3rd year), leading to an exchangeable sodium percentage (ESP) of 8.5%. Another effect was the increase in sodium adsorption ratio (SAR) values at the end of the study period (6.2 meq l^{-1}), both parameters directly associated with effluent chemical properties. No difference was observed in soil structure when compared to plots without effluent applications (T0), as represented by the values of bulk density, porosity, infiltration rates and hydraulic conductivity. Our results reveal the importance of monitoring soil properties in the short run when paper mill industrial treated effluent is applied.

Key words: chemical and physical soil properties, sodium adsorption ratio, exchangeable sodium percentage, soil structure

INTRODUCTION

The surface of forest plantations in Chile was about 2 million ha until the end of 2018 (INFOR 2020), being the most important species Pinus radiata D. Don (PIRA), *Eucalyptus globulus Labill* (EUGL) and, *Eucalyptus nitens* (Deane and Maiden) Maiden (EUNI) plantations (Salas et al, 2016), representing 55.8% and 37.2%, respectively the first two species (INFOR 2020). Forest plantations are concentrated in Biobío region (37°S), with 39.2% of the national surface (902,259 ha) and the same proportion of *Pinus* and *Eucalyptus* plantation which corresponds to about 40 % of commercial forest surface of Chile (INFOR, 2020). Wood of both species are the main raw material for the pulp and paper mill industry in Chile.

Chilean pulp and paper mill industry produces 5,205 Mt and 4,947.2 Mt, respectively (INFOR, 2020) which is considered one of the most important pulp producers worldwide (Simao et al, 2018). This industry is growing every year following a worldwide tendency. As a consequence, the amount of generated waste is increasing, along with increasing concern and the importance of this topic. In Chile waste production is about 1,284MM m3 effluents to 297 waste water treatment plant (SISS, 2018), among those, Nueva Aldea pulp mill produces about 28 MM m3 per year of effluent, and according to Kinnarinen et al. (2016) global waste production is most likely over one million metric tons per year.

The disposal of wastewater from paper mill industries is a challenge considering the volume of effluents produced and because its reuse requires treatment in order to meet environmental standards and be economically attractive for increasing agricultural or forest productivity. In this sense, an alternative use of waste water started to be explored through irrigation of different productive soils. However, current research is limited and it has mainly focused on the use of water on agricultural soils from treated urban and industrial sewage (e.g. Santos, Fonseca et al., 2007; Gloaguen et al., 2007; Heidarpour et al., 2007). The study of the effects on soil properties of the use of waste from paper mill industries in soils is even more scarce (e.g. Rezende et al., 2010; Morris et al., 2012; Singh et al., 2013, Almeida et al., 2017).

The reuse of wastewater in forest soils is an interesting option despite that there is no, to our knowledge, irrigation research in soils of forestry use in Chile. However, it is known that forest productivity is limited during the warm season, as for example in the central region of the country (Uribe et al, 2014). Reuse of wastewater in forestry soils can be an option because forest trees are not part of the human diet; it will prevent its discharge into bodies of water in rivers and sea, improving the environmental image of the industry and be an alternative to apply in some areas, since forested areas soil are generally found at short distances from the factory facilities, and considerable volumes can be applied on small areas (Almeida et al., 2017). However, the latter implies the use of technified irrigation in consideration to de slope of the soils of forest use and the organic matter content of the wastewaters, among others. Moreover, this type of wastewaters is rich in Na and with a high Na adsorption ratio, and therefore its increase in soils can cause physical and chemical degradation and ultimately affect plant growth (Almeida et al., 2017; Rodriguez et al, 2018). Consequently, soil monitoring of their application in time is advisable.

Recent studies support the use of effluents for irrigation from paper mill industrial wastewater under tropical conditions (Almeida et al 2017; Rodriguez et al, 2018). However, there is a lack of knowledge about the impact on soil properties of its application in soils of forestry use in temperate conditions in the medium term. Moreover, the effect long term effects of irrigation with paper mill waste water requires to be assessed for commercial forest soil in such environment. Therefore, our objective was to study the impact on some relevant physical and chemical properties in a soil of forestry use and after three years of paper mill industrial treated effluent applications.

MATERIALS AND METHODS

Site location, treatments and experimental design

The experimental site is located in the semi-arid region of south-central Chile, known as the Secano Interior (interior dryland), is located on the eastward slope of the Chilean Coastal Mountain Range (H 18; 710645 E; 5940505 S), on the eastward slope of the Chilean Coastal mountain range (Uribe el al, 2014). According to Del Pozo and Del Canto (1999) climate is described as Mediterranean, with an average annual precipitation of 775 mm concentrated between May and September. The warmest months are January and February with a mean daily temperature of 20 °C (27 °C average daily maximum and 12 °C average daily minimum). Potential evaporation is 1.10 m yr^{-1} with the highest rates occurring in December, January, and February (CNR-CIREN-CORFO, 1997). Sources of surface water are limited at the site of study in dry season which limits agriculture activity and economic development of local communities. Soil is classified as Ultic Palexeralfs (Stolpe et al., 2008). Some chemical and physical properties are shown in Table 1

We evaluated the impact of irrigation with paper mill industrial treated effluents in soils of forestry use, in a *Pinus radiata* plantation clones, by comparing effects on soil with no irrigation (T0); and under irrigation with paper mill effluents (T1). Treatments are replicated four times in a random block design. Irrigation was applied uniformly with a microjet system, and the chemical composition of irrigation wastewater is shown in Table 2. Microjet system was chosen to avoid runoff and considering the organic matter content of the waste water that could produce problems in the drop irrigation system. The amount of water applied as irrigation to each plot was about 600 mm, during the warm/dry season (October-March period), which was determined based on the requirements of the plants and the climatic conditions. A pilot experiment was conducted, in which soil was incubated to which cellulose effluent was applied. The results indicated that an amount of 200 mm per season apparently did no cause changes in soil properties. Since. 600 mm was the water deficit in the area for pine, this amount was applied for each period according to Table 3. Accordingly, two lysimeters per plot at two depths (0-30, 60 cm) were established to monitor possible lixiviation, despite the technified irrigation system used.

