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INDICES DE CALIDAD DEL SUELO Y ALMACENAMIENTO DE CARBONO BAJO MANEJO SILVOPASTORIL: RECUPERACION DE BOSQUES NATIVOS DEGRADADOS EN LA ZONA PRECORDILLERANA DEL CENTRO-SUR DE CHILE.

Tesis para optar al grado de Doctor en Ciencias Forestales

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RESUMEN

Cerca del 63% de los procesos de degradación a nivel mundial se relacionan con el suelo (30% de manera directa), afectando 40% de la superficie agrícola global (9% severamente), generando a su vez 38% de las emisiones globales de gases de efecto invernadero (GHG). En Chile, el 49.1% del territorio presenta degradación del suelo, encontrándose inhabilitada 30.4% de la superficie agrícola histórica. Como parte de los sistemas agroforestales (AFS), los sistemas silvopastoriles (SPS) (asociaciones intencionales de árboles (T_{REE}), herbáceas (H_{RB}) y animales (A_{NM}), son reconocidos como usos recomendables de la tierra frente a los escenarios de seguridad alimentaria y cambio climático, siendo capaces de promover la conservación del suelo y sus funciones ecosistémicas, denominas "*calidad del suelo*" (SQ). Los SPS destacan entre los distintos AFS por su alta capacidad de secuestro subterráneo de carbono (C) (C→SOC) (1.8 - 6.1 Mg SOC ha año^{-1}). Al respecto, se han identificado 25 principales mecanismos relacionados con el C→SOC-SQ, 12 como funcionalidades individuales (6 $T_{REE,}$ 3 $H_{RB,}$ 3 A_{NM}) y 13 interactivos (8 mutialistas, 5 tripartitos). El objetivo del presente estudio fue determinar el efecto de SPS-AFS bajo distintas densidades y condiciones arbóreas (niveles de degradación previos) en la recuperación de suelos de bosques templados nativos de *Nothofagus* en la precordillera del centro-sur de Chile. Se evaluaron variaciones de SOC y SQ (estimada a través de índices de SQ (SQI), y a su vez indicadores de SQ (S_{IND}) que corresponden a distintas propiedades físicos-químicos-biológicos edáficas) a 0-5 y 5-20 cm, entre los distintos SPS, y en comparación con el AFS principal de agrobosques ($A_{GRO}F_{RST}$) manejado como banco de proteína para SPS-A_{NM}. Los resultados establecieron que los SPS con promedios intermedios de luz entrante ($I_{N}L$) (65-75%) y densidades arbóreas (T_{DEN}) de 134 ha^{-1} (SPS_{SOP}), presentaron mayores potenciales de C→SOC (0-20 cm) (7.5 Mg ha^{-1} año^{-1}) (SQI: 28.8) en comparación con bajo sombreado ($I_{N}L$: 85-95% , T_{DEN}: 60) (SPS_{O}) (4.8 Mg ha^{-1}año^{-1}) (SQI: 29.8), alto sombreado ($I_{N}L$:45-55% T_{DEN}: 258 ha^{-1}) (SPS_{SC}) (1.6 Mg ha^{-1} año^{-1}) (SQI: 37.6). Sin embargo el sistema $A_{GRO}F_{RST}$ ($I_{N}L$: 35-45%, T_{DEN}: 446 ha^{-1}) (6.88 Mg ha^{-1} año^{-1}) (SQI: 37.8) y SPS ($I_{N}L$: 35-45%), (T_{DEN}: 173 ha^{-1} -*N. obliqua:* 133 –*N. dombeyi:*40-) (4.83 Mg ha^{-1}año^{-1}) (SQI: 31.0). En relación a la SQ, ésta presentó una alta variabilidad ($p < 0.05$) en los S_{IND} químicos y microbiológicos, no así físicos, relacionable con las características del sustrato y prácticas de manejo, donde se observaron mejores condiones generalizadas en la profundidad 0-5 cm, demostrando la efectividad de los SAF-SPS en la generación y almacenamiento de SOC, mejorando las potencialidades del suelo.

ABSTRACT

About 63% of lad degradation processes worldwide are related to soil (30% directly), affecting 40 of the global agricultural area (9% severely), also generating 38% of total greenhouse emissions (GHG). In Chile, about 49.1% of national territory presents soil degradation mostly due to the over-utilization of natural resources, including 30.4% of the historical agricultural area is currently unsuitable. As a part of agroforestry systems (AFS), silvopastoral systems (SPS), defined as intentional associations of trees (T_{REE}), herbaceous (H_{RB}) and animals (A_{NM}), are internationally recommended land uses facing food security and climate change scenarios, due to their ability to promote soil conservation and its ecosystem functions, collectively referred to as "soil quality"(SQ). Moreover, SPS stand out among the different AFS sequestering soil organic carbon (C) (CO_{2eq} →SOC) at 1.8 - 6.1 Mg SOC ha yr^{-1}. In this regard, through a literature review on SPS , 25 main mechanisms related to C→SOC-SQ have been identified, 12 as individual funcionatilites (6 $T_{REE,\ 3}$ $H_{RB,}$ 3 A_{NM}) and 13 interactive (8 mutualist, 5 tripartite). Accorddingly, the objective of this study was to determine the effect of SPS under different tree densities (corresponding to previous degradation levels) on soil reclamation of native *Nothofagus* temperate forest in the pre-mountain range of south-central Chile. For that purpose, variations of SOC and soil quality (estimated through SQ indexes (SQI), on the basis of soil indicators (S_{IND}) (corresponding to different physical-chemical-biological soil properties-processes) were evaluated (at 0-5 and 5-20 cm), between different SPS and in comparison with the major AFS agro-forest ($A_{GRO}F_{RST}$). The results established that SPS with intermediate averages of incoming light (I_NL) 65-75%) and tree densities (T_{DEN}) of 134 trees ha^{-1} exhibited C→SOC potentials (0-20 cm) (7. 5 Mg ha-1 yr^{-1}) (SQI: 28.8) compared to low shading (INL:85-95% , TDEN: 60)(SPSO) (4.8 Mg ha-1yr-1) (SQI: 29.8), high shading (INL:45-55% TDEN: 258 ha^{-1}) (SPSSC) (1.6 Mg ha^{-1} año^{-1}) (SQI: 37.6) . When comparing $A_{GRO}F_{RST}$ and SPS, the results were [(I_NL:35-45% , T_{DEN}: 446 ha^{-1}) (6.88 Mg ha^{-1}año^{-1}) (SQI: 37.8)] and [(I_NL:35-45%), (T_{DEN}: 173 ha^{-1} -*N. obliqua: 133 –N. dombeyi:40*-) (4.83 Mg ha^{-1}año^{-1}) (SQI: 31.0)], respectively. The SQ was clearly. presented a high variability ($p < 0.05$) in the chemical and microbiological S_{IND}, but not physical, related to the characteristics of the substrate and management practices, where better generalized conditions were observed in the 0-5 cm depth, demonstrating the effectiveness of the SAF-SPS in the generation and storage of SOC, improving the soil potentialities.

INTRODUCCIÓN GENERAL

Las complejas interacciones del ser humano con su entorno han modificado flujos de materia y energía a nivel global, generando desbalances en los principales ciclos biogeoquímicos (e.g. C y nitrógeno (N)). Lo anterior promueve entre otros fenómenos, el acelerado enriquecimiento atmosférico con GEI (e.g. dióxido de C (CO_2), óxido nitroso (N_2O), metano (CH_4)), propiciando alteraciones en los patrones de radiación (e.g. calentamiento global), que afectan directa o indirectamente la estructura, abundancia, distribución, relaciones y procesos dentro de la biósfera (Lashof y Ahuja, 1990; Rohde, 2007; Meinshausen et al., 2009; Al-Ghussain, 2019). Por ejemplo, los cambios en el uso del suelo (e.g. agricultura, actividad forestal), contribuyen anualmente con 10-12 Pg $CO_{2\ eq}$, lo que corresponde al 24-33% del total de emisiones globales de GEI (49 Pg de $CO_{2\ eq}$ año^{-1}) (Hegerl et al., 2007; Edenhofer, 2015), con un incremento de 24% en el mismo periodo (Lorenz y Lal, 2014; Smith et al., 2015). Otro efecto principal asociado a variaciones no sustentables de los patrones vegetacionales, es la degradación del suelo (e.g. erosión), referida como la limitación o incluso pérdida de su productividad y capacidad de prestación de servicios ecosistémicos (e.g. regulación hídrica), y que representa uno de los mayores impactos antropogénicos sobre los ciclos naturales. Al respecto, se estima que mundialmente alrededor de 1094 Mha se encuentran erosionadas por agentes hídricos (69% severamente), mientras que 549 Mha por la acción eólica (54% severamente) (Lal, 2003). Regionalmente, Sudamérica se sitúa como la región con mayores tasas de erosión a nivel mundial, promediando pérdidas del orden de 22.1 Mg ha año^{-1}, circunstancia estrechamente ligada a la acelerada pérdida del 8.7% de superficie forestal durante las últimas décadas (Lal, 2003; Casanova et al, 2013).

Al respecto, diversos esfuerzos de carácter internacional se han realizado para afrontar las contingencias ambientales descritas (e.g. Convención Marco de las Naciones Unidas Sobre el Cambio Climático, Agenda 2030 para el Desarrollo Sostenible), donde el $CO_2 \rightarrow COS$ ha sido una estrategia principal. De entre los usos recomendados de la tierra capaces de promover $CO_2 \rightarrow COS$, los SAF poseen el mayor potencial con 600 Tg C año^{-1}, seguidos de los manejos sustentables de praderas-pastoreo, forestal eficiente, coberturas en superficies agrícolas, la restauración de zonas degradadas y manejo de arrozales con 375, 250, 150, 50 y 20 Tg C año^{-1}, respectivamente (Abbas et al., 2017). Dentro de los SAF, los SPS registran las más altas tasas de $CO_2 \rightarrow COS$ (1.8-6.1 Mg C ha^{-1}), maximizando la captura y aprovechamiento de recursos del medio (e.g. energía solar, agua, nutrientes) a partir de interacciones biofísicas de sus componentes, que dan lugar a procesos bio-constructivos y bio-protectivos (Nair et al., 2008; Alonso, 2011; Udawatta y Jose, 2011).

Siendo el C orgánico del suelo (SOC), el principal atributo pedogénetico, regulador de un gran número de procesos edáficos (e.g. disponibilidad y ciclaje de nutrientes, actividad y diversidad micro-meso-macro biológica, procesos de agregación, capacidad de retención de humedad) (Sollins, 1996), de crucial importancia no únicamente dentro de ambientes productivos de manejo (e.g. agro sistemas), sino en el total de sus funciones ambientales. Al respecto, durante las últimas décadas se introdujo el término "*Calidad del Suelo*" (SQ), refiriendo la capacidad de un determinado suelo para promover simultáneamente actividad biológica y servicios ecosistémicos, que resulten en un apropiado desarrollo vegetal, animal y consecuente bienestar humano. La SQ se determina a través de indicadores de calidad de suelo (S_{IND}), que corresponden a los distintos tipos de propiedades edáficas (e.g. pH, conductividad hidráulica, actividad enzimática) (Linn y Doran, 1984). Por tanto, en virtud del constante aporte de materia orgánica generado dentro de los SPS (e.g. hojarasca), que es eventualmente transformada e incorporada al suelo (SOM), siendo aproximadamente 58% SOC (Gasch y DeJoung-Hughes, 2019), mejorará progresivamente la SQ.

Al ser Chile un patrimonio genético mundial debido a la gran cantidad de endemismos vegetacionales que posee (1957), equivalente al 50.3% del total de especies nativas, distribuidas principalmente en 35 nichos ecológicos (CONAF, 2017). Se estima además que cerca de 13.5 Mha del territorio nacional corresponde a la categoría de bosques nativos, correspondiente a 85% de la superficie forestal total (INFOR, 2013). Sin embargo, vastas áreas con vegetación nativa han permanecido por largos periodos bajo intensas presiones antropogénicas, bien por sobre pastoreo, sobre talaje, habilitación de cultivos agrícolas, etc. (Dube et al., 2018). De las 75,6 Mha que conforman la superficie peninsular, se determinó que cerca del 49,1% presenta limitaciones en la productividad asociadas a la degradación- baja fertilidad del recurso suelo (Flores et al., 2010) (11.1% en condición ligera, 13.8% moderada, 14.8% severa y 9.2% muy severa), siendo el factor antropogénico el agente causal principal (Casanova et al, 2013).

Particularmente, en el centro-sur de Chile, las regiones del Ňuble y Biobío, son una de las principales zonas con tradición agrícola y forestal, ocupando el 3er puesto en términos de superficie cultivada a nivel nacional (ODEPA, 2012), mientras que 1º en plantaciones forestales y 5º en bosque nativo (CONAF, 2011). Debido al histórico sobre aprovechamiento principalmente de recursos forestales, se estima que el 74,3% de los suelos de la Cuenca del río Biobío (2.4 Mha) presenta degradación del suelo. Esta situación es extrapolable a la mayoría de las cuencas regionales, siendo la zona precordillerana, una de las más críticas (76,0% de su superficie degradada), debido a su importancia como reservorio de especies nativas y regulación del ciclo hidrológico (Carrasco et al., 1993).

Distintos estudios sobre bosques nativos se han realizado contemplando diversos enfoques como: bosques prístinos (e.g. Pérez et al. 1998, Perakis y Hedin, 2001; Leiva y Godoy, 2001; Pérez et al. 2004), comparación de bosques prístinos y secundarios (Rivas et al., 2007; Pérez et al., 2009), comparación en la actividad biológica de bosque sobre maduro siempre verde y secundario caducifolio (e.g. Alvear et al., 2007), efecto de tala selectiva sobre CO_2→COS y otras propiedades del suelo (e.g. Panichini et al., 2017), comparación de propiedades de suelos equiparables bajo distintos tipos de uso (e.g bosque, plantación forestal, pastizal) (e.g. Huygens et al., 2005; Rivas et al., 2009; Dube et al., 2009; Panichini et al., 2012; Bown et al., 2014). Sin embargo, existe poca información disponible acerca de: i) bosques degradados y el efecto que el nivel de cobertura arbórea en éstos (e.g. cierre de dosel) ejerce sobre propiedades del suelo, ii) determinación comparativa de la calidad del suelo en superficies forestales; iii) estudios sobre SAF en bosque nativo (incluso a nivel mundial), iv) efecto del silvopastoreo en la recuperación de suelos degradados y su potencial de CO_2→COS. Lo anterior, patenta una necesidad genuina de estudios de suelo relacionando SPS y bosques nativos en Chile, que permitan el correcto aprovechamiento de los recursos forestales ante la inminente intervención a que son sujetos, pero también como oportunidad de potenciar reservorios de C que contribuyan en la mitigación de los efectos del cambio climático.

Características de la zona de estudio

El Bien Nacional Protegido “Ranchillo Alto” (SPS-RA), es un fundo perteneciente a la Provincia de Diguillín, Comuna de Yungay (37° 04’ 52” S y 71° 39’ 14” O; 1200-2000 msnm; 3000 mm precipitación), localizada en la Región del Ñuble, Chile. El predio que cuenta con una superficie de 635 ha y se localiza entre los Sectores “El Avellano” y ”Calabozo” (33 Km de

Yungay), actualmente consignado en administración y usufructo a la Facultad de Ciencias Forestales de la Universidad de Concepción, como parte del Centro de Investigaciones en Agroforestería (CIAF) (Dube et al., 2016, Dube et al., 2018). Los componentes del estrato vegetal corresponden a: a) arbóreo: Coigüe (*Nothofagus dombeyi*), Raulí (*Nothofagus alpina*), Lenga (*Nothofagus pumilio*), Roble (*Nothofagus obliqua*), Radal (*Lomatia hirsuta*), b) sotobosque: Rebrotes de radal, quila, roble, michay, y c) herbáceas: avena (*Avena sativa*), vicia (*Fabaceae purpurea*), trebol (*Trifolium incarnatum, T. subterraneum* y *T. vesiculosum*), *Lolium multiflorum westerwoldicum*, *Phalaris acuatica*, *Lolium perenne*, *Festuca arundinacea* y *Dactylis glomerata.*

En SPS-RA, los suelos presentes corresponden al orden Andisol (USDA, 2014), suelos derivados de materiales volcánicos, poco evolucionados, formados sobre cenizas recientes depositadas sobre un sustrato fluvioglacial (Stolpe, 2006), dominados por minerales de rango corto (e.g. alofan), ferryhidrita y complejos Al-húmicos con alta superficie específica, baja densidad aparente comúnmente (0.5-0.9 g cm^{3}), fuerte retención de P y alta capacidad de almacenamiento hídrico, por lo que tienden a acumular materia orgánica (Tosso, 1985, Aguilera et al., 1997, Panichini et al., 2012). La serie corresponde a Sta. Bárbara (medial, amorphic, mesic Typic Haploxerands), conocidos localmente como “trumaos” (CIREN, 1999; Stolpe, 2006), donde a pesar de tener una alta resiliencia (e.g. erosión), su constante mal manejo ha provocado su degradación (cerca de 852.245 ha sufren erosión geológica y alrededor de 270.772 ha, erosión acelerada de moderada a muy severa (Carrasco et al., 1993). Lo anterior reviste una enorme importancia debido a que estos suelos, como todos los de la zona de alta cordillera, desempeñan un papel básico en el ciclo hidrológico como receptores de nieve. En relación a los problemas de degradación del suelo relacionados con procesos históricos de sobrepastoreo, ramoneo, tala para madera aserrada, leña y carbón presentes en SPS-RA se tienen: i) pérdida del horizonte superficial (e.g. leucinización), presencia de canalículos debido al flujo hídrico superficial ii) pasturas discontinuas, debido al sobrepastoreo y principalmente a la pérdida gradual de materia orgánica, que redunda en una menor capacidad productiva del suelo (AMBAR, 2010). En consecuencia, las condiciones socioeconómicas a nivel comunitario sitúan a esta población dedicada principalmente a la agricultura de subsistencia, ganadería y prestación de servicio en empresas forestales, dentro de la categoría E (que corresponde a pobreza). A la fecha, la principal acción realizada con el fin de recuperar los servicios ecosistémicos y la productividad ha sido la implementación de SSP-RA, donde se ha limitado la presión antropogénica, promoviendo la repoblación con árboles nativos y cobertura del suelo con una mezcla de herbáceas (*Poaceae* sp., *Fabaceae* sp.), a fin de frenar la pérdida de suelo y restituir sus funciones ecosistémicas, así como de modelo de aprovechamiento sustentable y rentable para los productores.

1.2 HIPÓTESIS Y OBJETIVOS

1.2.1 Hipótesis:

Las Regiones del Ñuble y su colindante Biobío, Chile, son de enorme importancia forestal a nivel nacional, ocupando el 1er sitio en superficie cubierta con plantaciones y el 5^{o} en bosque nativo, de los cuales, un total de 541.209 ha están cubiertas por renovales principalmente de Roble (*Nothofagus obliqua*) (83% superficie), sin embargo y producto de este aprovechamiento, una histórica presión antropogénica ha sido ejercida, particularmente sobre los bosques nativos sobre aprovechados por tala para madera aserrada, leña, carbón y ramoneo principalmente, reportándose degradaciones a nivel estructural (e.g. pérdida de densidad) e incluso funcional (pérdida regenerativa). Lo anterior se asocia directamente a procesos de degradación del suelo (e.g. leucinización), presentes en 25% del territorio regional (10% de manera muy severa) y 2.47 Mha en riesgo. De acuerdo con lo anterior, se plantean las siguientes hipótesis:

a) El manejo silvopastoril en Ranchillo Alto (SSP-RA), aumentará el contenido de MOS promoviendo cambios periódicos significativos en la fracción lábil (FL) de COS, así como procesos de estabilización de COS, reflejados en variaciones del contenido de COS estable (FE).
b) Tales efectos, generaran variaciones en las propiedades bio-físico-químicas del suelo, aumentado comparativamente su calidad y potenciando su capacidad como receptor neto de C en conjunto con el resto de los componentes del SSP.

1.2.2 Objetivo general:

Determinar el efecto acumulativo que el SPS-RA bajo distintos niveles de perturbación previa (cierres de dosel) y comparado con otro sistema agroforestal mayor (cultivos intercalados), ejerce sobre la calidad del suelo, a partir de procesos de almacenamiento de materia orgánica.

1.2.3 Objetivos específicos:

1) Evaluar la calidad del suelo (SQI) asociada a distintos niveles de perturbación previa mediante indicadores físicos, así como S_{IND} relacionados con la fertilidad (químicos).
2) Comparar la calidad del suelo (SQI) entre SPS-RA y el sistema agroforestal agro-bosques ($A_{GRO}F_{RST}$) mediante S_{IND} físicos, químicos y biológicos.

CAPÍTULO I

ESTADO DEL ARTE

Silvopastoral Systems on Degraded Lands for Soil Carbon Sequestration and Climate Change Mitigation

Juan Ortiz, Marcelo Panichini, Gustavo Curaqueo, Pablo Neira, Neal B. Stolpe, Erick Zagal and Francis Dube*

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Abstract

Land degradation (L_AD_{EG}) (e.g., deleterious processes affecting the biophysical environment of soils), reduces the natural or agricultural capacity of soil to support plant growth (e.g., NPP), promoting a broad-scale, net loss of soil organic carbon (SOC) to the atmosphere through increased CO_2 emissions from soil to the atmosphere and lower C fixation from the atmosphere (e.g., aboveground C storage in biomass). Consequently, L_AD_{EG} represents the main threat to food security worldwide. At present, about 40% of the global land area is affected by L_AD_{EG} (9% is severe). Silvopastoral systems (SPS), (e.g., planned combinations of trees, forage-herbs and livestock), a type of agroforestry system (AFS), currently cover about 450 Mha (28% of the global AFS area); they are one of the main recommended land use regarding land conservation-reclamation, and are able to reduce-offset C emissions from soil by promoting the formation of soil organic matter (SOM) and increasing SOC, enhancing soil quality, also improving ecosystem services (e.g., water and nutrient cycling) and livestock well-being. Accordingly, we conducted a review of the literature on SPS, where 25 major mechanisms responsible for the above-mentioned SPS attributes were identified, including: 12 individual functions for the woody (6), herbaceous (3) and animal (3) components, in addition to 13 symbiotic drivers (8 mutualistic and 5 tripartite). Whereas the reported values of C fixation in SPS are 1-5 Mg C ha^{-1} y^{-1} and $CO_2 \rightarrow SOC$ range from 1.8 to 7.5 Mg C ha^{-1} y^{-1}, demonstrating the potential of SPS to

ameliorate or reverse L_AD_{EG}, while also being an ethically responsible option for food production. However, the scientific background of AFS-SPS (e.g., $CO_2 \rightarrow SOC$) is regionally specific and primarily from developed countries, which suggests that this may be potentially useful in addressing L_AD_{EG} since those territories have soils that are among the world's most degraded for silvo agricultural production.

Keywords: Sustainable agriculture, soil reclamation, soil quality

1.2 Introduction

Humans have caused a continual transformation of the planet's surface since ancient times (7,500-10,000 yr ago) (Dotterweich, 2013), inducing deleterious changes on the structural and functional patterns of terrestrial ecosystems (Ludwig et al., 2005), which comprises soil, near surface air, vegetation, other associated biota and water, collectively named "*land*" (Henry et al., 2018).

The cumulative net land modifications include: the creation and expansion of urban centers and massive deforestation caused by the expansion of the agriculture frontier (both subsistence and intensive agriculture), and/ or over-exploitation of native species, which are collectively termed as "land use changes" (LUC) (DeFries et al., 2004). Although LUC can vary greatly both spatially and temporarily, they frequently involve the vicious cycle of "extractive acquisition of natural resources for immediate human use", a phenomenon designed as "land degradation" (L_AD_{EG}) (Vitousek, 1997).

According to Mohamed et al., (2019), L_AD_{EG} is defined as a "*set of processes that lead to changes in the values of the biophysical environment and land characteristics to be deleterious*". L_AD_{EG} is a multi-factorial and interdependent phenomenon, comprising a myriad of detrimental physical-chemical-biological processes (simultaneous or successive) that are mediated by natural or human induced factors (Figure 1.1), which impact the ability of an ecosystem to support net primary production (NPP) (e.g., annual C absorption by living plants), which is a reason why a decreasing NPP is an indicator of L_AD_{EG} (Barbier and Hochard, 2018)

According to FAO (2007), major human pressures or drivers that affect L_AD_{EG} include demands from: agriculture, nutrient mining, waste disposal, population growth, intensive cultivation, over grazing and excessive irrigation. Examples of historic LUC- L_AD_{EG} include:

deforestation, which is responsible for about 77% of global C losses (Houghton and Nassikas, 2018); the conversion of freshwater wetlands (about 1% earth's surface) for agricultural purposes (Dixon et al,, 2016); a worldwide utilization (direct or indirect) of one third of the land surface for livestock production (that also promotes detrimental shifts of vegetational patterns via overgrazing and erosion) (Giraldo et al., 2011; Kuzyakov et al., 2016); and salinization that currently affects 13% of agricultural area through various processes (e.g., deficient water management for crop production in arid and semi-arid zones), but is expanding at a rate of 1.6 Mha yr^{-1} (Mohamed et al., 2019).

The mechanisms responsible for L_AD_{EG} are diverse (mostly mediated by human activities), and result from a wide range of multi-temporal events, that include short-term storms (minutes), decade length processes of gully formation to century-long extractions of soil nutrients (Coppus and Imeson, 2002; Johnson and Lewis, 2007), as discussed in the broad overview of all processes causing L_AD_{EG} and their implications by Olsson et al., (2019) (Table 1.1). Additional drivers that influence L_AD_{EG} have been detected and include: land tenure changes and variation in crop prices, both of which exert shifts of LUC or management that potentially cause L_AD_{EG} (Millennium Ecosystem Assessment, 2005). Among the consequences of L_AD_{EG} are: i) ecosystem fragmentation patterns, resulting on a decline of biodiversity through habitat loss and connectivity between habitats and ii) soil and water degradation, that may extend beyond their natural boundaries (e.g., marine and freshwater systems) (Sala et al. 2000; Stocking et al., 2001), iii) weakened regulation of ecosystem services / terrestrial cycles such as nutrients and C (Vitousek, 1997; Gashaw et al., 2014; Olsson et al., 2019), iv) enhanced emission of greenhouse gases (e.g., atmospheric compounds that able to absorb-emit infrared radiation, forcing thermal atmospheric alterations (e.g., carbon dioxide [CO_2], methane [CH_4] and nitrous oxide [N_2O]), which are strongly associated to climate change and dates back from at least 3000 years ago from the origins of LUC) (Ellis et al 2013; Vavrus et al., 2018), v) detrimental changes in soil productivity, biological productivity, ecological integrity (Stockings and Murnaghan, 2000), vi) habitat destruction, loss of biodiversity (including extinction of vulnerable species flora and fauna), changes in human population (both size and distribution), diffuse events of pollution (e.g., atmospheric deposition) and other off-site impacts (FAO, 2007) (Table 1.1, Figure 1.1). From a social point of view, L_AD_{EG} exerts effects on both cultural and economic spheres, frequently modifying the dynamics of market and technology, and demographic patterns. L_AD_{EG} has progressively affected the daily life of more than 42% of world’s population (Nachtergaele et al., 2011; Olsson et al., 2019). Moreover, despite L_AD_{EG} being frequently defined-described at a local scale (in terms of the natural resources which are depleted-restricted), it expands at a rate of 5-10 Mha y^{-1} (Scherr and Yadav, 1996), globally impacting 40% of the agricultural area (9% severe) (Mohamed et al., 2019), of which Africa accounts for 65% of L_AD_{EG} in croplands, affecting 188-485 million people therein (Thiombiano and Tourino- Soto, 2007; Barbier and Hochard, 2018). Current trends indicate that about 19.2% of the global population (1310.7 billion in 2010) live in areas affected by L_AD_{EG} (Asia- Europe - Pacific: 78.1%, Africa: 14.4%, Latin America: 2.5%; developed countries: 5%) (Barbier and Hochard, 2018).

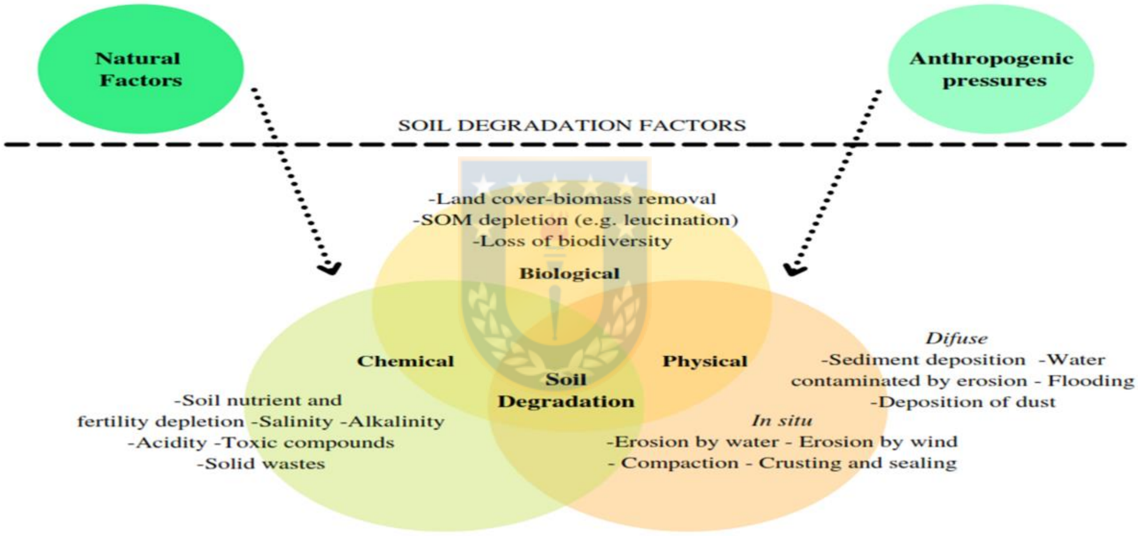

Fig. 1.1 An overview of main soil degradation processes- $L_AD_{EG,}$ as natural and/or anthropogenic phenomenon, divided into physical, chemical or biological factors, showing interactivity-simultaneity-interdependence, thus causing a net effect leading to ecosystem modification to destruction gradients (after Olsson et al., 2019).

Consequently, it is expected that by the year 2100, L_AD_{EG} will be the most important factor causing decreased biodiversity (Mohamed et al., 2019; Olsson et al., 2019), even when masked by the technological agricultural advances of the last decades (Pingali, 2012; Webb et al., 2017). Major threats caused by L_AD_{EG} in future scenarios include an expansion of about 78% of global dryland due to decreased supplies of fresh water for irrigation (Huang et al., 2015), followed by rising food insecurity, vulnerability of agricultural systems to climate change and poverty (Stocking, 2003; Lal, 2004; Foley et al., 2005; West et al., 2014; Barrett and Bervis, 2015).

Table 1.1 Principal mechanisms of L_AD_{EG} and their main implications (after Olsson et al., 2019).

Processes	Probable causes	Effects
[1] Organic matter decay$^{(S)}$	Conventional / intensive cultivation (monocultures), tillage, removal of groundcover / vegetation clearing, overgrazing, deforestation. Drainage of waterlogged soils. Influenced by most of L_AD_{EG}	-Net C release -Warming enhances soil respiration - Decrease of litter quality (greater C:N ratio) - Variations on water cycle (e.g., logging) - Changes on fire events
[2] Compaction$^{(S)}$	Land use change, conventional / intensive cultivation (monocultures), over-utilization of machinery, intensive grazing	-Reducing actual SOC and potential SOM intake -Limiting root developed-, air supply and ultimately plant growth - N_2O emissions
[3] Biological soil crust removal $^{(S-B)}$	Land use change, overgrazing– excessive trampling	- Modification of rainfall patterns - Albedo increase - Radiative cooling via dust release - Variation on fire regimes

[4] Soil micro –meso faunal shifts (S-B)	Modified fire regimes, N content variations (e.g., N deposition), over-fertilization, pesticide pollution, alteration of vegetational resources	-Habitat losses
[5] Nutrient depletion(S)	Soil nutritional status decline / harvested nutrients (e.g., conventional / intensive cultivation - monocultures)	-Net C losses via alterations of SOC reservoir -Possible changes in land uses (e.g., cropland) -Possible overfertilization
[6] Acidification and / or overfertilisation(S)	Overutilization of N-based fertilizers / cation depletion / acid rain	-N_2O release - Release of C in inorganic forms
[7] Pollution(S-B)	Use of herbicides / pesticides	-Potential increase of pest and weed resistance - incidence
[8] Metal toxicity(S)	Cation depletion, fertilization processes, mining activities	-Possible alteration in food chain - Adverse health effects for most species
[9] Subsidence (S-W)	Groundwater volume reduction, over-pumping, peatland disruptions / drainage	-Rising drought events - Enhancing decomposition processes - Net SOC release in peatlands
[10] Flooding (W)	Expansion of impervious surface and infrastructure, land clearing	- CH_4 release - N_2O emissions - Sea level increase - Rising rainfall intensity - Shifts of vegetational patterns
[11] Waterlogging (W)	Poor drainage practices / deforestation	- CH_4 release - Water balance alterations - Shifts of vegetational patterns

[12] Eutrophication (W-B)	Erosive agents, over-fertilization, uncontrolled grazing practices; sewage	-CH_4 and N_2O emissions -Algal proliferation-nutrient loads - Net N losses
[13] Drying of continental waters wetland/ lowlands(W)	Overgrazing / excessive drainage or groundwater consumption, trampling	- Net C release - N_2O emissions - Alteration of drought events
[14] Salinization (S-W)	Poor drainage practices	-High sulfate loads -Reduction on CH_4 emissions - Increment of sea level - Water balance shifts
[15] Sodification (S-W)	Deficient water management	-Net C losses via breakdown of stable aggregates releasing occluded SOC - Water balance shifts - Albedo increase
[16] Water erosion(S)	Conventional / intensive cultivation (monocultures), tillage, removal of groundcover / vegetation clearing, overgrazing, deforestation, fire regime shifts, deficient designed roads and paths	-Net C release -Albedo increase
[17] Wind erosion(S)	Conventional / intensive cultivation (monocultures), tillage, removal of groundcover / vegetation clearing, overgrazing, deforestation, fire regime shifts	- Changing wind/drought patterns - Radiative cooling - Ocean fertilization

[18] Coastal erosion (S-W)	Detainment of sediments, coastal agriculture, mangrove forests removal, subsidence	-Sea level rise -Increase of frequency and intensity of storms -Release of stable / buried/ old C pools
[19] Increased burning (S-B)	Changing precipitation regimes	-Warming increase -Net C (e.g., CO2, CO, CH_4) and N_2O release -Albedo increase - Possible changes on soil nutrient status -Long-term drop of NPP
[20] Invasions (B)	Deliberated or accidental introduction of exotic species	-Habitat shifts / decline for native or preexistent species
[21] Woody encroachment (B)	Invasive processes, shift of fire regimes or fire suppression,	-Albedo decrease -Net C storage
[22] Pest outbreaks (B)	Large scale land use change, conventional / intensive cultivation (monocultures)	- Habitat alterations and -Faster reproductive cycles via climate modification - Net C losses
[23] Species loss / compositional shifts (B)	Logging and selective grazing resulting on modification of vegetative mosaic; inducing changes on microbial and mesofaunal soil communities via pesticides	-Habitat losses - Landscape fragmentation -Migratory processes -Loss of habitats connectivity -Species isolation -Genetic erosion -Local to global extinction
[24] Permafrost thawing(S-W)	Warming	- Accelerated snow smelt - Net C losses - CH_4 release

[1, 2…24] Process number; [S / W / B] Land component in which a determined L_AD_{EG} process acts, where: **S**: soil; **W**: water; **B**: biota. **Sources**: [1]Bonde-Lamberty et al., 2018; Crowther et al., 2016; van Gestel et al., 2018; Houghton et al., 2012; Eglin et al., 2010; [2] Stockings and Murnaghan, 2000; Olsson et al., 2019; [3] Reed et al., 2012; Maestre et al., 2013; Belnap et al., 2014; Rutherford et al., 2017; [4] Pritchard, 2011; Ratcliffe et al., 2017; [5] Stockings and Murnaghan, 2000; Olsson et al., 2019; [6] Oertel et al., 2016; [7] Stockings and Murnaghan, 2000; Olsson et al., 2019; [8] Olsson et al., 2019; [9] Stockings and Murnaghan, 2000; Olsson et al., 2019; [10] Panthou et al., 2014; Arnell and Gosling, 2016; Vitousek et al., 2017; [11] Piovano et al., 2004; Osland et al., 2016; [12] Olsson et al., 2019; [13] Burkett and Kusler, 2000; Nielsen and Brock 2009; Johnson et al., 2015; Green et al., 2017; [14] Colombani et al., 2016; Schofield and Kirkby, 2003; Aragüés et al., 2015; Benini et al., 2016; [15] Jobbágy et al., 2017; [16]Stockings and Murnaghan, 2000; Nearing et al., 2004; Shakesby, 2011; Panthou et al., 2014; Wang et al., 2017; Chappell et al., 2016; [17]Stockings and Murnaghan, 2000; Bärring et al., 2003; Sheffield et al., 2012; Davin and Noblet-Ducoudré 2010; Pinty et al., 2011; [18]Johnson, 2015; Alongi, 2015; Harley et al., 2017; Pendleton et al., 2012; [19] Jolly et al., 2015; Abatzoglou and Williams, 2016; Taufik et al., 2017; Knorr et al., 2016; Page et al., 2002; Pellegrini et al., 2018; ; [20] Hellmann et al., 2008; Hulme 2017; [21] Van Auken, 2009; Wigley et al., 2010; [22] Pureswaran et al., 2015; Cilas et al., 2016; Macfadyen et al., 2018; [23] Vincent et al., 2014; Gonzalez et al., 2010; Scheffers et al., 2016; [24] Liljedahl et al., 2016; Peng et al., 2016; Batir et al., 2017; Schuur et al., 2015; Christensen et al., 2004; Walter Anthony et al., 2016; Abbott et al, 2016.