Soil sampling

Soil samples were taken between the rows plantation, along the irrigation lines. For the soil chemical evaluation, 40 subsamples were collected for both treatments from 0-20 cm depth and composite samples using a spad. For physical evaluation, undisturbed soil samples were collected for both treatments from 0-20 cm depth, which range is expected to have the highest effect of irrigation, because trees consume higher amount of water and nutrients from that depth, as indicated by Tromp-van Meerveld and McDonnell (2006); and Liu et al (2019). Eight undisturbed soil samples for each plot were obtained using a standard cylindrical cores of 250 cm^3

Physical and chemical laboratory analysis

Analyses of soil physics and chemistry were done after each irrigation cycle; samples analyzed with saturated paste, and after the following winter in each period of study, in order to assess the effect of precipitation during winter season rains on soil properties.

Physical properties determined were bulk density following the cylinder method and total porosity as described in Sandoval et al (2013). Field capacity (-33 kP) and permanent wilting point (-1.5MP) were quantified as described for Monteith y Unsworth, 2013. K Sat Saturated hydraulic conductivity; water storage; infiltration rate were quantified as described for Guevara y Márquez (2012), Electrical Conductivity (EC), SAR (sodium adsorption ratio); ESP (Exchangeable Sodium Percentage (ESP) Sadzawka et al (2006).

Chemical analysis conducted for soil organic matter and exchangeable bases (K, Ca, Mg and Na) were determined following protocols described by Sadzawka et al (2006).

Wastewater and soil analysis methods

The sampling of waste water was carried out by taking water sub-samples every 1 hour from a treatment system at a Kraft wood pulp mill in Chile, until completing a period of 24 hours. The physical and chemical parameters of paper mill effluent were analyzed by standard methods described by APHA (2005). Chemical properties of soil (taken in different pots) were analyzed by standard methods described by Trivedy and Goel (1986). The pH of the sample was measured by calibrating digital pH meter with buffer solution of pH 4 and 9. Total dissolved solids (TDS) of the sample were determined by TDS meter. Conductivity of the effluent sample was measured with a probe and conductivity meter. Chlorides of the samples were estimated by silver nitrate solution, Sodium, Potassium, Calcium and Magnesium in effluent and soil were measured by Flame Photometer. Alkalinity of the sample was measured by EDTA titration method. (Gupta et al, 2016)

Gravimetric humidity; pH soil:water ratio 1:2,5 per potentiometric; interchangeable aluminum (Al) by potassium chloride extraction (KCl) 1 molar and determination by atomic absorption spectrophotometry; electrical conductivity (EC) by saturation and conductivity extract; organic matter (MO) by oxidation with dichromate in sulphuric acid and colorimetry; calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) available by extraction with 1 molar ammonium acetate pH 7 and atomic absorption spectrophotometry; iron (Fe), copper (Cu), manganese (Mn) and zinc (Zn) available by extraction with DTPA and atomic absorption spectrophotometry; phosphorus (P) by extraction with 0,5 molar sodium bicarbonate and colorimetry with molybdenum blue (Olsen; Sadzawka et al., 2006).

Statistical analysis

Data were analyzed for one-way analysis of variance (ANOVA) to determine the effects of waste-water irrigation to soil properties. Used standard deviation for chemical and physical soil characteristic, in case of ANOVA with significant differences, Fisher's least-significant difference (LSD) multiple comparison test was then used, parametric tests were realized by tests for normal distribution per plot, and for homogeneity of variance between plots. A significance level of $P < 0.05$ was applied in statistical tests. With the help of MS Excel (Microsoft Corporation. (2018). Microsoft Excel. Retrieved from https://office.microsoft.com/excel), INFOSTAT (2020).

RESULTS AND DISCUSSION

The irrigation with industrial effluent did not cause lixiviates at any time (they were not observed when collecting). At the same time the irrigation treatment did no cause either significant changes in soil chemical properties as pH, organic matter (OM), K, Ca and Mg exchangeable cations (Figures 1-3), with the exception in Na concentrations (Figure 4). Some reduction in OM after the third year of irrigation between non-irrigated (T0) and irrigated plots (T1), can be associated to better moisture conditions that lead to higher microorganism activity. Despite the fact that the effluent contains organic matter as indicated by the BOD values (Table 2), these are low and increases in SOM are not evident after three years of effluent applications. Our results are different from other studies that found increases in organic carbon after paper mill effluent applications (Lin et al., 2008, Singh et al., 2012), but these authors applied wastewaters with high organic matter contents. Nevertheless, our results are similar to the study of Almeida et al. (2017) that did not found increases in organic carbon (OC) after six years of effluent applications.

Both Ca^{2+} and K^{+} in soil were low (e.g. between ranges of 2.1-4.0 and 0.16-0.30 cmol kg^{-1}, respectively), and medium to high in the case of Mg^{2+} (e.g. 0.46- >0.8 cmol kg^{-1}). However, Na^{+} in soil showed high to very high concentrations (e.g. >1.0 cmol kg^{-1}), as a result of the high concentrations of this element in the paper mill effluents applied (Table 2). On the other hand, Na^+ can displace other exchangeable bases in the soil by mass effect, avoiding its sorption to soil sites, and partially explaining the low contents observed, although naturally these soils have low exchangeable bases content (Table 1), because it is a soil with a high level of degradation.

The higher Na^+ content also increased the CEC at the end of the study (3rd year), leading to an exchange sodium percentage (ESP) of 8.5 (Figure 5). This phenomenon was also observed in a soil planted with eucalyptus and after six years of paper mill effluents applications (Almeida et al., 2017), where the ESP reached 11.68%. Both results support the importance of soil properties monitoring in situations where effluent is applied. The reuse of wastewater caused as well an increase in sodium adsorption ratio (SAR) values at the end of the study period, which can be directly associated with effluent chemical properties (Table 2). As reported by Almeida et al (2017) small changes in EC values during the application period of effluents, suggest a low salt concentration that combined with high values of SAR (Figure 9) and/or high Na+ contents in the soil solution can cause an expansion of the diffuse double layer in the soil, favoring soil dispersion. Although no negative signs were found in the Pinus trees after 3 years.