1.2 Climate change and L_AD_{EG}

Although there is considerable literature regarding L_AD_{EG} and climate change, less is known about their possible linkages and synergism as deleterious forces (Webb et al., 2017). In this respect, it is considered that L_AD_{EG} and climate change reciprocally accelerate each other, but few actual studies supporting the premise [L_AD_{EG} → climate change] have been reported (e.g., Stockings and Murnaghan, 2000). On the contrary, more information is available regarding [climate change → L_AD_{EG}], such as permafrost thawing (Schuur et al., 2015; Batir et al., 2017), ground subsidence (Keog and Törnqvist, 2019) and tree mortality (Allen et al., 2010), since climate change could be considered a mechanism and a driver of L_AD_{EG} at the same time.

According to Lin et al. (2017), there are three main factors associated to climate change that can escalate L_AD_{EG} processes, including: periodic variations of temperature, precipitation and wind, which exert modifications on the distribution, intensity and periodicity of extreme events. However, despite the pronounced and visible adverse effects of climate change, it has been stated that a positive aspect of climate change could be the expansion of cultivable areas in northern latitudes of about 560 Mha (Zabel et al., 2014).

1.2.1 Relationship between L_AD_{EG}, SOC, soil quality and greenhouse gas emissions

1.2.1.1 Relevance of soil degradation in L_AD_{EG}

L_AD_{EG} is widely linked to soil disruptions, of which the 24 processes identified by Olsson et al., 2019 are precursors of L_AD_{EG}, and 15 are directly related to soil (7 utterly) (Table 1.1). Therefore, soil degradation as defined by FAO (2007) is the: "*change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Degraded soils have a health status such, that they no longer provide the normal goods and services for the particular soil in its ecosystem*". The soil is therefore a principal focal and/or starting point of L_AD_{EG}.

Soil degradation occurs as: **i)** erosion or displacement of soil materials via superficial water flow (comprising 56% of global soil degradation), via wind (28%), both causing losses and deformations from topsoil to subsoil (e.g., gullies) and **ii)** alterations within soil matrix via **iia)** chemical degradation which reduces the fertility status, causes pollution and/or salinization-sodification, (12% of global soil degradation), and also by the following the L_AD_{EG} processes: acidification, salinization, nutrient depletion (e.g., reduction of exchange capacity, increase of Mn or Al toxicity, Ca or Mg deficiencies, leaching of available N forms such as NO^{3-}) and **iib)** physical degradation, linked to the L_AD_{EG} processes: compaction, crusting, reduced water infiltration, increased surface runoff, greater soil temperature fluctuations and flooding (4% of global soil degradation) (CP, 2013; Lal et al., 2015).

1.2.1.2 The role of SOC in L_AD_{EG}

Soil organic matter (SOM) is formed by biomass production, litter-fall, root exudates, and biological activity is defined as "*The heterogeneous mixture of organic compounds* *encompassing molecules released from both living plant and microbial cells (e.g., extracellular enzymes, surface-active proteins, chelating compounds) and complex plant, microbial and animal residues in various stages of alteration due to biotic and abiotic processes*" (Baldock and Skjemstad, 2000). SOM contains about 56-60% of soil organic carbon (SOC) (Heaton et al., 2016).

Thus SOM is a broad inclusive concept of key relevance because it involves a myriad of ecological processes, grouped in: i) improvement of soil fertility status through the release of different nutrients such as N, P (Odhiambo et al., 2001; Akinnifesi et al., 2007), and Mg, K, Ca (Haynes and Mokolobate, 2001), ii) regulation of hydrological cycle (Alavalapati et al. 2004), iii) protection of soil against erosive agents (e.g., wind and water) (Alavalapati et al. 2004), iv) $CO_2 \rightarrow SOC$, v) increasing soil-aboveground agro-biodiversity that also serve as biological corridors for other species (Rigueiro-Rodriguez et al., 2008) and vi) reduction of necessary input requirements to the ecosystem (e.g., El-Ramady et al., 2014).

Since L_AD_{EG} potentially modifies the environmental drivers affecting soil formation including: structural internal organization, temperature, moisture, climate, plant/animal presence, soluble/exchangeable cations, pH and litter input (Sollins et al., 1996), soil degradation thereby exacerbates SOC losses (e.g. SOC destabilization) and limiting-inhibiting the formation of new SOC (Lal et al., 2015).

The mechanisms of SOC destabilization are described by Sollins et al. (1996), and refers to the overall processes by which: i) SOC became less resistant to degradation (e.g., recalcitrance) by depolymerization processes involving changes in enzymatic production mediated by an enhancement of microbial activity, which is usually expected to be caused by changes in the quality and quantity of detritus/substrate (e.g., degradation rates are related to litter chemistry, their C:N ratio, and lignin/tannin contents), ii) increased desorption of C in organo-mineral forms, as a consequence of microbial activity-enzymatic production leading the formation of more biodegradable SOC forms (dissolved organic carbon) and/or iii) the increase of microbial accessibility to protected or occluded SOC, via physical breakdown of detritus and soil aggregates (e.g., tillage), increasing the activity of soil fauna and microbial-extracellular enzymes, promoting the solubilization of binding agents. However, aggregate stability varies according to clay mineralogy and presence of Na^+, which deflocculates clays.

1.2.2 L_AD_{EG} and soil quality

L_AD_{EG}- soil degradation may induce a decline in specific soil properties-processes, affecting its capacity to sustain vegetation and provide ecosystem services, both of which are considered in the term "*soil quality*" (SQ) (Arshad and Martin, 2002; Karlen et al., 2003; UNEP, 2016).

According to the Soil Science Society of America, SQ is defined as: "*The fitness of a specific soil-type, to function within its capacity, and within natural or managed ecosystem boundaries, to sustain animal and plant productivity, maintain or enhance water and air quality, and support human health and habitation*" (Arshad and Martin, 2002). The SQ thus represents the *status quo* of a particular soil with respect to its potential at a given moment (UNEP, 2016).

The SQ is measured by identifying comparative and space-time sensitive soil properties among different types of management, under similar pedo-climatic conditions. These are accordingly named soil quality indicators (SI_{ND}) which express different aspects of soil functionality (Arshad and Martin, 2002; Karlen et al., 2003). Additionally, the SQ is also a useful tool to diagnose and monitor L_AD_{EG}- soil degradation.

1.2.3 L_AD_{EG} and greenhouse gases emissions

Diverse L_AD_{EG} processes and LUC (e.g., deforestation) proceed from net SOC destabilization processes, thereby accelerating the biological active emission of CO_2 from soil, contributing to climate change (Mohamed et al., 2019; Olsson et al., 2019). In addition, there are a complex set of indirect side effects during SOC destabilization caused by diverse L_AD_{EG} processes and LUC (e.g., tillage), that further intensify SOC decline in soil and CO_2 release to the atmosphere. For instance, during the disruption of soil structure (or disaggregation), the amount of arbuscular mychorrhizal fungi are reduced (Wall et al., 2004) affecting the potential formation of stable forms (resistant to degradation) of SOM such as glomalin, whilst SOC translocation via bioturbation is also limited due to a decline in earthworm populations, and a reduction of vertical movement of dissolved forms of SOC via diminution of water infiltration to soil and soil water holding capacity (Wall et al., 2004;Wang et al., 2017). To date, during the period 2007-2016, C emissions from LUC were about 1.3 ± 0.7 Pg y^{-1} (Le Quéré et al., 2018), while IPCC (2006) reports that 47% of CO_2 emissions originate from soil.

Conversely, the N_2O emissions from soil are mediated by soil microbial activity which is affected by soil disruptions-management practices and climate conditions, whilst CH_4 emissions are primarily proportional to the amount of SOC-waterlogging, both of which are strongly correlated to L_AD_{EG}-LUC-soil degradation (Dou et al., 2016; Oertel et al., 2016; Olsson et al., 2019). Indeed, according to IPCC (2006), approximately 35% of global CO_2, 47% of CH_4 and 53% of N_2O emissions are generated from soil.

1.3 L_AD_{EG} assessment

As previously highlighted, industrial agriculture (crops and livestock production) and forestry models, as well as subsistence agriculture practices, are the main drivers of L_AD_{EG} processes, with soil degradation leading the overall decay of the ecosystem (Wall et al., 2004; Altieri, 2011). Basic tools for L_AD_{EG} diagnosis include the following observations: i) presence of a LUC, ii) variations on biotic assemblages and distribution patterns (e.g., species loss or invasion of new ones), iii) modification of landscape flows (e.g., shifts in species habits, alterations of water and/or nutrient fluxes), iv) changes on aesthetic value), v) erratic occurrence, removal and fragmentation of native vegetation (Hobbs, 2005).

However, in order to reverse the complex adverse effects of L_AD_{EG} and soil degradation, there are available different technologies and sustainable land -agricultural practices (SLP) including: bioenergy, afforestation, reforestation, biochar use, C capture and SOC management (Olsson et al., 2019).

Concerning the adoption of agricultural-oriented SLP focused on soil conservation, special attention should be paid to C capture, SOC management, SOC-N budgets (e.g., promoting SOC stabilization mechanisms), and neutral to negative greenhouse gas emissions, because the SOC pool is the most reliable SI_{ND} for monitoring and reversal of soil degradation (and L_AD_{EG}), besides affecting other important aspects of soils such as contents and cycling of water, nutrients and other inputs (Lal, 2015).

Among those recommended SLP are precision agriculture, climate smart agriculture (e.g., AFS) and perennial crops, which satisfy some of the following conditions: i) increased retention of crop residue (e.g., mulch), ii) incorporation of a cover crop in the rotation cycle, iii) integrated nutrient management and suppression of mechanical disturbances of the soil (Lal, 2015).

Estimated projections for 2040 indicate that the potential C accumulation (Tg yr^{-1}) in different SLP as follows: water land restoration (20), restoration of degraded land (50), forest management (250), grazing management (375), rice management (20), crop and land management (150), AFS (600) (Abbas et al., 2017).

However, the particular actions that are selected to reverse L_AD_{EG} within a specific area may include a spectrum of possible practices for its eventual "*rehabilitation*" (e.g., restitution of the system to some / defined pre-existing condition) or "*restoration*" referred to the recovery of ecosystem vigor, organization and resilience (e.g., complete reassembly of composition, structure, pattern, heterogeneity, functions, species interactions, dynamic and resilience). Such practices, however, are mostly oriented to individual plots (Hobbs, 2005).

The primary goals to improve affected areas depends on the presently active L_AD_{EG} processes, extent of degradation, pedo-climatic conditions, and specific objectives, which entail: i) the removal of causative agent if possible (e.g., introduced herbivores), ii) amelioration of physical and chemical properties of the substrate, iii) periodical return to productivity (biomass rates), based on the retention of existing biota / prevention of their further suppression, iv) preference for native species whenever possible and iv) the gradual reestablishment of ecological processes from plot to landscape scales (Hobbs, 2005).

However, Stocking and Murnaghan (2000), highlighted the crucial role of prioritizing a farmer-perspective for L_AD_{EG} assessment, particularly in developed countries where there may be limitations for the implementation of certain technologies or to their large-scale execution (e.g., mechanized soil conservation).

Thus, an integration of the different visions and capabilities from researchers, policy makers, institutions and local professionals should be included, in order to support farmers and motivate them in using soil conservation practices while waiting for soil improvement and increased yields.

1.3.1 Monitoring L_AD_{EG} through SQ

According to Doran and Jones (1997), a SI_{ND} should satisfy the following considerations: i) link ecosystem – level processes (e.g., $CO_2 \rightarrow SOC$), ii) incorporate physical, chemical and biological soil properties, iii) be simple to test, measure and replicate (e.g., field conditions), iv) exhibit sensitiveness to both, land use and climatic changes, v) be commonly included in soil databases to be able to compare SI_{ND} of previous investigations and vi) be accessible and helpful to the widest possible range of users (e.g., expert-end users).

Despite the challenging task of selecting a representative set of SI_{ND} to evaluate SQ-monitoring soil degradation, from a single SI_{ND} (e.g., soil organic matter / SOC) (Canals et al., 2007) to multiple SI_{ND} (e.g., Oberholzer, 2012; Ortiz et al., 2020).

Nonetheless, Doran and Parkin (1997), proposed a minimum SI_{ND} dataset including: i) cation exchange capacity (CEC), which provides information about SOC and clay type, ii) hydraulic conductivity (HC) – water holding capacity (WHC), that are associated with SOC, soil texture and bulk density (BD), iii) microbial activity – C and N cycling, that are related to soil respiration (SR), pore space, soil temperature, pH and electrical conductivity (EC), iv) rooting depth that is correlated with WHC, BD and pH, and v) leaching potential, which is related to soil texture, pH, SOC, HC, CEC, depth.

Bünemann et al. (2018) analyzed a total of 65 publications related to SQ, and found that the most frequently proposed SI_{ND} were: SOM/SOC (91%), pH (82%), available P (74%), WHC (60%), BD (54%), available K (49%), texture (45%), total N (40%), EC (34%), CEC (33%), available N (29%), structural stability (29%), depth (29%), penetration resistance (27%), microbial biomass (26%), N mineralization (26%), heavy metals (22%), HC (20%), porosity (19%), aggregation (18%), other macronutrients (Mg. S, Ca) (17%), infiltration (15%), worms (15%) sodium / salinity (15%), micronutrients (15%), labile C (LF) and available N (13%). The different qualitative ranges for soil processes that are potentially useful as SI_{ND} in L_AD_{EG} diagnosis-assessment across pedo-climatic environments are listed in Table 1.2.

Through the summation, weighting and interpretation of a selected set of SI_{ND} for a particular condition-land use / purpose, it is possible to establish soil quality indexes (SQI), either as a general diagnostic tool or for specific purposes when sub-divided by SI_{ND} groups based upon their nature (chemical, physical and biological SQI) with the aim to later implement specific L_AD_{EG} remediation strategies.

Likewise, the association of SQI from conterminous land uses could provide valuable information on the present local L_AD_{EG} processes such as nutritional deficiencies-yield, compaction, presence of erosion agents and pollution risks. Moreover, the systematic integration of SQI data, may be useful to determine the overall patterns of ecosystem services in a watershed or regional scale, including: $SOC \rightarrow CO_2$ / $CO_2 \rightarrow SOC$, biodiversity, acidification, sedimentation, water infiltration and flooding, among other L_AD_{EG} processes (Karlen et al., 2001, Drobnik et al., 2018).

Beyond the inherent SQ variations among soil types, climates and land uses, the major differences in SI_{ND} are highly interdependent on specific mineral, textural and depth attributes of a given soil pedon (e.g., inverse correlation between SOC content and particle size) (Oades, 1988). This is the so called “native SQ“ (or inherent SQ), which controls: i) SOM decomposition rates and release of essential nutrients (e.g., N, P, S) into the mineral-nutrient pool and ii) formation and release of reactive C and N compounds into the atmosphere (e.g., CO_2, N_2O), and surface-ground water flows (NO_3^-, dissolved organic C and N) (Carter et el., 1997; Nieder and Benbi, 2008).

Table 1.2 Ranges of selected environmental and edaphic factors related to soil degradation vulnerability, degradation status and amelioration-land reclamation strategies.

Factor	Indicator	Ranges
[1]Soil texture	Physical criteria: (silt % / clay %)	A-B: > 0.2 C: 0.2-0.3 D: 0.3-0.7 E: > 0.7
	Chemical criteria: Textural class	A-B: Clay C: Silt D-E: Sand

[2]Climate	Physical criteria: Σ [monthly precipitation / annual precipitation]	A-B: 0-50 C: 50-500 D: 500-1000 E: > 1000
	Chemical criteria: Potential evapotranspiration / [annual precipitation + irrigation] $\cdot 10$	A-B: < 0.1 C: 0.1-0.3 D-E: 0.3-0.5 E: > 0.5
[3]Topography	Physical criteria: Slope (%)	A-B: 0-2 C: 2-8 D-E: > 8
[4]Waterlogging	Water table (cm)	A-B: >150 C: 150-100 D: 100-50 E: < 50
[5]Salinization	Electric conductivity (decisiemens m^{-1})	A-B: ≤4 C: 4-8 D: 8-16 E: > 16
[6]Alkalinization	Exchangeable sodium content (%)	A-B: ≤10 C: 10-15 D: 15-30 E: > 30

[7,8,9]Compaction	(7,8) Penetration resistance criteria (PSI)	A-B:100-200 C: 200-300 D-E: > 300
	(9)Bulk density criteria (cm gr^{-3})	A-B: ≤1.2 C: 1.2-1.4 D: 1.4-1.6 E: > 1.6
[10]Architecture	Porosity (%)	A: < 0.1 B: 150 C: 150-100 D: 25-40 E: > 40
[11]Stability	Water stable aggregates (%)	A-B: ≤1.2 C: 1.2-1.4 D: 1.4-1.6 E: > 1.6
[12]Aluminum toxicity	Aluminum saturation (%)	A-B: ≤1.2 C: 1.2-1.4 D: 1.4-1.6 E: > 1.6
[13]Water movement	Infiltration velocity (cm day^{-1})	A-B: 20-43.2 C-D: 8.64-20 E: < 8.64

[14]Reactivity, nutrient availability	pH	A-B: 5.5-7.5 C-D: 4.0-5.5; 7.5-8.5 E: < 4.0; > 8.5
[15,16]Biological activity, nutrient storage-cycling	SOC (%)	A: > 15 B: 5-15 C: 3-5 D-E: < 2
[17]Nitrogen content	N (%)	A-B: > 0.5 C-D: 0.1-0.5 E: < 0.1
[18]Substrate quality	C:N	A-B: 1-10 C-D: 10-20 E: > 20
[19]Available nitrogen	NO_3^- (mg kg^{-1})	A-B: > 20 C-D: 10-20 E: < 10
[20]Available nitrogen	NH_4^+ (mg kg^{-1})	A-B: > 50 C: 25-50 D-E: < 25
[21]Critic nutrient	P (mg kg^{-1})	A-B: > 16 C-D: 5-15 E: < 5

[22]Major nutrient	K (mg kg^{-1})	A-B: > 500 C-D: 100-500 E: < 100
[23]Major nutrient	Mg (mg kg^{-1})	A-B: > 500 C-D: 50-500 E: < 50
[24]Major nutrient	Ca (mg kg^{-1})	A-B:100-1000 C-D: 50-500 E: < 50
[25]Microbial activity	Respiration (micrograms of CO_2 per gram of dry soil^{-1})	A: > 0.85 B: 0.65-0.85 C: 0.5-0.65 D:0.3-0.5 E: < 0.3

[26] (Heavy) Metal concentration	(mg kg^{-1})	Max allowed
	a) Beryllium	a) 0.0061
	b) Selenium	b) 0.11
	c) Thallium	c) 0.25
	d) Antimony	d) 0.53
	e) Cadmium	e) 0.76
	f) Vanadium	f) 1.1
	g) Mercury	g) 1.9
	h) Nickel	h) 2.6
	i) Cooper	i) 3.5
	j) Chromium	j) 3.8
	k) Arsenic	k) 4.5
	l) Barium	l) 9.0
	m) Zinc	m) 16
	n) Cobalt	n) 24
	o) Tin	o) 34
	p) Lead	p) 55
	q) Molybdenum	q) 253

Degree of severity: A: very slight, B: slight, C: moderate, D: severe, E: critical. Sources: [1,2,3] FAO and UNEP, 1978; [4,5,6,9] UNEP,1991; [7, 11]Lal and Eliot, 1994; [8] Carter, 2002; [10]Pagliai, 2002; [12,21]Villaroel, 1989; [13]Reynolds et al., 2003; [14,15, 16,17, 18,22,23,24]Amacher et al., 2007; [16,19,20] Vidal, 2007; Mohamed et al., 2019; [25] Moebius-Clune et al., 2016; [26] Vodyanitskii, 2016.

However, despite the great number of scientific publications dealing with agricultural systems (about 35,000) (Smith et al., 2018), including 3469 related to sustainable land management (Strauss, 2013), and around 1500 to SQ (this being a principal topic during the last decade) (Gil-Sotres et al., 2005; Smith et al., 2018), there is only a limited amount of literature that addresses the role of SQ over $L_{A}D_{EG}$ – and climate change diagnosis-monitoring-amelioration, or the variations of SQ as a function of AFS-SPS managements.

1.4 Potentialities of AFS for $L_{A}D_{EG}$ assessment and climate change mitigation

The term agroforestry (AFS) refers in a broad sense to an intentional-intensive-integrated-interactive associations of trees, plants and/or animal-pastures within a determined space (Gold and Garret, 2009; Nair, 2012). Despite the historical origins of AFS as a subsistence-smallholder and flexible indigenous land management (Nair et al., 2015), nowadays, AFS are widespread around the globe, covering broad extensions (Table 1.3) and are present across natural-rural-peri-urban-urban gradients (Mosquera-Losada et al., 2018), mainly due to their evolution to an economically and social-environmentally profitable ”agro-solution” in local and emergent economies (Pachauri, 2012), contributing to the livelihoods of about 900 million people (Cardinael et al., 2018). The social functionality of AFS is based on seven fundamental precepts: i) economic and agricultural diversification, ii) environmental impact mitigation, iii) land and water rehabilitation and restoration, iv) increased food production, v) sustainable use of marginal or fragile land, vi) natural habitat enhancement and vii) profitability (Thevathasan et al., 2019).

Table 1.3 Global area covered by principal AFS and tree-based agriculture

System	Area (million ha)	% of SAF
Alley cropping	700	44
SPS	450	28
Protective SAF (e.g., windbreaks, riparian buffer)	300	19
Multi-strata	100	6
Scattered trees	50	3
Global SAF	1000**-1600	
* % of tree-based production and AFS respect to global agriculture area		7.6 - 20.3

Source: Nair, 2012, * Nair, 2012B and Zomer et al., 2016: ** Cardinael et al 2018.

The factors controlling the functional aspects of AFS (CO_2→SOC, or climate change mitigation) are: i) plant attributes: tree species, age, density, specific crops that are included, biodiversity), ii) amount and quality of biomass inputs, iii) climatic conditions: altitude, wind, precipitation, iv) soil properties: SOC content, structure, texture, fertility status, (Nair, 2012B; Gold and Garret, 2015; Feliciano et al., 2018; Cardinael et al., 2018). According to Lorenz and Lal (2005) and Nair (2012 B), in agro-systems with a marked presence of woody species (e.g., AFS), high amounts of SOM are produced that results in net annual increases of ecosystem C, of which about 60% of C is in the form of SOC. The mean C stocks in AFS have been estimated at 300 Mg SOC ha^{-1} (0-1 m depth), with a potential capacity to mitigate up to 2% of the annual global C emissions (Lorenz and Lal, 2014).

However, the C fixation or aboveground C capture in AFS occurs in the aboveground structures (e.g., stem, branches, twigs) (50-60%), in the grass (10%) and the remainder in form of belowground structural C (root systems) (Sharrow and Ismail, 2004). Moreover, it has been observed that individual trees in AFS develop faster than those in forests, allowing greater comparative C fixation rates (Sharrow and Ismail, 2004). Africa shows the greatest AFS diversity, being alley-cropping and improved fallows the most common systems (based on 25 and 17 publications, respectively), which also achieve the highest C fixation rates (12.95 Mg C ha yr^{-1})

However, Feliciano et al. (2018) pointed out the importance of considering the temporal C variations in AFS, since there there are net losses immediately after the implementation of an AFS, then gradually there is increasing C fixation as a result of system-age / tree growing cycle: establishment phase (0-5 yr) > initial phase (5-10 yr) > full vigor phases (>10 yr), finally a decline (>15 yr) is experienced, tending to the steady state (e.g., null C fixation) at maturity, depending on species characteristics, site nutrient status, climatic conditions and management.

Others, however, have reported that upon the adoption of AFS there is a positive but variable result in terms of CO_2→SOC, where a large number of drivers may influence the outcome, including: amount of biomass inputs, previous land use, soil disturbances during AFS establishment, pedo-climatic conditions, type and specific properties of the adopted AFS (e.g., tree species-density), and management characterisitcs (Cardinael et al., 2018). Both the aboveground C fixation and CO_2→SOC rates as estimated by AFS type are provided in

Table 1.4. The variations of CO_2→SOC capacity (Mg C ha yr^{-1}) depend on previous land uses, whereby Cardinael et al. (2018) estimated: cropland to AFS (+0.75±0.19), forest to AFS (+1.15±1.02). Feliciano et al. (2018) estimated changes of CO_2→SOC from previous land managements into AFS types as follows: rangelands to homegardens (+3.8±1.54), croplands to improved fallows (+1.9±1.9) and grasslands to SPS (+4.4±0.86).

Table 1.4 Global C sequestration capacity reported for distinct AFS

System	C fixation (MgChayr-1)	CO_2→SOC ($MgChayr^{-1}$)
Alley cropping	1.65	1.87
Homegardens*	2.18	0.95
Improved fallows**	7.13	1.91
Shadow systems***	2.57	1.48
SPS	1.28	3.30
Woodlots	6.35	0.34

*Refers to diverse animal-herbaceous-tree species on small parcels surrounding homestands; **planning trees (mostly legume species) emplaced over degraded soils in order to enrich soil in relative short periods; ***combination of tea/cocoa/coffee shrubs with multipurpose shade species (Source: Feliciano et al 2018).

Although there is inherent complexity of AFS in terms of "temporal-spatial-biological-management-purposes" variability (Mosquera-Losada et al., 2018), their operative nature is typically highly pluralistic, and involves multi-agency interdisciplinary, participatory and continuous learning frameworks (Thevathasan et al., 2019), reasons for which AFS are considered viable SLP alternatives in the recovery of L_AD_{EG} –affected areas, particularly in developing countries, small / subsistence economies and geographically restricted areas that are highly dependent on local organizations.

Among the world-regions, where L_AD_{EG} is severe, it is therefore more likely to adopt AFS is Africa, which has been regarded as the only macro-area (besides Central Asia) showing negative trends on biomass C balance in agrosystems (PgC) (period 2000-2010), as follows: Eastern and Southern Africa 2.31-2.30 (-0.17%), North Africa 0.11-0.11 (-0.01%), West and Central Africa 5.57-5.45(-2.18%) (Abbas et al., 2017). In addition, about 80% of food production there comes from smallholder farmers, for whom agriculture represents both food security and the main/single source of income (Swaminathan, 2012). Africa is also the continent where it is projected that by 2020, approximately 72-250 million people are living under water stressed conditions (Pachauri, 2012). Furthermore, the literature related to C fixation and $CO_2 \rightarrow SOC$ in AFS, mainly comes from Africa (41.5%), Central Latin America (30.9%) and Southeast Asia (14.1%) (Feliciano et al., 2018), probably due to the previously stated origins of these systems. However published scientific research besides local knowledge-experience, may enhance the potential of site-specific AFS solutions with regards to L_AD_{EG} and climate change. For instance, Dixon (1995) estimated that in tropical latitudes one hectare (ha) of AFS can provide goods and services that potentially offset between 5 and 20 ha of deforestation.

1.4.1 Ecological importance of trees in AFS

The presence of trees not only contributes to a greater C fixation being also increases the potential utilitarian and consumer assets, but in AFS, the trees also operate as active or passive banks of protein (e.g., browsing in SPS) without compromising yields and animal wellness when properly managed (Clough, 2011). Furthermore, AFS has been recognized as SLP able to play complementary roles other than food production, such as buffer spaces for conservation of biodiversity, depending on the combination tree species-density-arrangement (Vandermeer and Perfecto, 2007; Harvey et al., 2008; Tscharntke et al., 2011) This is because trees serve as seed producers and providers of habitat and food for animals (Kabir and Webb 2009) and can be used in buffer zones or biological corridors (Donald, 2004; Mas and Dietsch, 2004) (See Fig 1.2 and its description), compared to agricultural areas (being commonly fragmented and degraded systems low in biodiversity).

1.5 The SPS approach to address L_AD_{EG} and climate change

Pastures covering about 3.4 billion ha are to a large extent under source-limited conditions and / or lack of appropriate management (Gurian-Sherman, 2011). In agreement, savannas (accounting for about 30% of NPP) (Grace et al., 2006) are among the most threatenedaffected biomes worldwide by L_AD_{EG} and the effects of climate change meaning desertification (e.g., degradation of dry lands), as a consequence of bad grazing practices, related to high stocking animals and / or cattle farming depending on low productive native grasses (Arevalo et al., 1998). Therefore, there is a broad potential for the implementation of SPS in such areas and those devoted to subsistence–smallholder agriculture and/or livestock.

By definition, SPS refer to: "*multifunctional systems that combine herbage, shrub and tree layers with grazing animals in a single site*" (Sales-Baptista and Ferraz-de-Oliveira, 2021), are resilient land managements recognized for promotion of land productivity, besides ecosystem-climatic and social benefits, including: C fixation in vegetational biomass (tree and herbaceous), and CO_2→SOC, compared to open and treeless areas (Aryal, 2019, Beer et al 2003), and increasing the carbon storage potential of grasslands (José and Bardhan, 2012; Feliciano et al., 2018), ecosystems services (e.g., water-nutrient cycling), pedogenesis, productive outcomes (e.g., timber, animal products), climatic benefits (e.g., climate and air regulation), aesthetic, educational and democratization values and protection of habitats (particularly encouraging endemic) (Maathai, 2012; Sales-Baptista and Ferraz-de-Oliveira, 2021), economically feasible (Sharrow et al., 2009). Currently, SPS cover worldwide about 450 Mha (28% of the total AFS) (Nair, 2012) (Table 1), having multiple possible combinations of components and arrangements, generating great adaptability to particular conditions and needs (Sales-Baptista and Ferraz-de-Oliveira, 2021).

In addition to the general benefits of SPS in common with other AFS (e.g., C fixation, CO_2→SOC and climate change resilience), SPS have a comparative potential advantage associated to the grazing cycle (Nair, 2012B). Adequate grazing practices contributes to the increase of SOM and potential CO_2→SOC by stimulating biological activity and consequently a net nutrient mineralization – nutrient availability (See Fig 1.2 and its description). For instance, faster annual turnover of shoot materials and variations in species composition has been observed (Reeder and Schuman, 2002), meanwhile reducing the production of annual forbs, also encompassing the develop of grasses with more dense and fibrous root systems (Rees, 2005).

The diversity and evolution of SPS extends from the presence of native trees within plots used for grazing livestock, pruning / pollarding for fodder, firewood collection and charcoal production without forest product recollection, and farming dating back to the 14th-18th centuries period (Sales-Baptista and Ferraz-de-Oliveira, 2021), to current intensive SPS supporting densities over 4,000-40,000 plants ha^{-1} (100-600 woody individuals) (Montagnini, 2020).

1.5.1 The C intake in SPS

Specifically, studies of SPS have reported that 1-5 Mg C ha y^{-1} are sequestered in aboveground biomass (Ibrahim et al., 2010), and belowground, SOC accumulation rates of 1.8-7.5 Mg ha^{-1} y^{-1} have been observed (Alonso, 2011; Udawatta and Jose, 2011; Feliciano et al., 2018; Ortiz et al., 2020). The conversion of grasslands to SPS leads to the highest total estimated C accumulation (4.4 Mg C ha yr^{-1}) (Feliciano et al., 2018).

These aforementioned rates depend on: i) the previous land use, and which woody species are to be incorporated into currently managed pastures, or vice versa, to create the SPS (Gordon et al., 2005), the amount of diversification to be introduced to intensive monoculture plantation systems (Peri et al., 2017), or whether there is reclamation of degraded forest (Ortiz et al., 2020) and prairies before the SPS (Dube et al., 2011), or cropland to be converted to SPS (Cardinael et al., 2018) ii) the dominant pedo-climatic-ecological conditions, iii) species selection and their density-spatial arrangement within the SPS, and iv) the SPS operative efficiency (main objective purpose, debris management, etc.) (Cardinael et al., 2018).

SPS have been reported to produce the highest CO_2→SOC conversion rates among the different AFS (Feliciano et al., 2018), which have been documented in regions such as Europe (Rigueiro-Rodriguez et al., 2009) and North America (Udawatta and Jose, 2011).

1.5.2 Bio-physical mechanisms for land conservation and C sequestration in SPS

The continuum biomass production in SPS (e.g., foliage-litter-fall, feces), which is generated from the interaction of SPS components, results not only in C fixation but in the formation of fresh SOM (or SOC) (Nair, 2012; El-Ramady et al., 2014), which is a crucial component that also controls most of the aforementioned soil and terrestrial ecosystem processes (Baldock and Skjemstad, 2000; Lal et al., 2015; Heaton et al., 2016) and is a key component of L_AD_{EG} assessment and potential of climate change mitigation. A summary of the synergistic processes within SPS is graphically described in Figure 1.2 and subsequently analyzed.

However, competitive interactions in the SPS understory for light, moisture and nutrients have been observed, that may lead to diverse adverse effects (e.g., nutrient uptake levels, yield loss, reduction of plant growth and increased mortality) (Mead, 2009), and losses of SOC via increased tree-understory development (Upson et al., 2016). Moreover, animal-plant interactions could also have detrimental influences, including premature fruit drop by trees (e.g., some pines, *Cupressus* sp.) (Fisher, 2007), higher parasite loads on livestock under shade (e.g. pines) (Mead, 2009) and damage to young trees via browsing (Mead et al., 1999). Therefore, the species selection, tree density-distribution, type of management practices and cattle loads are some of key criteria that should be considered prior to SPS establishment and-or during the initial stage of operational activities.

1.5.2.1 Individual mechanisms

A) Trees / woody component

① Ecological sustaining-improving through the inclusion of native, N-fixing (e.g., *Hippophae rhamnoides*, *Alnus incana*) and/ or fast growing species (e.g., *Populus* sp) and /or species of social-economic interest (e.g., timber production, fruit trees) (Nair et al., 1999; Gordon and Thevathasan, 2005; Jose et al., 2019).

② Promoting animal welfare trough shading, providing temperatures around the animal-thermoneutral zone and protecting new-born individuals (e.g., chilling) and offspring survival (Fisher, 2007; Hu *et al.*, 2005; Murgueitio et al., 2013; Broom et al., 2013).