The potential risk of the effluent of causing soil salinity problems is shown at the end of the period by the very high Na^+ content (Figure 4), and CEC, SAR and ESP values found in the irrigated plots (T1) (Figures 5-6). A similar tendency was reported by Almeida et al (2017) but after six years of effluent applications in a *eucalyptus* planted tropical soil, revealing the importance of the interaction between soil type, climate and wastewater quality. In our temperate conditions precipitation during winter time is relevant in controlling salt concentration in the soil, as a result of effluent applications. Therefore, future soil properties monitoring should include water-dispersible clay (WCD); clay dispersion index (CDI); aggregate size distribution as estimated by geometric mean diameter (GMD); mean weight diameter (MWD) (e.g. Almeida et al., 2017), in order to detect possible soil structure degradation.

At the end of the study in plots under *Pinus* with irrigation (T1), no difference was observed in soil structure when compared to plots without effluent applications (T0), as represented by the values of bulk density (Bd) (Figure 7), total porosity (Figure 8), infiltration rates (figure 9) and saturated hydraulic conductivity (Figure 10). Although the latter showed some tendency to increase during year 1 and 2, this is not supported by the analysis of other physical parameters. However,changes in structure for soils is more notorious in soils not degraded. In our case, soils are already physically and mechanically affected, and therefore this fact difficults the evaluation of negative effects after 3 irrigation cycles with paper mill effluent

CONCLUSIONS

The reuse of treated wastewater from an industrial paper mill effluent to soil of *Pinus* plantation of Southern Chile after three years' applications had an impact in some of the soil properties, specially soil Na^+ content, and SAR and ESP values, revealing the importance of soil monitoring in order to observe possible soil structure degradation. However, our results also show that paper mill industry effluents can be used for pinus trees under technified irrigation management and a continuous program for monitoring soil properties in the medium and long term.

ACKNOWLEDGEMENTS

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Table legends

Table 1: Chemical and physical characteristics of soil at the experimental site.

Table 2: Chemical composition of paper mill waste water as irrigation source to a forest plantation soil.

Table 3: Amount of effluent applied for irrigation to soil at the experimental site.

Figure legends

Figure 1: Changes in soil pH, irrigated with and without paper mill effluent treated in three irrigation cycles

Figure 2: Content of soil organic matter (SOM), irrigated with and without paper mill effluent treated

Figure 3: Potassium, calcium and magnesium content in soil treated with paper mill effluent, before and after three irrigation cycles.

Figure 4: Sodium content in soil treated with paper mill effluent, before and after three irrigation cycles.

Figure 5: Electric conductivity in soil treated with paper mill effluent, before and after three irrigation cycles.

Figure 6: Sodium absorption ratio (SAR) and exchange sodium percentage (ESP) in soil treated with paper mill effluent, before and after three irrigation cycles.

Figure 7: Changes in bulk density of soil before and after irrigation with paper mill effluent in three irrigation cycles

Figure 8: Distribution of soil porosity before and after irrigation with paper mill effluent

Figure 9: Soil infiltration rate in soil treated with paper mill effluent, before and after three irrigation cycles.

Figure 10: Saturated hydraulic conductivity of soil porosity before and after irrigation with paper mill effluent in three irrigation cycles

Table 1:.

Chemical properties	**Values**
Cloruros (mg L^{-1})	336,95
Cobre (mg L^{-1})	<0,01
Conductividad Eléctrica	3,93
DBO_5 (mg L^{-1})	6,4
DQO (mg L^{-1})	242
Fósforo (mg L^{-1})	1,5
Potasio (mg L^{-1})	88.5
Calcio (mg L^{-1})	49.5
Magnesio (mg L^{-1})	9.8
Hierro (mg L^{-1})	0,04
Manganeso (mg L^{-1})	0,03
Nitrógeno Total (%)	0,90
$NO_3 + NO_2$ (mg L^{-1})	0,05
Nitrógeno Total Kjeldahl (mg L^{-1})	0,85
pH	7,5
Sodio porcentual (%)	82,4
Sólidos Suspendidos Totales (mg L^{-1})	2,5
Sulfatos (mg L^{-1})	452,5
Zinc (mg L^{-1})	0,04

Fuente: Elaboración propia.

Table 2:

Period of effluent application	Applied effluent (mm)
2014-2015	595
2015-2016	608
2016-2017	608
TOTAL	**1,811**

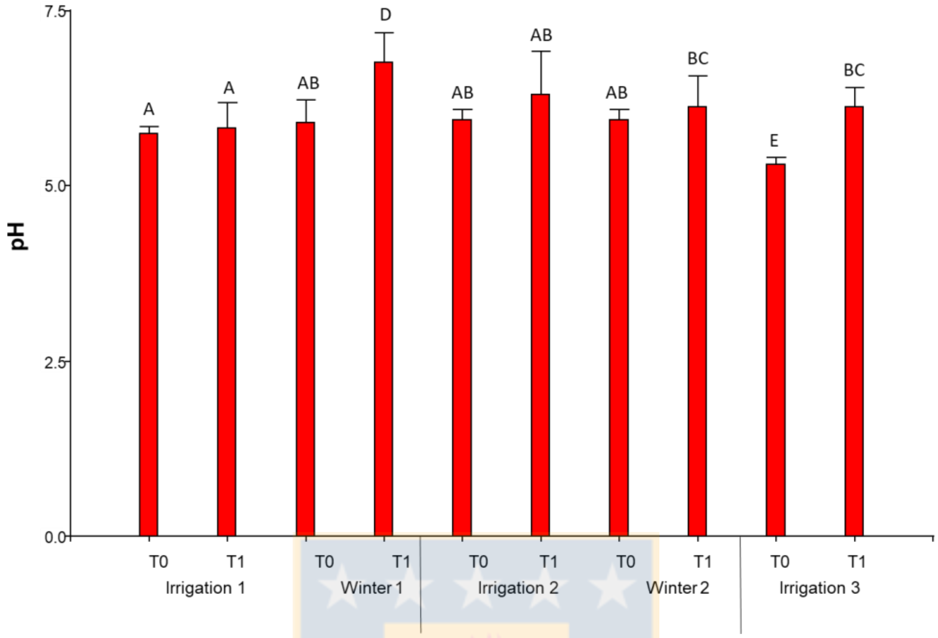
Fuente: Elaboración propia.

Table 3:

Soil characteristics			
Chemical		Physical	
	Values		Values
C.E. (dS/m)	0,25	Bulk density (Ton/m3)	1.4
pH water	5,26	Total porosity (%)	48.6
MO (mg/kg)	1,00	Field capacity (%)	41.3
N Total (mg/kg)	4.41	Wilting point (%)	22.9
P (mg/kg)	2,97	Hydraulic conductivity (m/day)	0.2
K (mg/kg)	0,21		
Ca (mg/kg)	2,24		
Mg (mg/kg)	1,16		
Na (mg/kg)	0,05		
Na (mg/kg)	10,46		
Bases (mg/kg)	14,07		
Sat Al (mmol/L)	6,63		

Fuente: Elaboración propia.

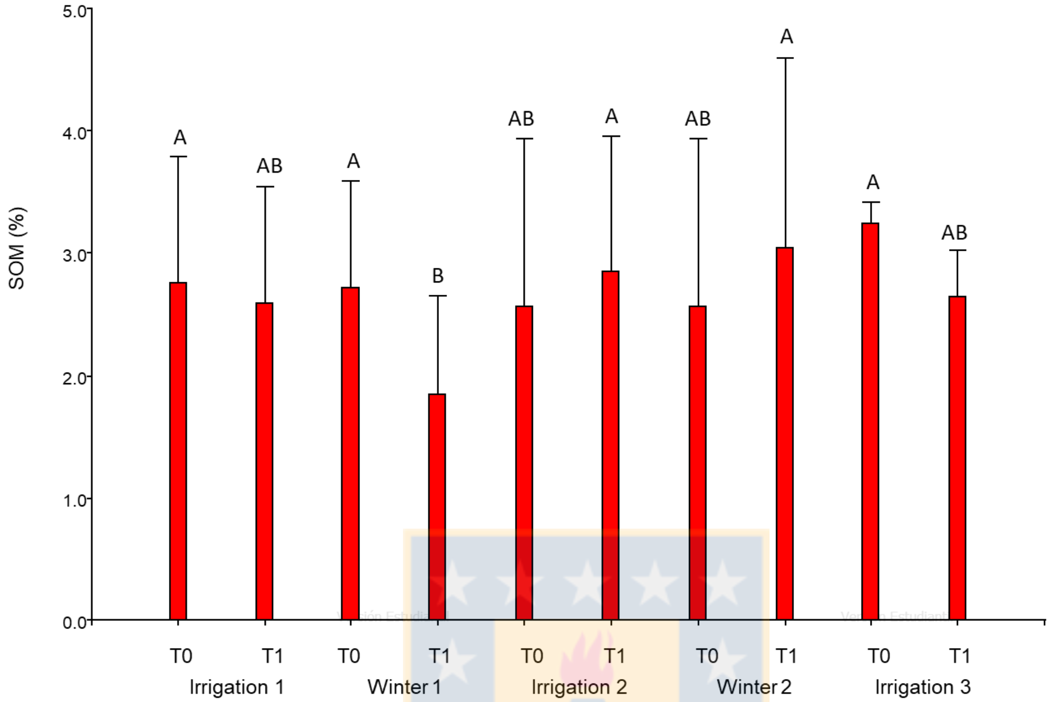
Figure 1:



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test ($P < 0.05$). Bars represent standard deviation. T0 no irrigation; T1 With irrigation.

Fuente: Elaboración propia.

Figure 2:



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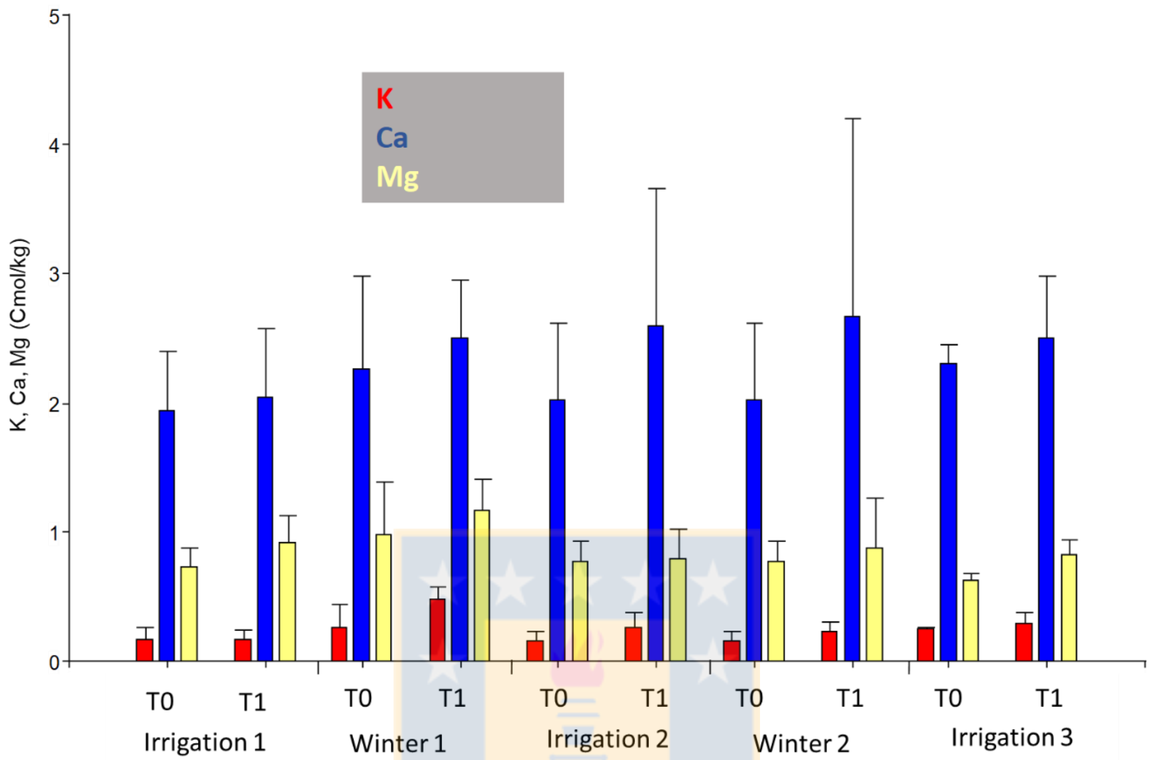
Fuente: Elaboración propia.