③ Limiting moisture losses via canopy (e.g., evaporation recapture, reducing potential hydric stress) and nutrient leaching (e.g. assimilation of residual NO_3^-), also reducing the impact of

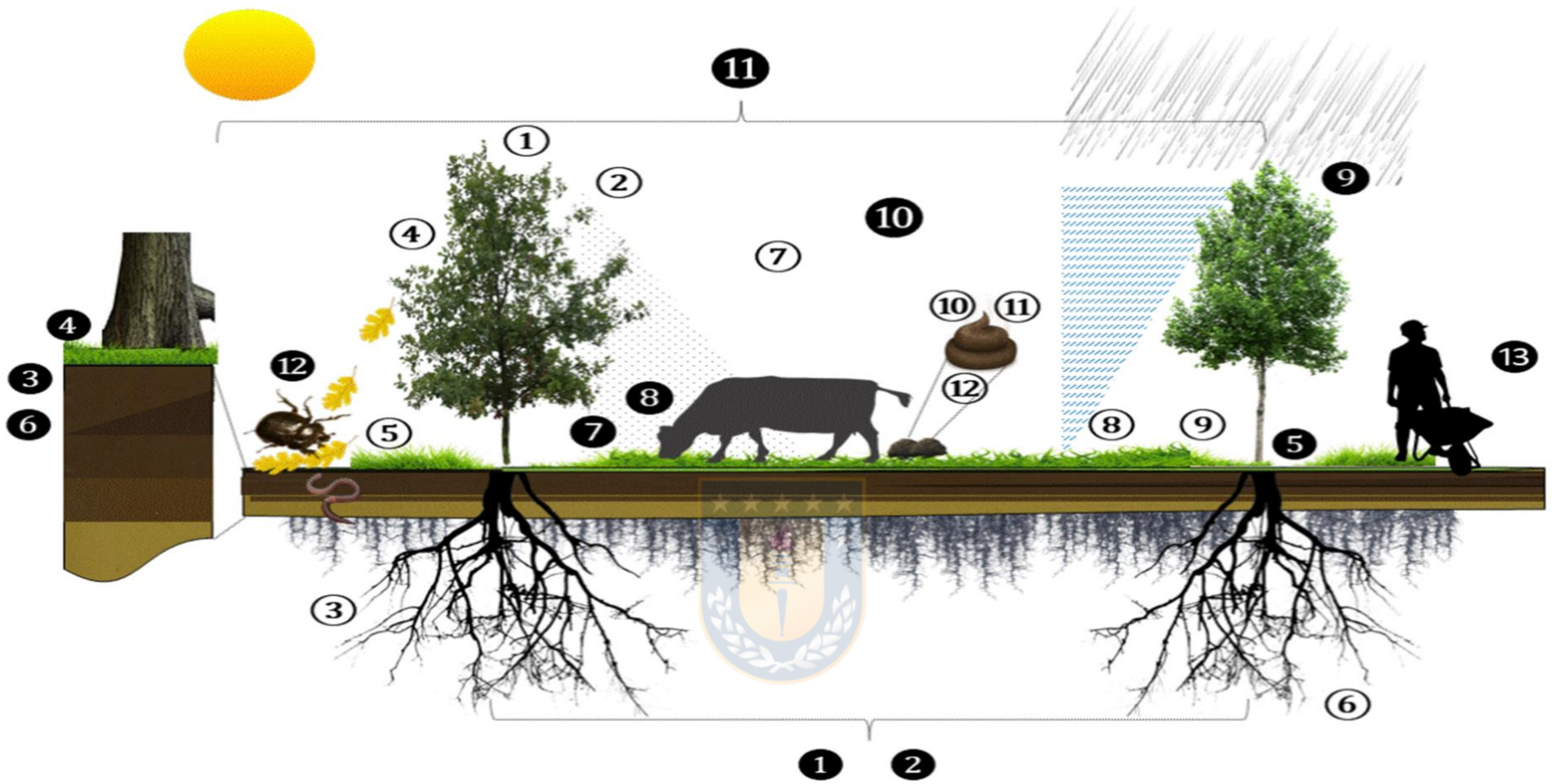

Figure 1.2 Main bio-physical mechanisms involving C→SOC, CO_2eq emission reduction and soil quality improvement in SPS: i) as individual functions: ① Stress reduction, ② Bio-protection, ③ Internal resource cycling, ④ C fixation ⑤Biomass input / SOM chemical protection, ⑥ Depth exploration**,** ⑦ Regulation of temperature- moisture fluxes, ⑧ Improvement of herbaceous resilience, ⑨ Mutualism, ⑩ Medium-term critical nutrient bio- disponibilization and SOM mineralization, ⑪ Short term critical nutrient bio- disponibilization and SOM mineralization, and ⑫ Direct input of organic matter; **ii) as component interactions**: ❶ Shrinking of dissolved C (DOC) losses, ❷ Groundwater pollution protection, ❸ Direct input of organic matter-nutrients, promoting SOM cycling, ❹ Bio-disponibilization, ❺ Dietary diversification, ❻ Physical and chemical protection of SOM, ❼ Increase of digestibility, ❽ Rotational grazing, ❾ Bio-construction, ❿ Generation of microclimatic conditions, ⓫ Autonomy, ⓬ Increase of biodiversity, resilience, dynamic of SOM, and ⓭ Human well-being.

erosive agents (e.g., raindrop impact) (Buresh and Tian, 1998; Fisher, 2007; Murgueitio et al., 2013; Ong and Kho, 2015; Kunst et al., 2016; Jose et al., 2017).

④ By reducing aboveground-belowground C:N ratios, including about 22% more C stored in woody elements compared to intensive land uses (e.g., plantations) (Dube et al., 2011).

⑤ Litterfall-debris rich in lignin, reduce SOC mineralization in respect to agricultural systems. However, litterfall also provides up to 90% of nutrients required for herbaceous component (Buresh and Tian, 1997). ⑥ Root exploration increases soil moisture retention and porosity, penetration resistance compared to cropland / grassland. water holding capacity and infiltration capacity improvement, Regulation of hydrological cycle (Buresh and Tian, 1997; El-Ramady et al., 2014).

B) Herbaceous component

⑦ Promoting the protection-development of topsoil by a permanent cover, avoiding the emission of water vapor, also preventing preferential flow pathways (e.g., formation of rills-gullies). Less sensitive to shade than other AFS (Giller, 1997; Montagnini and Nair, 2004; Cardinael et al., 2017).

⑧ The use of mixed species may enhance resistance to environmental changes, potential diseases and pests (Sarabia et al. 2020).

⑨ Combination of forage and N-fixing species, facilitating availability of a critical nutrient and incorporating SOC even more efficiently than trees. Increases yield of 100% have been observed compared to monoculture-pastures (De Stefano and Jacobson, 2017; Sarabia et al. 2020).

C) Animal component

⑩ Feces increase soil nutritional status with contributions of P, K, Mg, Ca and N. This last is about 90% in organic forms, which is slowly released (24 months period) in forms of NO_3^-, preferred by woody plants. Cattle contribution on soil fertility includes about: 6.9, 7.5 and 4.5

mg kg^{-1} of N, P and K respectively (Saarijärvi and Virkajärvi, 2000; Rochette et al., 2014; Uscola et al., 2014; Bélanger, 2015).

⑪ Urine contributes with readily useful (weeks period) N (NH_4^+), which is utilized primarily by herbaceous component, commonly resulting in higher growth rates, yield and coverage (Saarijärvi and Virkajärvi, 2009; Uscola et al., 2014).

⑫ Livestock introduces litter into mineral soil via trampling, increasing around 12% SOC within 0-15 cm. Livestock is also effective in the weed control-herbaceous competition and preventing potential wildfires by keeping the vegetation sparse (Naeth et al 1991; Hewins et al., 2018).

1.5.2.2 Mutualistic mechanisms

Bipartite

A) Relationships between trees

❶ Reduction in nutrient - C losses via leaching (e.g., dissolved organic C (Dupraz and Liagre, 2008).

❷ Root associations limit lixiviation processes of potentially harmful compounds (e.g., NO_3^-) (Beaudoin et al., 2005; Dupraz and Liagre, 2008).

B) Relationships between trees and herbaceous

❸ Root exudates endorse biological activity, where tree roots introduce organic matter in deep soil, out of the rhizosphere and herbaceous roots acts as a green manure, contributing around 50-92.7 % of stable SOC (Odhiambo et al., 2001; Sokol et al., 2019).

❹ Functioning as a bank of protein and nutrients and animal health protection, including productivity (growth rates), and the reduction in parasite infestation. Common inclusion of N-fixing species (about 650 available woody species, able to fix 100-500 Kg N ha yr^{-1}), transferring N to animals via fiber (about 120 kg N ha^{-1} required) and other vegetal components via soil solution. N fixing diet (via condensed tannins) also provides increases in reproductive rates, expansion of immune cells, reduction in nematode parasite fecundity, parasite populations and favoring helminthic control (Lefroy et al., 1992; Nguyen et al., 2005; Nair et al., 1999; Odhiambo et al., 2001; Mupeyo et al., 2011; Pitta et al., 2005; Ramirez-Restrepo et al., 2010; Sarabia et al. 2020).

❻ Root systems from both woody and herbaceous (exudates and other forms of SOM), promotes the formation of stable aggregates, organo-mineral associations (avoiding potential toxic elements such as Al^{3+}), and the formation of condensed organic matter (e.g., humic substances) (Giller, 1997; Buresh and Tian, 1997; Kunst et al., 2016).

C)Relationships between herbaceous and animals

❺ Leaf complementary diet (e.g., *Carpinus betulus*, *Corylus avellana*) rather than only grain ensures both, usability of non-profitable resources for humans and the reduction of ecological pressure linked to intensive fodder production (e.g., soybean) (Broom et al., 2013; Boerema et al., 2016; Vandermeulen et al., 2016).

❼ Introduction of rumen fermentation modifier species, having high contents of saponins-tannins with associated anti-protozoa-methanogenic properties up to 22% more than intensive livestock farming (Galindo, 2004; Hu et al., 2005; Sarvade et al., 2019).

❽ Animal habits have a key roil on: i) promoting plant propagation, ii) reducing the risk of fire generation – propagation, and iii) generating a green cover, reducing in about 16-40% the weeding costs (Lacorte et al., 2016; Sarvade et al., 2019).

Tripartite

❾ The optimization in the use of local resources (about 40% more) compared to intensive land uses (e.g. plantations), results in a more efficient growth of tree aerial-lateral structures (e.g., aboveground C), ultimately SOC input (Dube et al., 2011).

❿ Modification of different environmental parameters (e.g., air and soil temperature (0-5 cm), % relative humidity, total radiation, wind speed, evapotranspiration (Dube et al., 2011; Jose et al., 2017).

⓫ Limiting requirements of external inputs (e.g., energy) compared to mono-biotic and conventional systems (e.g., fuels, manure management) (Nair et al., 1999; Moreno et al., 2014).

⓬ Promoting connectivity between landscape fragments. Associated environmental services including pollination, pest and weed control, translocation of SOM (e.g., bioturbation) (Odhiambo et al., 2001; Ibrahim et al., 2010).

⓭ Improving job satisfaction, promoting food security, family-social integration, economic production, poverty reduction, considering a global decline of household food production in rural sectors of approximately 60% (Ispikoudis and Sioliou, 2005; Broom et al.,2013; Montagnini et al., 2013; Sarabia et al. 2020).

1.5.3 Influence of SPS on changing SQ

The SPS are able to store and conserve C in vegetation and soil, increase SOC stock (e.g., $CO_2 \rightarrow SOC$) progressively influence physical, chemical and biological soil properties and ensuring the associated ecological benefits (Sollins, 1996). In different studies it has been demonstrated the positive variations of soil properties and ecosystems services (e.g., SI_{ND}) apart from $CO_2 \rightarrow SOC$ due to SPS management, such as: i) improving water cycling and retention: by reduction of soil bulk density, increased water infiltration capacity, and reduced mechanical resistance, ii) improving nutrient status (by increased total and available N, and K), iii) improving sorption-desorption by decreased soil acidity, and greater immobilization of pollutants and potential toxic ions by reducing aluminum saturation (e.g., Arevalo et al., 1998; Blanco and Lal, 2008; Ortiz et al., 2020).

1.5.4 Impact of SPS on soil communities

The management and environmental conditions of SPS exert a marked influence on the activity and diversity of soil organisms. In these systems, the availability of food, the variability in the composition, in terms of flower richness, and the rest of the edaphic and cultural factors are of great importance. This shows that in environments with greater potential for biological complexity there may be conditions that favor the improvement of soil characteristics, as a result of the activity of the organisms in it, which in turn would have positive effects on biomass production (Alonso 2011; Fierer 2017; Neira et al 2021).

1.5.5 Effects of SPS on animal behavior

Diverse ethological changes have been observed in livestock in SPS compared to treeless pasture systems. Trees enlarge the growth curve of the associated prairies, not merely by increasing seasonal food availability, but also by improving environmental conditions; consequently avoiding an excessive energy investment by animal energy in thermoregulation and displacements for water acquisition-consumption (Peri, 2011; Dube et al., 2018). The latter depends upon the canopy density, distribution and species present, whereby around 300-500 steams ha^{-1} and/or 65-75% of solar radiation inflows), have been reported to promote the development of valuable forages, while the opposite situation occurs in highly shaded conditions, with a concomitment and widespread presence of species having a lower nutritional quality (Peri, 2011; Dube et al., 2018).

1.5.6 Reported contributions of SPS for offsetting greenhouse gases other than CO_2

With reference to the potential of SPS to counteract emissions from different sources than CO_2, diverse evidence has been reported:

Methane (CH_4^+): Agriculture causes 50% of the global CH_4^+ emissions, out of which 32.7-39 % (80 Tg) are from enteric fermentation (e.g., biological process of macromolecular break down in the rumen of livestock) (Moumen et al. 2016). Extensive grazing (rangelands), tends to deplete valuable resources of fodder, leading to the intake of lower quality forages (having less than 45% digestibility) (e.g., perennials / poorly palatable species with low concentrations of crude protein, and having high levels of complex molecules such as lignin). Additionally, intensive livestock management requires massive production of fodder at a high environmental cost (Steinfeld et al., 2006; Sarabia et al. 2020). However, in SPS, it is common to include N-fixing species that contain condensed tannins and saponins with medium to high values of digestibility (55-85%), that decrease CH_4^+ emissions by 12-15% (Steinfeld et al., 2006; Montagnini et al., 2013).

Moreover, soils can act as CH_4^+ sinks via two main mechanisms: i) direct diffusion of CH_4^+ into pore spaces and ii) methanogenic bacteria oxidation to CO_2. Edaphic factors controlling CH_4^+ intake include BD, soil moisture and pore architecture-effective porosity (Priano et al., 2017). Since tree-based land managements (e.g., AF-SPS) promote: i) favorable soil structural processes, ii) soil biodiversity and a more efficient water cycling (moisture trapping via the tree canopy), they also actively contribute to CH_4^+ sequestration (De Bernardi et al., 2020). For example, Priano et al. (2020) found 100 and 204% higher CH_4^+ intake (ng CH_4^+ m^{-2} s^{-1}) in a pine plantation in the Province of Buenos Aires, Argentina, compared to conterminous rangelands and croplands, respectively.

Nitrous oxide (N_2O): Livestock production is a source of 75-80% of N_2O emissions from agricultural activities (65% of overall global emissions) (Steinfeld et al., 2006), since N is inefficiently used by animals (only 5-30% of the N in feed) (Oenema et al., 2008). Specifically in the case of N_2O emissions, livestock generates at least 1.8 Tg N yr^{-1}, which represents 33% of the global agricultural emissions (Syakila and Kroeze, 2011; Skiba and Rees, 2014).

Other major sources of N_2O are a consequence of: i) the application of synthetic N fertilizers (~120 Tg N yr^{-1}), which is an equivalent amount to that captured by global processes of biological N fixation (Smith et al., 2017) and ii) anthropogenic soil disruptions (e.g., tillage, fertilization processes), where low aeration (oxygen levels) in combination with other factors (e.g., presence of **SOC_{LF}** and slightly acid to alkaline pH), that lead to denitrification events in soils. Intensive agriculture also generates diffuse emissions based on N losses from soil (e.g., leaching of NO_3^-, and contained in runoff), where N_2O is subsequently formed outside the soil system (e.g., superficial water bodies) (Syakila and Kroeze, 2011; Skiba and Rees, 2014).

Nevertheless, in SPS, the use of N-fixing species may partially or totally decrease the necessity of N fertilizers, thereby: i) the necessity of their direct utilization, ii) limiting NO_3^- leaching-denitrification that could produce N gas, and iii) minimization of their contribution to global emission of the 14 Tg CO_2 that annually emanate from commercial fertilizer production (Steinfeld et al., 2006).

1.5.7 Considerations prior to SPS establishment

Competitive interactions in the SPS understory for light, moisture and nutrients have been observed, which may lead to diverse adverse effects (e.g., nutrient uptake levels, yield loss, reduction of plant growth and increased mortality) (Mead, 2009), and losses of SOC via increased tree-understory development (Upson et al., 2016).

Moreover, animal-plant interactions could also result in detrimental outcomes, including premature fruit drop by trees (e.g., some pines, *Cupressus* spp.) (Fisher, 2007), higher parasite loads on livestock under shade (e.g., pines) (Mead, 2009) and damage to young trees via browsing (Mead et al., 1999). Therefore, the species selection, tree density-distribution / shadow rate, type of management practices and cattle loads are some of key criteria that should be considered prior to SPS establishment and during the initial operative activities.

In developing regions (e.g., semiarid) SPS consist of open grazing by free-roaming animals under scattered natural areas of trees and shrubs (Nair, 2012b), and regions where there is frequent utilization of halophytes (e.g., plants in edaphic environments with at least 200 mM UNIDAD? of salt concentration) for feed purposes, which represents a challenge, mostly due to the high salt content of the plants and the consequent nutritional constraints for animal feed (Öztürk and Güvensen, 2019). However, to accurately assess the nutritional value of a particular species for its potential use as fodder in SPS and how it regulates animal preferences-behavior-productivity, is necessary to determine the different properties which influence its palatability such as dry matter, ashes content, crude protein, neutral detergent fiber, metabolizable energy, amino acids and fatty acids (Schmidt et al., 2013).