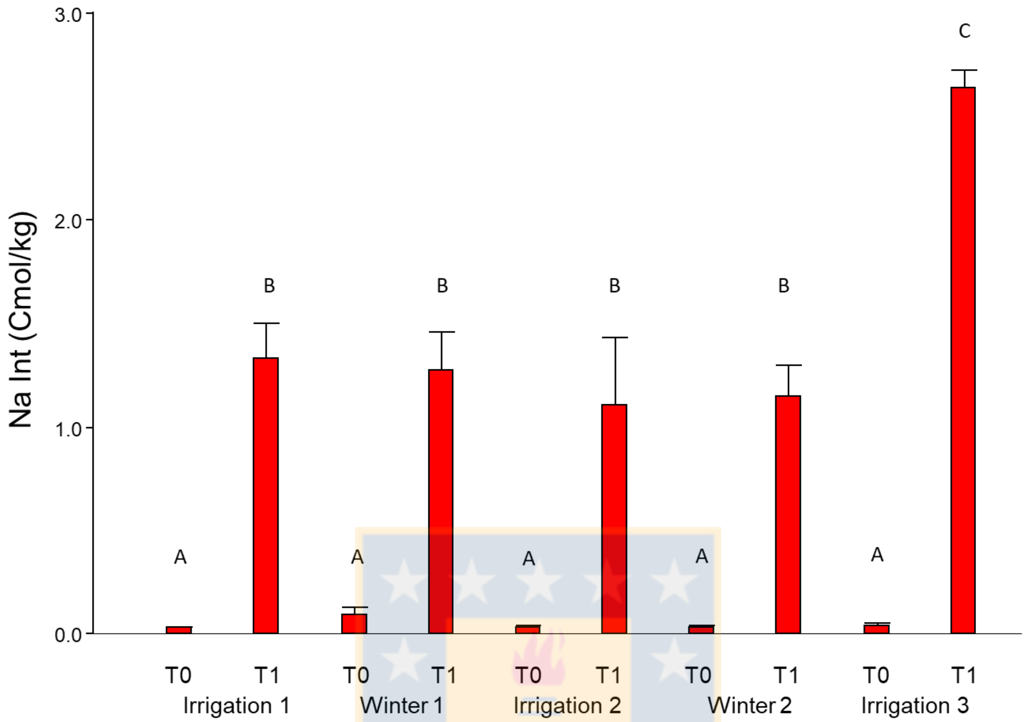
Figure 3



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test ($P < 0.05$). Bars represent standard deviation. T0 no irrigation; T1 With irrigation

Fuente: Elaboración propia.

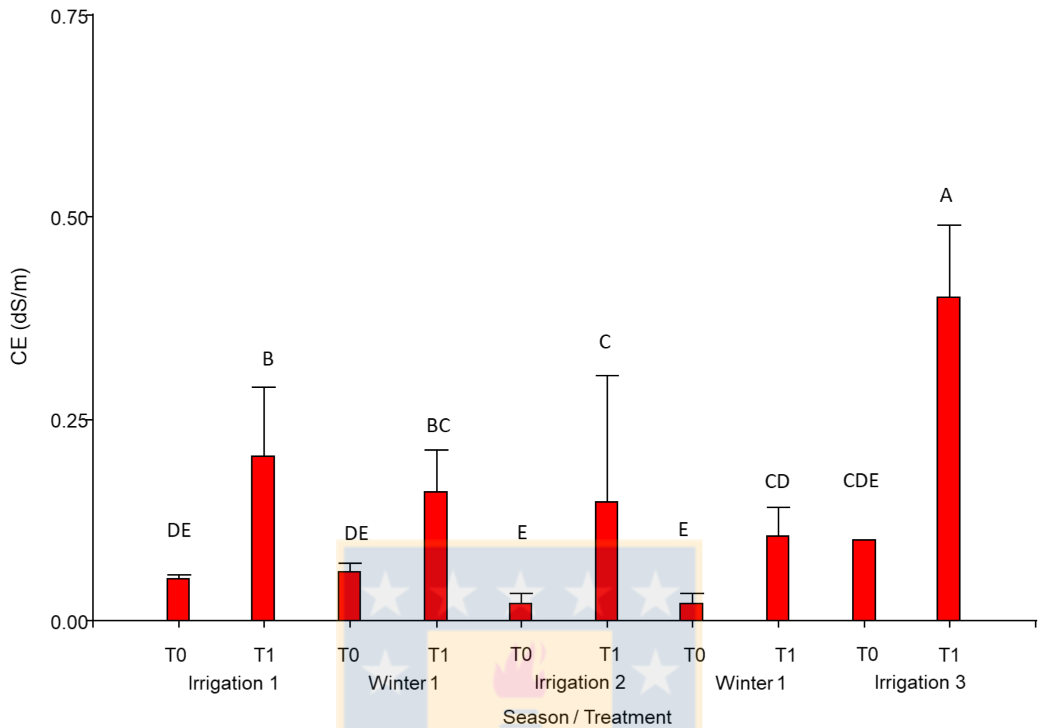
Figure 4:



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test ($P < 0.05$). Bars represent standard deviation. T0 no irrigation; T1 With irrigation

Fuente: Elaboración propia.