Another important aspect to consider before SPS implementation (and AFS in general) is the legal frame concerning "*regulatory managements*" (SLP) in order to avoid conflicts of interest (e.g., land tenure) between farmers – local communities – and large states supported by governments. Noordwijk et al. (2008) stated the principal issues restricting the potential for farmers planting trees and establishing AFS in general include: i) inconsistent terminology for forest, plantations and reforestation, ii) limited accessibility to appropriate planting material, iii) lack of management skills and information linking products to lucrative markets, iv) overregulation of logging mostly restricting the marketing of tree sub-products, v) lack of rewards for enhanced environmental services after AFS-SPS adoption, vi) lack of legal and institutional frameworks supporting AFS-SPS.

1.6 Conclusions

Considering that 5.5 billion people live in developed countries and depend on agriculture for their livelihood (20% are small holders) (Lal, 2015), and those territories are the most affected by L_AD_{EG}, they and their lands represent a suitable scenario for the implementation of SPS, especially in the most vulnerable soil/ecosystems and/or societies. The principal types of SLP, SPS (and AFS in general) not only promote social integration but are also able to reverse different L_AD_{EG} processes such as SOC depletion, soil erosion, soil compaction, pests, species migration-extinction through their complex bio-physical interactions, resulting on a continuous SOM-SOC production, which has been recognized as one of the most reliable terrestrial variables to measure ecosystem productivity. Since L_AD_{EG} originates mainly in the soil, is necessary to periodically assess different soil properties-processes apart from SOM, or, in other words, to evaluate-monitor the effects of SOM on other important parameters of soil quality (SQ). However, the use of SQ has not received enough attention in the literature as a complementary tool addressing L_AD_{EG}. In spite of the foregoing and other literature documenting the importance and transcendence of SLP, there has been only a 7% rate of implementing no tillage-SLP systems Derpsch (2011) from conventional agriculture. Finally, it is necessary to not loose sight that the primary and most valuable opportunity to confront L_AD_{EG} and climate change effects is the reduction of widespread LUC, mainly through conversion of natural ecosystems to unsustainable biomass production models (e.g., mono-biotic, conventional and/or industrial agriculture). However, L_AD_{EG} control at the local level is difficult for small farmers and landholders from developed countries because of limited resources, which triggers the vicious cycle of “land degradation-poverty”.

1.7 References

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CAPÍTULO II

Soil Quality Changes within a *(Nothofagus obliqua)* Forest Under Silvopastoral Management in the Andes Mountain Range, South Central Chile

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Abstract

In Chile, 49.1% of the national territory is affected by soil degradation (including erosion and loss of soil organic matter), whereby of the 51.7 Mha that have been historically associated with agricultural-livestock and forestry activities, only 35.5 Mha are being used at the present. Consequently, soil degradation has resulted in the release of about 11.8 Gg yr^{-1} of carbon (C) equivalent (CO_{2eq}) to the atmosphere. Silvopastoral systems (SPS), however, can increase soil organic C (SOC) through sequestration (C→SOC), improve ecosystem services, and have been internationally recommended for sustainable land use. Therefore, it was proposed to determine the effects of SPS on soils, over five years, in degraded sites that were in the Ranchillo Alto (SPS-RA) (37°04′52” S, 71°39′14” W), Ñuble region. The sites were rated according to previous canopy disturbance levels (+) as follows: open (O_p)+++, semi open (SO_p)++, and semi closed (SC)+. The analysis was performed on different physical and chemical soil properties (0–5 and 5–20 cm depths), that were expressed as soil indicators (S_{IND}) for chemical and physical properties, which were used to calculate a soil quality (SQ) index (SQI). The results indicated overall SQI values of 37.6 (SC) > 29.8 (O_p) > 28.8 (SO_p), but there were no significant variations ($p < 0.05$) in physical SQ, whereas chemical SQ varied in all conditions, mostly at 0–5 cm in O_p and SO_p. Increases of SOC were also observed (2015–2018 period) of 22.5, 14.5, and 4.8 Mg ha^{-1} for SO_p, O_p, and SC, respectively, showing that SPS promote the reclamation of Ranchillo Alto soils.

Keywords: Agroforestry systems; sustainable land management; C sequestration; Andisols.

2.1 Introduction

At present, of the 10–12 Pg yr^{-1} of the world emissions of carbon equivalent (CO_{2eq}) (greenhouse gas emissions expressed as CO_2) (Hegerl et al., 2007; Edenhofer, 2014), deforestation is the second largest anthropogenic source of CO_2 emissions (Lal, 2001). Additionally, of the 4033 Mha that comprise the world forest areas, around 3.24% has been subjected to logging, which has resulted in the release of approximately 20% of the global soil organic C (SOC) depletion, mainly due to the expansion of agricultural frontiers (Adams, 2012). Specifically, South America is the second leading region of the world for CO_{2eq} emissions from agricultural-forestry and livestock practices (40%) (Calvin et al., 2016), resulting in losses of approximately 8.7% of the forest areas (Adams, 2012).

As a part of the international efforts addressing climatic change, silvopastoral systems (SPS), which are defined as predetermined associations of woody and herbaceous species and livestock and are a subtype of an agroforestry system (AFS), have remarkable carbon sequestration (C→SOC) potential, and can store around 1.8–6.1 Mg SOC yr^{-1} (Nair et al., 2008; Alonso, 2011; Udawatta and Jose, 2011), which is critically relevant to natural pedologic processes, management practices, and environmental functions. In this regard, Karlen et al. (1997), introduced the concept soil quality defined as, “Soil capacity under a determined management or ecosystem fringe to sustain biological productivity, preserve environmental functions, promoting plant and animal development and consequently human health". Soil quality (SQ) is measured through SQ indicators (S_{IND}), which directly or indirectly reflect soil functionality at different timescales (Arshad, 2002; Karlen et al., 2003). According to (Doran and Parkin, 1994; Doran and Parkin, 1996; Bünemann et al., 2018), the selection criteria for soil indicators (S_{IND}) should include the following: (i) a correlation with ecosystem processes (e.g., C→SOC); (ii) integration with chemical physical and biological properties, (iii) easily measured, replicated, and verified; (iv) a sensitivity to seasonal or atmospheric variations and realistic management practices; (v) compatibility with previous data; and (vi) usefulness for different professionals.

Regarding the specific case of Chile, decades of overutilization of natural resources has resulted in 49.1% of the national territory being affected by soil degradation (Flores et al., 2010), which has caused yearly emissions of approximately 11.8 Gg CO_{2eq}, of which approximately 38% comes from agricultural soils (UNFCCC, 2018). Moreover, of the 51 Mha that have been historically used in agricultural-forestry and livestock production, only 35.5 Mha presently remain active (ODEPA, 2019), mostly because of a massive loss of forest biomass that has had a critical effect on optimal soil functionality (e.g., erosion) (Lal, 2001).

On that basis, different government and institutional initiatives have been implemented (e.g., National Forest Program), in order to mitigate soil degradation. However, SPS have achieved only a limited presence in the regulatory framework, a fact that has been documented by scientific researchers (Dube et al., 2016). In Coyhaique, of the Chilean Patagonia, (Dube et al., 2011) an investigation compared SPS to an introduced plantation (both comprised of *Pinus ponderosa*), with results that showed C stocks of 224 Mg C ha^{-1}, 199 Mg C ha^{-1}, and a net C accumulation of 1.8 Mg yr^{-1} (800 trees) and 2.5 Mg yr^{-1} (400 trees) for the SPS and plantation, respectively. The authors concluded that trees in SPS use the site resources more efficiently (up to 30%). Therefore, it was proposed to study the SPS within a native Roble (*Nothofagus obliqua*) forest in the Region of Ñuble (SPS-RA) having distinct levels of degradation, with the objective to determine the effect of SPS over the physical and chemical aspects of SQ, after five years of establishment. It was hypothesized that the SQ index (SQI) in the SPS-RA, would tend to increase at depths of 0–5 cm as a result of improved silvopastoral management, with annual net accumulation of SOC, regardless of the initial site condition, resulting in values above the minimal range reported in the literature for SPS (1.8 Mg SOC).

2.2 Materials and Methods

2.2.1 Study site description

The silvopastoral systems (SPS) are located in the Ranchillo Alto area which is a state-owned property in the Ñuble region (37°04′52” S, 71°39′14” W; 1200–2000 m.a.s.l) covering an area of about 635 ha and 120 km east of the City of Concepcion (Dube et al., 2016 ; Dube et al., 2011; Dube et al., 2018).

The silvopastoral systems located in the Ranchillo Alto area (SPS-RA) comprise 24 ha and were established mainly to recover the ecosystem value of the native forest along with the promotion among the community of sustainably oriented, rural economic practices. The woody element in the SPS-RA is Roble (*Nothofagus obliqua*), while the herbaceous component includes oats (*Avena sativa*), vetch (*Fabaceae purpurea*), clover (*Trifolium incarnatum, T. subterraneum* y *T. vesiculosum*), *Lolium multiflorum westerwoldicum*, *Phalaris acuatica*, *Lolium perenne*, *Festuca arundinacea, Dactylis glomerate),* and the re-sprouting of Radal (*Lomatia hirsuta*), and Quila (*Chusquea quila*). According to USDA, 2014 (USDA, 2014), the soils are Andisols, “Santa Barbara” series (medial, amorphic, mesic Typic Haploxerands), and locally known as “trumaos”.

Andisols in Chile are of major importance for agricultural production, corresponding to approximately 60% of national arable land (2.5 Mha) (Besoain and Sepúlveda, 1985). Moreover, Andisols constitute about 30–70% of the total surface in the Andean Mountain range, which have critical relevance in terms of water cycling (e.g., preventing potential flooding downstream) (CIREN, 1999; Stolpe, 2006). However, previous conditions in the SPS-RA include over grazing and browsing and excessive logging, generating degradation processes evidenced by discontinuous soil cover, topsoil removal, formation of gullies, and massive losses of soil organic matter (SOM) (AMBAR, 2010).

To determine the SQI in the SPS-RA, the respective SQ indexes (S_{IND}) were examined and grouped as follows: (i) chemical parameters such as pH, %SOC, total N, NH_4^+, NO_3^-, P, K^+, Ca^{2+}, Mg^{2+}, Na^+, S, exchangeable Al (Al_{EXCH}), % of Al saturation ($\%Al_{SAT}$) that are linked to soil fertility, and therefore to C→SOC and (ii) physical parameters such as particle density (PD), bulk density (BD), total porosity % (P_{OR}), % of water stable aggregates (WSA), infiltration velocity ($I_{NF}V$), water holding capacity (WHC) and penetration resistance ($P_{EN}R$) which couple soil particle arrangement and environmental services (e.g., water cycling).

2.21. Soil Sampling and Analysis

A total of thirty-six soil samples, randomly chosen, were collected in January 2019 from the depths of 0–5 and 5–20 cm for the three considered conditions (open (O_p), semi open (SO_p), and semi closed (SC)) (Table 2.1). Each sample (analyzed in triplicate) was air-dried, mixed, ground, and passed through a 2 mm sieve for determination of the respective S_{IND}. The work was carried out at the Agricultural Research Institute (INIA, Quilamapu) to determine most of the properties (except for SOC% and N%).

Table 2.1 General information for each tree cover condition in the silvopastoral systems located in the Ranchillo Alto area (SPS-RA)**.**

Cond	Location	Total Area (ha)	N° P and Area (ha)	Tree Density (N^{o} ha^{-1})	Forest Species	Tree Cover Description	Previous Degradation	Soil Sampling
O$_p$	37°14′51″ S, 72°26′30″ W 1250 m.s.n.m	4	3 × 1.33	60	Roble (*Nothofagus obliqua*)	Ground with 85–95% of external light (average area)	+++	2 depths (0–5 and 5–20 cm) × 6 sampling points
SO$_p$	37°14′50″ S, 72°26′30″ W 1250 m.s.n.m	4	3 × 1.33	134	Roble (*Nothofagus obliqua*)	Soil with 65–75% of external light (average area	++	2 depths (0–5 and 5–20 cm) × 6 sampling points
SC	37°14′49″ S, 72°26′30″ W 1250 m.s.n.m	4	3 × 1.33	258	Roble (*Nothofagus obliqua*)	Soil with/ 45–55% of external light (average area)	+	2 depths (0–5 and 5–20 cm) × 6 sampling points

* Cond, condition; Nº P, number of plots. A, area

The chemical S$_{IND}$ of SOC and total N were analyzed at the Soil and Natural Resources Laboratory (Faculty of Agronomy, University of Concepción), according to Wright and Bailey (2001) (Wright, 2001). The temporal variation of SOC and N was determined by comparison of the current to previous data from the sites. The remaining indicators of pH$_{(water)}$, %SOM, [NH$_4^+$,

NO_3^-, P, K^+, Ca^{2+}, Mg^{2+}, effective cation-exchange capacity (ECEC), Na^+, S, Al_{EXCH}] concentrations, and %Al_{SAT} were conducted using the methods proposed by Sadzawka et al. (2006). Regarding the physical S_{IND}, %WSA (water stable aggregates) was measured according to Kemper and Rosenau (1986), where soil samples were placed in a 0.250 mm sieve and immersed within an aluminum chamber containing distilled water during 3 min, with a cycling of 1.3 cm (35 rep min^{-1}). The dispersed soil was placed in containers and dried at 105 °C, while the remaining soil was re-immersed into an aluminum chamber containing sodium hexametaphosphate (2 g L^{-1}) during 15 min with a cycling of 1.3 cm (35 rep min^{-1}). Once dried, samples from both procedures were weighed in order to determine each proportion within the total sample. The WHC (water holding capacity) was determined according to Zagal et al. (2003). A sample with a 1:2 soil water ratio was placed into a plastic cone sealed with adhesive tape at the bottom for about 12 h, after which the tape was carefully perforated to allow the water to drain which was collected into a plastic bottle, and then the subsequent liquid volume was measured.

The $P_{EN}R$ determination was carried out by using a penetrometer model Soil Compaction Tester Dickey-John (Auburn, IL, USA); and determinations were made by following a transect over the 60 plots for each site condition in order to achieve a reliable representativity. Field measurements of unsaturated hydraulic conductivity (K) were performed using an infiltrometer model Mini Disk Infiltrometer S (Pullman, WA, USA). The methodology proposed by Zhang (1997), was used to determine K (cm day^{-1}), based on the cumulative infiltration measurements. Bulk density (BD) was measured in soil that was sampled using cylindrical soil cores (211 cm^3), which were subsequently dried at 105 °C until reaching a constant weight, (Stone, 1991). The soil particle density (PD) was evaluated through the pycnometer method (Blake et al., 1996), and net pore space (P)% was calculated from BD and particle density (PD) values, using the following equation:

$$P = [PD - BD/PD] \times 100 \tag{1}$$

2.2.3. Soil Quality Assessment

Soil quality estimation was performed by the selection of different S_{IND}, based on their relevance to the properties of the SPS-RA (e.g., soil fertility reclamation, C→SOC), and the previously stated selection criteria. Once a specific S_{IND} was analytically characterized (in the field or laboratory), a numerical point value (score) was, then, assigned to it, based on qualitative ranges (low, medium, and high) reported in the literature (e.g., Amacher et al. (2007) and Vidal (2007)). Those ranges were related to different soil functionality levels, from critical to optimal, in which an individual S_{IND} can influence the overall status of soil quality SQI. However, in this study, the overall SQI was subdivided into chemical ($SQI_{CHEMICAL}$) and physical ($SQI_{PHYSICAL}$) and most of the ranges (low, medium, and high) for any single S_{IND} were taken from (Amacher et al. 2007), although in some S_{IND}, the ranges were adjusted with the aim of improving their local representativity, based on the national scientific literature and the unique properties of Andisols. Additionally, another S_{IND} was included from the original proposal that was conducted by Amacher et al. (2007) , in order to calculate the proposed global SQI (see Appendix A) for the specific purposes of this study. Accordingly, the chemical SQI was calculated as follows:

$$\begin{gathered} SQI_{CHEMICAL} = \Sigma\ [pH + \%SOC + CEC + N + NH_4^+ + NO_3 + C{:}N + P + K + \\ Ca^{2+} + Mg^{2+} + Na + S + Al_{EXCH} + Al_{SAT}] \end{gathered} \tag{2}$$

where $SQI_{CHEMICAL}$ is the chemical soil quality index, %SOC is the percentage of SOC, ECEC is the effective cation-exchange capacity, N is total N, NH_4^+ is available ammo nium, NO_3 is available nitrate, C/N is the C:N ratio, P is available phosphorus, K^+ is potassium content, Ca^{2+} is calcium content, Mg^{2+} is magnesium content, Na is sodium content, Al_{EXCH} is exchangeable aluminum, and Al_{SAT} is aluminum saturation (%).

Subsequently, physical SQI by S_{IND} was calculated as follows:

$$SQI_{PHYSICAL} = \Sigma\,[I_{NF}V + \%WSA + WHC + P_{EN}R + BD + PD + P_{OR}] \qquad (3)$$

where $SQI_{PHYSICAL}$ is the physical soil quality index, $I_{NF}V$, is infiltration, %WSA is water stable aggregates %, WHC is water holding capacity, $P_{EN}R$ is penetration resistance, BD is bulk density, PD is particle density, and P_{OR} is total porosity.

Therefore, a global SQI was estimated using the means of both SQI types as follows:

$$SQI_{GLOBAL} = \Sigma\,[SQI_{CHEMICAL} + SQI_{PHYSICAL}]/2 \qquad (4)$$

Finally, the % valuation for any site condition was calculated as:

$$\%\,SQ = [\text{number of } S_{IND} \text{ at critical level/number of } S_{IND} \text{ estimated}] \times 100 \qquad (5)$$

2.2.4. Statistical Analyses

The data were input, and calculations made for each S_{IND}, and the conversion to the SQI (Equations (2)–(5)), were performed using Microsoft Excel. All site conditions were analyzed in a completely randomized design that considered both the site conditions and soil depths. Statistical analyses were carried out using one-way ANOVA's; and when a source of variation showed a significant effect ($p \leq 0.05$), a means separation by Tukey's was performed in order to establish differences among the means of every S_{IND}. Additionally, a global Pearson's correlation was conducted in order to identify possible associations among the various S_{IND} ($r \geq \pm 0.7$). The data were analyzed using SPSS (statistical software V11.0, Inc, Chicago, IL, USA).

2.3 Results and discussion

2.3.1. Soil Chemical Indicators

The evaluation of the means of the chemical S_{IND} showed that for each condition and soil depths there were adequate levels for pH, K, S, and Na (Amacher et al. 2007) (Table 2.2, Table 2.3 and Appendix B –Table 2.9).