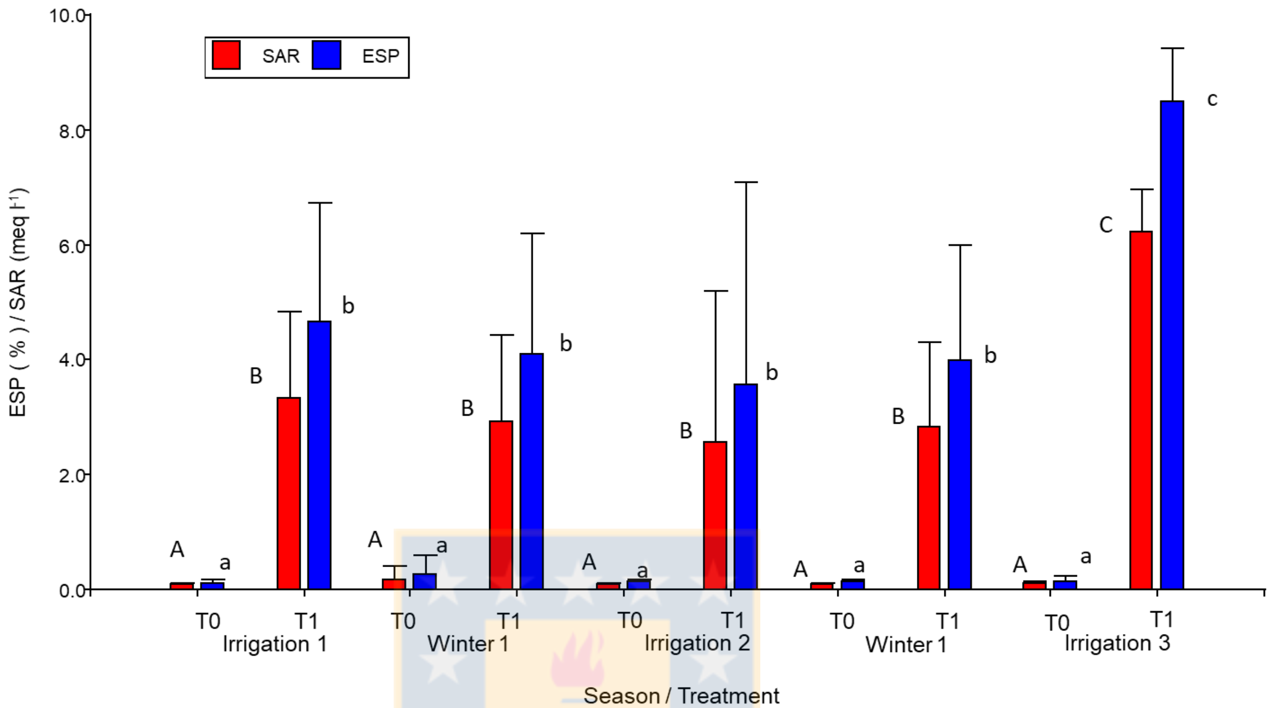
Figure 5:



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test ($P < 0.05$). Bars represent standard deviation. T0 no irrigation; T1 With irrigation.

Fuente: Elaboración propia.

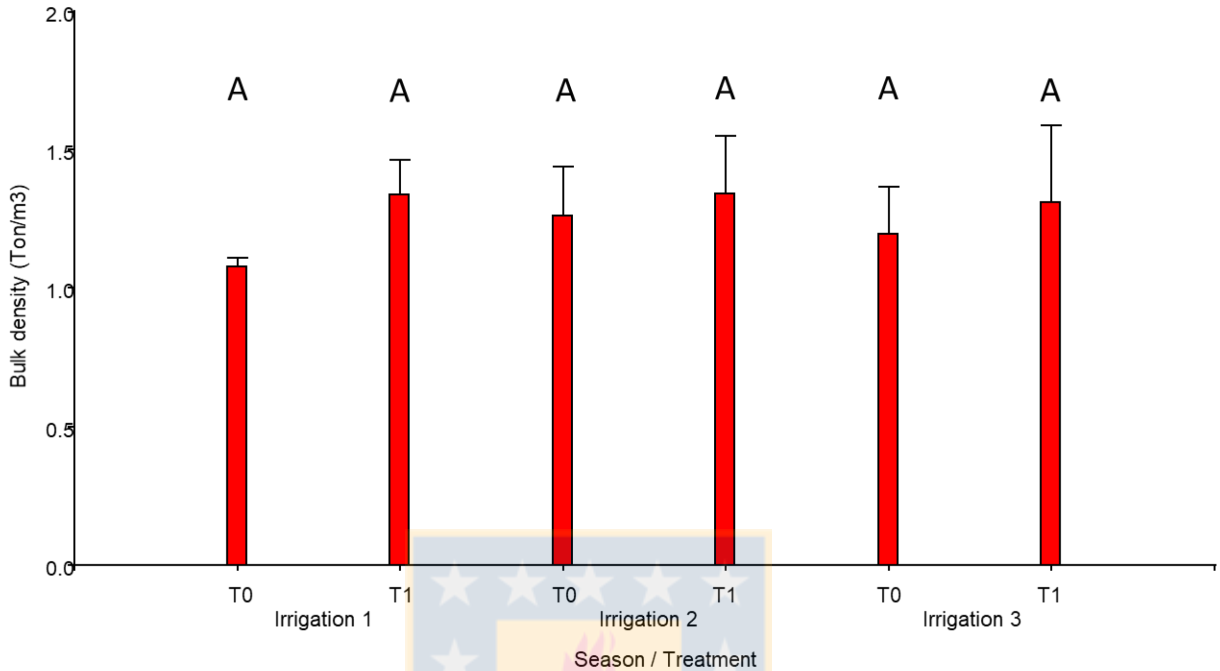
Figure 6:



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test ($P < 0.05$). Bars represent standard deviation. T0 no irrigation; T1 With irrigation.

Fuente: Elaboración propia.

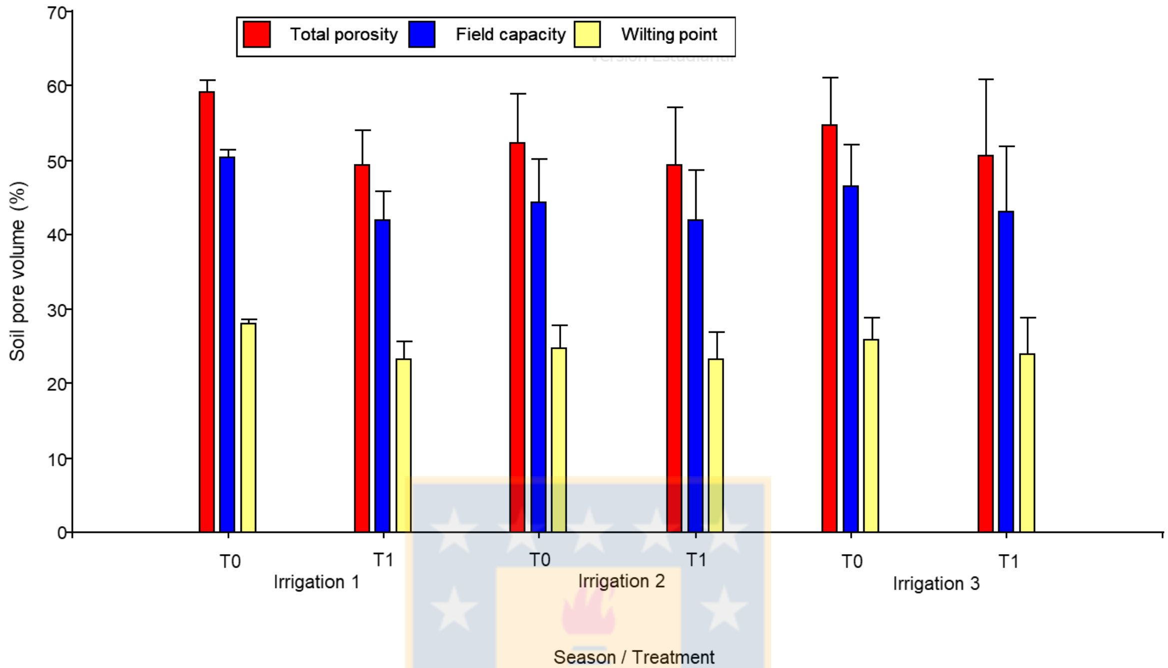
Figure 7:



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test ($P < 0.05$). Bars represent standard deviation. T0 no irrigation; T1 With irrigation.

Fuente: Elaboración propia.

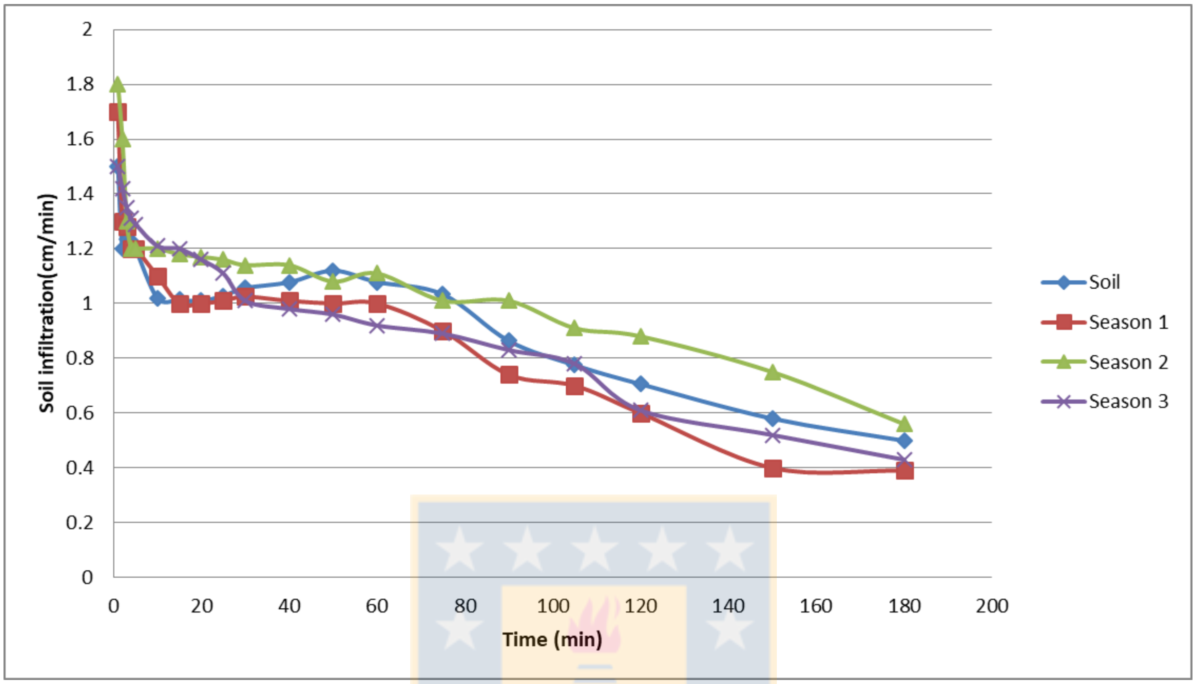
Figure 8:



Bars represent standard deviation. T0 no irrigation; T1 With irrigation.

Fuente: Elaboración propia.