Table 2.2. Soil chemical characterization results.

Cond/Depths	pH (H_2O)	SOC (%)	N (%)	C/N	P *	K *	Ca **	Mg **
O_p 0–5	5.63Aa	14.17Aa	0.61Aa	23.05Aa	2.98Aa	109.9Aa	1.6Aa	0.28Aa
O_p 5–20	5.59Ab	13.33Aa	0.61Aa	22.09Ab	2.08Ab	73.8Ab	0.46Ab	0.16Aa
SO_p 0–5	5.93Ba	12.57Ba	0.48Ba	26.31Ba	3.66Ba	87.6Ba	4.58Ba	0.58Ba
SO_p 5–20	5.59Bb	11.49Ba	0.45Ba	25.37Bb	2.13Bb	62.2Ba	1.37Bb	0.25Ba
SC 0–5	5.9Ca	10.82Ca	0.46Ba	22.37Aa	3.63Ba	113.7Aa	3.23Ba	0.32Ba
SC 5–20	5.85Cb	13.87Cb	0.53Ba	21.78Ab	2.15Bb	70.1Ab	3.33Ba	0.47Ba

* Cond, conditions; *n*:18; $p < 0.05$; * mg kg^{-1}; ** cmol (+) kg^{-1}. Distinct capital letters mean significant differences among conditions whereas lowercase letters refer to significant differences between depths.

Table 2.3. Soil chemical characterization results B. Continuation.

Cond/Depths	Na **	Al_{EXCH} **	ECEC	% Al_{SAT}	S *	NO_3^- *	NH_4^+ *
O_p 0–5	0.1Aa	0.34Aa	2.70Aa	12.74Aa	8.37Aa	16.78Aa	10.59Aa
O_p 5–20	0.1Ab	0.26Ab	1.16Ab	22.09Ab	9.23Ab	10.27Ab	9.07Aa
SO_p 0–5	0.05Ba	0.11Ba	5.55Ba	2.02Ba	9.26Ba	23.72Ba	18.92Ba
SO_p 5–20	0.07Bb	0.30Bb	2.15Bb	13.75Bb	10.73Bb	15.63Bb	13.43Ba
SC 0–5	0.08Aa	0.14Ca	4.06Ba	3.54Ca	13.20Ca	9.16Aa	12.85Ba
SC 5–20	0.13Ab	0.14Ab	4.25Bb	3.25Cb	11.93Cb	12.75Ab	15.68Ba

* Cond, conditions; *n*:18; $p < 0.05$; * mg kg^{-1}; ** cmol (+) kg^{-1}. Distinct capital letters mean significant differences among conditions whilst lowercase letters refer significant differences between depths. *n*:18; $p < 0.05$; * mg kg^{-1}; ** cmol (+) kg^{-1}.

The mean values of soil pH were 5.6, 5.7, and 5.9 (±0.03) ($O_p < SO_p <$ SC), with significant differences measured among the SPS conditions and soil depths. Lower values of pH were observed in the 0–5 cm horizon, which could be attributed to a higher acidic condition that was favored by a greater content of OM (Binkley and Fisher, 2013), however, in all cases the pH values were within desirable ranges for supporting plant grow (Amacher et al. 2007). Soil organic C% content values at the 0–20 cm depths were 13.5, 13.1, and 11.8% (±0.28) for O_p, SC, and SO_p, respectively (Table 2.4). The greatest SOC% occurred in the O_P, despite having the lowest tree cover, as well as being the more anthropogenically affected area. This contradiction could be related to the extensive history of agricultural burns for the potato crops (*Solanum tuberosum*), thereby generating pyrogenic C, as identified by the presence of charcoal fragments and intense black color in soil samples.

Pyrogenic C, is highly resistant to oxidation due to its poly aromatic structure, and therefore could be a persistent fraction of total C. In forests of *Araucaria-Nothofagus* spp., of the Tolhuaca National Park, Chile (36°52′ S y 71°56′ 14″ O), Rivas et al. (2012) it has been estimated that pyrogenic C represented up to 5% of the total SOC. Concerning SOC storage (0–20 cm) in the present study, stocks of 150.5, 149.8, and 143.5 Mg ha^{-1} were estimated for SO_p, SC, and O_p, respectively (Figure 2.1).

Table 2.4. Variation of soil organic C (SOC) and total N in the period 2015–2018.

Conditions	* SOC_{2015}	SOC_{2018}	* N_{2015}	N_{2018}	*$C:N_{2015}$	$C:N_{2018}$
O_p 0–20	7.1	13.5	**0.32**	0.61	22.3	22.3
SO_p 0–20	7.1	11.8	0.38	0.46	19.2	25.6
SC 0–20	8.0.	13.1	0.42	0.52	19.5	22.0

SOC and N (%) * from Alfaro et al. (2018), weighted values * from (Alfaro et al. 2018).

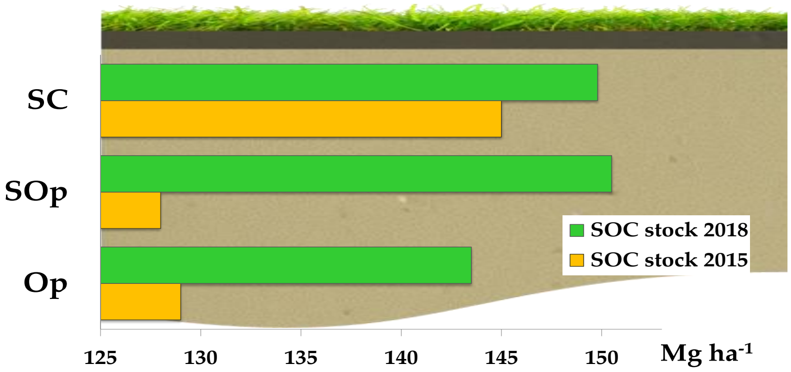

Figure 2.1. Temporal variations (2015–2018) of SOC stocks (0–20 cm) in the SPS-RA. O_P + 14.5 Mg C ha^{-1}; S_{OP} + 22.5 Mg C ha^{-1}; and 1.6 Mg of SOC for semi open (SO_P), open (O_P), and semi closed (SC), respectively.

The estimated carbon concentrations in the SPS-RA are significantly higher than those found in other soil conservation managements (e.g., conservation and no tillage cropping systems). In agriculturally managed Andisols, with wheat stubble incorporation from Yungay, Chile, Panichini (personal communication, May 2019), estimates indicate a mean SOC of 6.9% and a C stock of 130 Mg ha^{-1}. However, Muñoz et al. (2012) determined SOC stocks that ranged from 33.1 to 35.5 Mg ha^{-1} C after 16 years of no-tillage in volcanic soils in south-central Chile.

In our study, the total N% (0–20 cm) ranged between 0.6 and 0.5 (±0.09), where $O_p > SO_p =$ SC, and were within acceptable levels. However, the bioavailable N forms had averaged values for NO^{3-} that ranged from 17.7 to 11.9 mg kg^{-1} ($SO_p > O_p =$ SC), whereas those for NH^{4+} were 15.0, 14.8, and 9.45 mg kg^{-1} (SC $> SO_p > O_p$, respectively), which were lower than the minimal requirements for most plants (Amacher et al. 2007). The N could be undergoing a net immobilization process in soil, or the low levels of NH^{4+} could be related to the high N demand by the herbaceous component, which preferentially uptakes this species because of its lower energetic cost to the plant as compared with NO^{3-}. Alternatively, the woody component favors

NO^{3-} absorption because of the high soil exploratory capacity by roots as occurs in the SC condition (Porter and Lawlor, 1991). Similarly, Alfaro et al. (2018) found a nitrification rate pattern ($NO_3^- \rightarrow NO_2^-$) of SC > SO_p > O_p in the SPS-RA, which was 45% higher for SC as compared with SO_p.

Nonetheless, it is expected that the NH^{4+} levels will increase in soils, to eventually become the dominant bioavailable N species, due to the ongoing fecal depositions from the animal component within the system (Saarijärvi and Virkajärvi, 2009). The temporal variation of SOC and total N are summarized in Table 4. The C/N ratio varied significantly at both ranges of depths (0–5 and 5–20 cm) as follows: O_p (23.1/22.1), SO_p (26.3/25.4), and SC (20.9/20.8). Ratios over 10 indicate a net immobilization of N, resulting in its incorporation into microbial biomass or by-products of microbial activity during the SOM cycling processes, consequently limiting its availability for plant growth (Vitousek and Matson, 1984). In a previous investigation (Dube et al., 2016), the authors found a C/N ratio of 18.0 in the SPS-RA during 2014, showing a progressive increase over time of this S_{IND}, probably highlighting the bio constructive effects of SPS in soils. Phosphorous concentrations were 2.3–2.5 mg kg^{-1} (±0.07) and corresponded to typical values in volcanic soils 3–165 mg kg^{-1} (Borie and Barea, 1983), with a mean of 4.6 mg kg^{-1} *p* for native forests (López, 2010).

However, the *p* values found in the SPS-RA were significantly lower than previously observed (Zagal et al., 2012) and ranged from 15.1 to 19.9 mg kg^{-1} P in volcanic soils under crop rotation of wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), subterranean clover (*Trifolium subterraneum* L.), canola (*Brassica napus* L.), and lentil (*Lens culinaris* L.) or natural grassland (6 mg kg^{-1} P).

Critical P levels in the SPS-RA could be related to P fixation mediated by P-OM associations and P-Al complexes in soil (Borie and Zunino, 1983). For other major nutrients, K concentrations at the 0–20 cm depths were $O_p > SC > SO_p$ (82.8, 81.4, and 68.6 mg kg^{-1}, respectively) (±1.86), which was slightly limiting for plant growth; the S determinations showed that $SC > SO_p > O_p$ (12.2, 10.4, and 9.0 mg kg^{-1}, respectively) (±0.27), and were adequate soil concentrations; there were moderate to low levels of Mg $SC > SO_p > O_p$ with values of 50.5, 48.1, and 26.8 mg kg^{-1} (±5.53), respectively, similar to Ca where $SC > SO_p > O_p$ (657.3, 596.2, and 215.5 mg kg^{-1}, respectively) (±63.1) were observed according to (Amacher et al. 2007). The measurement of soil ECEC at the 5–20 cm depths showed that $SC > SO_p > O_p$ (4.2, 3.0, and 1.5 cmol kg^{-1}, respectively), which was an intermediate level (except for O_P 5–20 cm) with higher values in O_P and SO_P (0–5 cm) (Villarroel, 2000). Regarding Al_{EXCH}, critical values were found of 0.3 and 0.1 cmol kg^{-1} (±0.02) ($O_p = SO_p > SC$), and the $\%Al_{SAT}$ with 19.8, 10.8, and 3.3 (±1.2) for O_p, SO_p, and SC, respectively. Both S_{IND} are typical for volcanic soils, but these still could lead to increased soil acidification, which would inhibit soil nutrient uptake (e.g., Ca and Mg) and restrict possible crop rotations that use Al sensitive species (e.g., barley and wheat) (Bernier and Alfaro, 2006).

2.3.2. Soil Physical Indicators

In the physical S_{IND} analyses, the BD, PD, P_{OR}, and $P_{EN}R$ were estimated to be at optimal levels in all site conditions (Table 2.5 and Appendix A –Table 2.8 -). Individually, BD showed representative values for Andisols with 0.50, 0.53, and 0.68 g cm^{-3} (±0.02) for SC, O_p, and SO_p respectively. The lowest mean was in O_p 5–20 cm (0.51 g cm^{-3}) and was possibly due to the presence of pyrogenic C (Blanco-Canqui, 2017), whereas higher means were observed in SO_p at the 5–20 cm depths (0.65 gcm^{-3}). Likewise, Panichini (personal communication, May 2019) determined a mean value of BD of 0.94 g cm^{-3} in volcanic soils of Yungay under stubble burning management. Moreover, PD varied from 1.95 to 2.1 g cm^{-3} (±0.05) with a mean value of 2.0 g cm^{-3}, which was within representative ranges of volcanic soils that are rich in OM, according to Nissen et al. (2005).

Table 2.5. Soil physical results.

Condition/ Depths	BD (g cm^{-3})	PD (g cm^{-3})	*P_{OR} Total (%)	WHC (%)	I_{NF}Vk (cm day^{-1})	WSA (%)	P_{EN}R (psi)
O_p 0–5	0.6Aa	1.9Aa	71.2Aa	60.8Aa	*	49.6Aa	100–200Aa
O_p 5–20	0.5Aa	2.0Aa	74.2Aa	58.9Aa	17Aa	49.7Aa	100–200Aa
SO_p 0–5	0.6Aa	1.9Aa	68.9Ba	59.2Aa	*	49.4Aa	100–200Aa
SO_p 5–20	0.7Aa	2.0Aa	68.3Ba	52.2Aa	18.3Aa	49.5Aa	100–200Aa
SC 0–5	0.5Aa	1.9Aa	73.6Aa	54.4Aa	*	51.2Aa	100–200Aa
SC 5–20	0.5Aa	2.0Aa	73.9Aa	62.9Aa	16.2Aa	50.4Aa	100–200Aa

n:18 and $p < 0.05$. Distinct capital letters mean significant differences among conditions, whereas lowercase letters refer significant differences between depths. * I_{NF}V values were considered for the total depth (0–20 cm) and * from the Equation (1). BD: bulk density, PD: particle density, P_{OR} Total: Total porosity, WHC: water holding capacity, I_{NF}Vk: Infiltration velocity, WSA: % of water stable aggregates, P_{EN}R: Penetration resistance.

The same authors determined similar PD values (1.92 g cm^{-3}) in forest soils (0–15 cm) of the Region of Osorno, Chile. Although there were no significant differences among %WSA (50.6–49.7 and 49.5%) (±0.65), there was a tendency for SC > O_p > SO_p, that could be related to previous site degradation. Gradual increases of %WSA are expected to occur though, and mediated by, emerging roots and hyphae associations (Tisdall and Oades, 1982; Wu et al., 2015). The soil compaction test (measured through its P_{EN}R) revealed ranges of 100–200 psi that were suitable for root anchoring/exploration and plant growth (Lal and Elliot, 1994; Carter, 2002). It should be noted that there were scattered points within O_p with P_{EN}R > 300 psi that had a visibly reduced coverage of vegetation.

In terms of hydraulic properties (0–20 cm), the P_{OR} presented optimal values in all conditions, with SC (73.8), O_p (73.5), and SO_p (68.5) that promote both water storage and root development. These results are consistent with (Nissen et al, 2005), who found a P_{OR} of 73.9. The WHC (0–5 and 5–20 cm) was within a range of acceptable values that promote water storage and redistribution processes according to Vidal (2007) and ranged as follows: O_p (60.8–58.9), SO_p (70.8–66), and SC (70.8–62.8) (±2.96); with the observed gradient probably corresponding directly with the previous disturbances of the sites, and additions of SOM (in SC and SO_P). In the case of soil with a high P_{OR} and low values of WHC (O_p), this could be due to hydrophobic conditions influenced by the possible presence of pyrogenic C.The S_{IND} that relates to water infiltration and percolation in soil ($I_{NF}V$) 0–20 cm, showed an intermediate level with k values of 17, 18.3, and 16.2 cm day^{-1} with $SO_p > O_p > SC$ (Reynolds, 2003).However, for O_P, many attempts were necessary to carry out the measurements because of compacted surface soil and hydrophobicity which impeded the proper functioning of the infiltrometer.

2.3.3 Determination of SQI

After calculating the sub-indexes for all S_{IND}, distinctive trends were observed in both the chemical and physical indicators (Figure 2.2) which illustrated some of the native (or inherent) characteristics of soil quality in volcanic soils (e.g., P, BD, P_{OR}, Al_{EXCH}, and Al_{SAT}). Additionally, the results showed the possible direct effects of silvopastoralism over some of the S_{IND} sub-indexes (e.g., SOC). Chemical SQI was higher at SO_P at the 0–5 cm depths (probably reflecting the more favorable tree density that favors the beneficial SPS interactions) and SC at the 5–20 cm depths at the less disturbed site (Table 2.6). Nevertheless, SOC as the most important S_{IND}, showed significant variations among all conditions, as evidenced in the O_P condition with a higher %C content (13.5) than the SO_P condition (11.8% SOC).