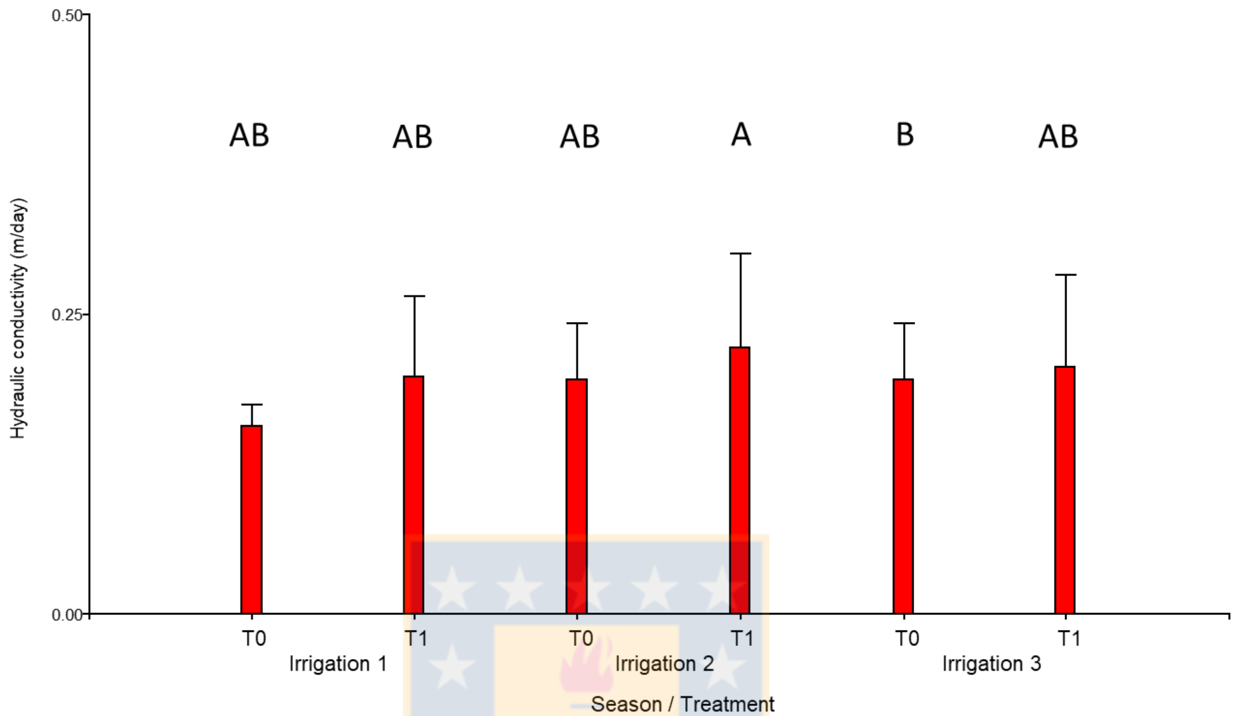
Figure 9:



Soil indicated initial condition on soil, season evaluations after irrigation with paper mill effluent.

Fuente: Elaboración propia.

Figure 10:



Different letters on the columns imply a significant difference according to Fisher's least-significant difference, LSD test (P < 0.05). Bars represent standard deviation. T0 no irrigation; T1 With irrigation.

Fuente: Elaboración propia.

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CAPITULO 3.

CONCLUSIONES GENERALES Y PROYECCIÓN

Conclusiones generales

La utilización de efluente tratado de la fabricación de papel como riego en suelos de uso forestal en este estudio muestra una alteración de la porosidad y las características químicas del suelo. Nuestsro resultados indican que la magnitud de dichas modificaciones, para las condiciones de los suelos usados en la presente investigación, está en función de 3 factores principales. Primero, los elementos contenidos en los efluentes utilizados; segundo, las características del suelo, en términos de su capacidad buffer frente a estos elementos; y tercero, del período de lluvias invernal, puesto que la precipitación permite desplazar ciertos elementos y evitar que su efecto sea permanente. No obstante lo anterior, los aumentos en los contenidos de Na en el suelo, asociado a mayores valores de la relación de absorción de sodio (RAS) y Conductividad eléctrica (CE) al final de la tercera temporada de riego, indican que su aplicación (efluentes) podría estar limitada en el tiempo y que es necesario desarrollar el criterio de aplicación en función de los tres factores antes mencionados. En términos de las características físicas, la porosidad mostró variaciones, aunque no en la magnitud, para el período, que signifique una degradación de la estructura del suelo, lo que reafirma que éste reacciona frente a las aplicaciones de estos efluentes en función de sus características intrínsecas.

Proyección

La aplicación de efluentes tratados en suelos de uso forestal es interesante porque los árboles no son un componente de la cadena alimentaria y demandan más agua en comparación a otros cultivos; y por lo tanto grandes volúmenes pueden ser aplicados en áreas reducidas, ofreciendo una oportunidad de revalorización de estos efluentes generados del proceso industrial de obtención de celulosa. Sin embargo, y como lo demuestran nuestros resultados las aplicaciones de estos efluentes tratados, van a modificar tanto a las características químicas como físicas de los suelos, por lo que es necesario el desarrollo de tecnología que permita su uso. Por otro lado, la magnitud de los cambios obedece a características intrínsecas de cada suelo, asociado con la variable climática y la naturaleza del efluente. Si aceptamos esta premisa como válida, para un correcto criterio de aplicaciones, se debe determinar para cada situación volúmenes y tiempos (períodos) de aplicación, de manera de preservar las características de los suelos. En este aspecto es relevante la determinación de las curvas de adsorción y desorción de compuestos presentes en los efluentes, como pueden ser Na, Cl, metales pesados entre otros, con el objetivo de definir un criterio de riesgo de aplicaciones de efluentes y a partir de ese criterio de riesgo, los criterios de aplicaciones de efluentes. Este criterio de riesgo, deberá involucrar no solo a la componente química del suelo, sino que también a su comportamiento en términos de cambios a nivel de la porosidad de esos suelos. Por otro lado, estas definiciones de riesgos de aplicación se hacen aún más evidentes cuando la utilización de este tipo de aguas residuales (o de otro origen) se orienta a la producción de alimentos, y en consideración a la escasez del recurso agua a nivel global.

A partir de lo anterior, una línea completa de investigación, en relación al uso de efluentes de diverso origen se plantea, no solo como plausible sino que necesaria. En el mundo se ha utilizado las aguas residuales, pero se deberá ajustar los criterios de utilización, puesto que en el escenario de restricción hídrica a escala global, el suelo jugará un rol fundamental en el desarrollo de criterios de eficiencia hídrica y uso seguro de estos recursos para la producción de alimentos.