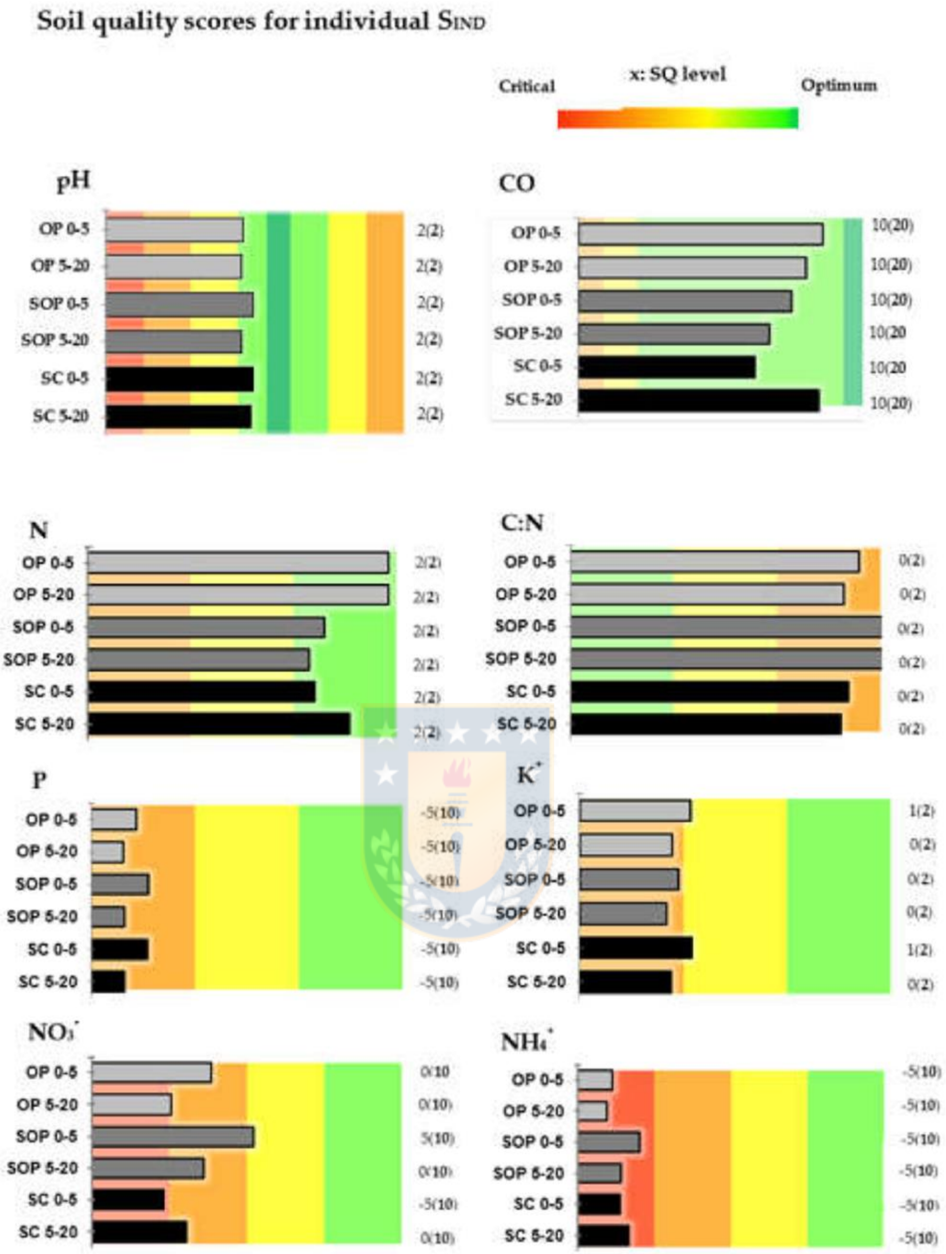

Figure 2. *Cont.*

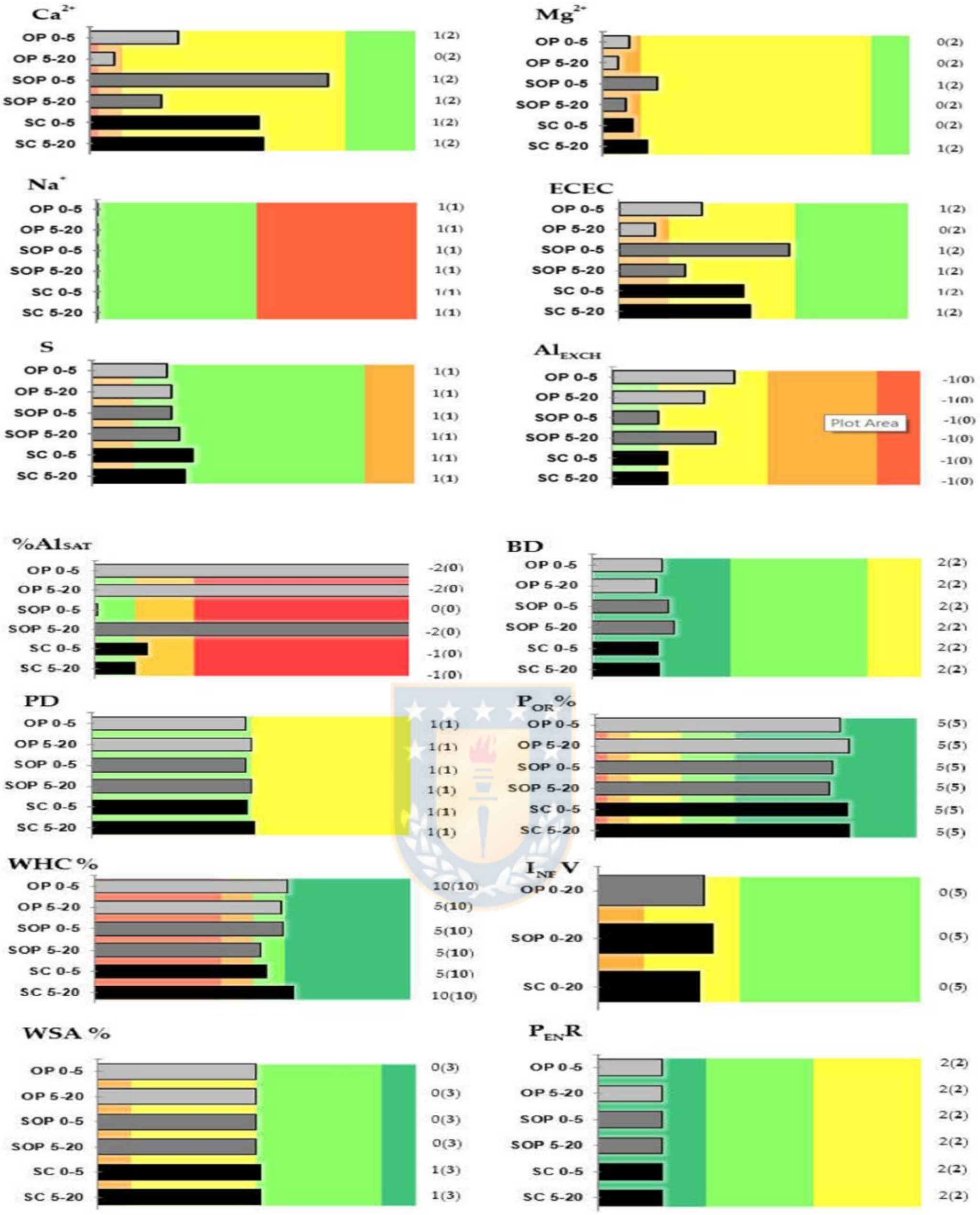

Figure 2.2. Integration of the different sub-indexes for all soil indicators (S_{IND}) considered. Each color corresponds to a different quality level, according to the ranges defined by Amacher et al. (2007). Greenish hues represent indexes from acceptable to optimal (differentiated from lower to greater color intensity respectively), reddish color symbolizes undesirable to critical levels; yellowish color indicates medium values of quality. Values in the columns on the right [x(**x**)], express x as the quality sub-index score, and (**x**) as the maximum possible sub-index value.

The Physical SQI showed less variation among the site conditions, with the highest scores in O$_P$ at the 0–5 cm depths and SC at the 5–20 cm depths. The Global (physical plus chemical) SQI revealed less variation with scores of 26.5–40.1 from SO$_P$ at the 5–20 cm depths and O$_P$ at the 5–20 cm depths with the lowest scores in SC at the 5–20 cm depths and O$_P$ at the 5–20 cm depths. The % "critical" SQI showed that the O$_P$ at the 5–20 cm depths was the condition with the most S$_{IND}$ that were at critical levels, likely as a result of the adverse impacts of logging, over grazing, over browsing among trees, cropping, and burning practices. In addition, historic logging and fire events, erosion, and percolation losses of nutrients (e.g., P, Ca^{2+}, and ECEC) via leaching have likely been the causes of the low fertility levels in O$_P$ at the 5–20 cm depths (Gerding, 2009; Úbeda, X.; Outeiro, 2009).

Table 2.6 Partial, global, and % soil quality index (SQI) scoring.

Condition/Depths	* $_{CHEMICAL}$SQI	** $_{PHYSICAL}$SQI (B)	*** $_{GLOBAL}$ SQI	**** SQI $_{\%}$
O$_p$ 0–5	13	64.2	38.6	22.7
O$_p$ 5–20	7.2	46.4	26.8	40.9
SO$_p$ 0–5	24.6	46.4	35.5	22.7
SO$_p$ 5–20	10.1	42.9	26.5	27.2
SC 0–5	10.1	50.0	30.1	22.7
SC 5–20	15.9	64.3	40.1	22.7

From the Equations * (2), ** (3), *** (4), and **** (5).

An overall correlation analysis among the S$_{IND}$ (Table 2.7) revealed some possible associations as follows: the %WSA was correlated with P$_{OR}$ and I$_{NF}$V ($r \geq 0.8$) indicating the importance of soil aggregation on hydraulic conductivity; Al$_{SAT}$ % and Al$_{EXCH}$ were correlated with pH, ECEC, Ca^{2+}, and Mg^{2+} ($r = -0.9$) showing the inverse relationship between soil nutrients and Al forms; and SOC was correlated with N ($r = 0.9$), P ($r = 0.7$), K($r = 0.8$), BD ($r = 0.8$), and P$_{OR}$ ($r = 0.7$) which underlined the key role of SOM in soil quality.

Table 2.7 Pearson's correlation coefficients for the distinct S_{IND} evaluated.

	pH	SOC	N	C:N	P	K	Ca^{2+}	Mg^{2+}	Na	Al_{EXCH}	ECEC	Al_{SAT}	S	NO_3^-	NH_4^+	BD	PD	P_{OR}	WHC	$I_{NF}V$	WSA
pH	1	NS	NS	0.91	NS	NS	NS	NS	0.8	NS	NS	NS	NS	0.7	NS	0.8	0.7	NS	0.7	0.8	NS
SOC	NS	1	0	0.91	0.7	0.9	NS	0.6	0.8	NS	NS	NS	NS	NS	NS	0.8	NS	0.7	NS	NS	NS
N	NS	0.9	1	N	NS	0.8	NS	NS	N	NS	NS	NS	NS	0.8	NS	NS	NS	NS	NS	0.6	0.7
C:N	NS	NS	NS	1	NS	NS	NS	NS	N	0.9	NS	NS	NS	NS	NS	NS	NS	NS	0.6	NS	NS
P	NS	NS	NS	N	1	NS	NS	NS	N	NS	NS	NS	0.7	NS	NS	NS	NS	0.6	0.9	NS	0.7
K	NS	NS	NS	N	0.8	1	NS	0.9	0.6	NS	NS	NS	0.8	0.9	NS	NS	NS	0.6	0.9	NS	NS
Ca^{2+}	0.9	NS	NS	N	0.7	NS	1	NS	N	NS	NS	NS	NS	NS	NS	0.8	0.8	0.6	0.7	0.8	0.6
Mg^{2+}	0.8	NS	NS	N	NS	NS	0.9	1	N	NS	NS	NS	0.6	NS	NS	NS	0.8	NS	NS	0.8	0.9
Na	NS	NS	NS	−0.8	NS	NS	NS	NS	1	0.8	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.6
Al_{EXCH}	−1	NS	NS	N	NS	NS	−0.9	−0.8	N	1	NS	NS	NS	0.7	NS	0.8	0.7	NS	0.7	0.8	NS
ECEC	0.9	NS	NS	N	0.7	NS	1	0.9	N	−0.9	1	NS	NS	NS	NS	0.8	0.9	0.6	0.6	0.8	0.7
Al_{SAT}	−0.9	NS	NS	N	−0.6	NS	−0.9	−0.9	N	0.9	−0.9	1	NS	NS	NS	0.9	0.7	0.8	0.8	0.7	NS
S	0.6	−0.6	NS	N	NS	NS	NS	NS	N	−0.6	NS	NS	1	NS	NS	0.6	NS	NS	NS	NS	NS
NO_3^-	NS	NS	NS	0.7	NS	NS	NS	0.6	N	NS	NS	NS	NS	1	NS	NS	0.7	NS	0.7	NS	NS
NH_4^+	0.8	NS	NS	N	NS	NS	0.9	0.9	N	−0.8	0.9	−0.8	NS	0.7	1	NS	0.7	NS	0.8	0.9	0.9
BD	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	NS	1	0.6	0	NS	NS	0.7
PD	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	NS	NS	1	NS	0.6	0.6	NS
P_{OR}	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	−0.6	NS	−0.7	NS	1	NS	0.7	0.9
WHC	NS	0.6	0.6	N	NS	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	1	NS	0.9
$I_{NF}V$	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	1	NS
WSA	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	N	NS	NS	NS	NS	NS	NS	1

Among remarkable correlations are the following: pH-ECEC (r = 0.9), pH and the cations Ca^{2+} and Mg^{2+} (r = 0.9, 0.8), pH-Al_{EXCH} (r = −1), pH-Al_{SAT}% (r = −0.9), these last inverse correlations demonstrating the importance of Al in nutrient availability. Complementary correlations such as Al_{EXCH}, Ca^{2+} (r = −0.9), Mg^{2+} (r = −0.8), S (r = 0.7), as with Al_{SAT}% and ECEC, Ca^{2+}, and Mg^{2+} (r = −0.9) showed the dominance of this element in the interchange sites as long as pH values decrease, thus substituting these cations. SOC correlated with different nutrients, i.e., N (r = 0.9), P (r = 0.7), K (r = 0.8) as well as the physical S_{IND} BD (r = 0.8) and P_{OR} (r = 0.7), which highlighted its crucial role on nutrient supply and particle arrangement.

Thus, this study demonstrated the importance of soil quality assessment in AFS, particularly SPS, and that the calculation of simple additive linear SQI is one of the most effective methods for detecting the impacts of management practices in soils (Askari and Holden, 2015). In the future, it is expected that there will be an improvement in some of the S_{IND}, thereby increasing SQI in the SPS-RA in the medium to long term (10–20 y), probably by the continuous thickening of the organic duff on the soil surface (O_f horizon), and the widespread depositions of animal excrements, in addition to the positive effects of root and hyphae that promote the formation of stable aggregates >2.00 mm through root biomass and colonization mechanisms, which in turn creates greater SOC stabilization (e.g., $C \rightarrow SOC$) (Tisdall and Oades, 1982; Wu et al., 2015) .

2.4 CONCLUSIONS

An overall chemical SQI was calculated that showed a large variability over all site conditions, with NH^{4+}, NO^{3-}, and P, being the most limiting chemical indicators (S_{IND}). Regarding the overall physical SQI, there were no significant differences between individual physical S_{IND} (except for P_{OR} in SO_p), presumably due to the timescale by which those properties underwent changes. The combined (chemical + physical) Global SQI (0–20 cm), showed the SC condition had the highest SQI (37.6), followed by O_p (29.8) and SO_P (28.8), demonstrating the importance of trees in preserving soil quality. However, the highest SQI was in SC at the 5–20 cm depths, reflecting its history of less disturbed management. There was an estimated increase of SOC stock of about 7.5, 4.8, and 1.6 Mg $ha^{-1}yr^{-1}$, in addition to the total N increase of 0.5, 2.0, and 1.2 kg ha^{-1} for SO_p, O_p, and SC, respectively. Nonetheless, NO_3^- and NH_4^+ availability is limited, which is strongly linked to the progressive increase of C/N ratios that was observed.

These preliminary results confirm the importance of the SPS-RA in the C→SOC sequestration process, with results that were generally within the typically reported values in the literature (only occasionally exceeding them, e.g., SO_P) and showing that these systems promote nutrient cycling and soil restoration. Future seasonal and long-term research is now required in order to understand the role of biological activity in SOM transformations and determine the soil C balances in order to elucidate the possible C stabilization processes involved.

2.5 APPENDIXES (ANEXOS)

2.6 REFERENCES

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CAPÍTULO III

Comparative study between silvopastoral and forest farming systems and their effects on soil quality: the case of a dirtubrd native *Nothofagus* forest in South Central Chile

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Artículo en preparación para ser enviado a *Agroforestry Systems*

Abstract

Agroforestry Systems (AFS) are a widely recognized collective of multi-purpose land uses which are used to address food security and climate change challenges, mainly at the smallholder farming scale. AFS are present in about 5% of the global forest area as a sustainable approach promoting productive soil conservation (e.g., soil organic carbon (C) sequestration (C_{SEQ})), as it occurs in some Regions of Chile to preserve the ecological value of native forests. Accordingly, we evaluated the soil quality as expressed as soil quality indexes (SQI), through 30 soil quality indicators (SI_{ND}), corresponding to different physical (7), chemical (15) and microbiological (8) properties, at two depths (0-5 and 5-20 cm) in conterminous agro forest ($A_{GRO}F_{RST}$) DONDE? and Silvopastoral (SPS) systems under *Nothofagus obliqua* (deciduous) and *N. dombeyi* – *N. obliqua* (evergreen-deciduous) forests, respectively, both located at the Ranchillo Alto state-owned property in the Ñuble Region (37°03’30’’S, 71°39’15’’W and 37°14’41’’S, 72°23’30’’W respectively). The results indicate an average C_{SEQ} of 6.88 and 4.83 Mg C yr^{-1} for $A_{GRO}F_{RST}$ and SPS, meanwhile the global SQI reached 37.8 and 31.0%, respectively (0-20 cm). Despite these significant differences ($p<0.05$) were observed in 13 S_{IND}, only 3 differed within all conditions (e.g., combinations of systems and depths) (SOC, K^{+} and Mg^{2+}), being mostly accentuated between depths (P^+, Ca^{2+}, S, ECEC and $Al_{SAT/}$) than encompassed by the systems themselves (BD, NH_4^+, NO_3^-) or in a single condition ($\beta\text{-}_{GLU}$ and N_{MIN}). However, out of the 30 S_{IND} that were analyzed, practically all of them presented better conditions at the 0-5 cm depth, which shows the generalized positive effects of soil organic matter (SOM) additions. Finally, among the identified interactions (Pearson's correlation) (R= $\geq$ 0.7), SOC correlated with most S_{IND} (e.g., N, NH_4^+, P^+, K^+, Ca^{2+}, Mg^{2+}, S, CEC, N_{MIN}). These results support the fundamental concepts and attributes of AFS related to the enhancement of SOC stocks, C_{SEQ} and SQ and their capability in soil remediation and as a sustainable forest management for food production.

Keywords: C sequestration, adaptive agriculture, agroforestry, soil reclamation, volcanic soils.

3.1 Introduction

Nowadays, about 51.42 to 52.7 Pg CO_{2eq} y^{-1} are globally emitted by anthropogenic activities (Poore and Nemecek, 2018; Mbow et al., 2019; Rosenzweig et al., 2020), from which 11.2 - 12.8 Pg, are generated via food supply systems (7.1-8 Pg from agricultural production itself and 3.2 – 5.7 Pg directly related to land use) (Poore and Nemecek, 2018; Crippa et al., 2021). Agroforestry Systems (AFS) are able to offset up to 2% of those aforementioned global emissions (Lorenz and Lal, 2014), since they can store nearly 300 Mg SOC ha^{-1} (0-1m depth) (Nair, 2012). AFS cover worldwide 1,023-1,600 Mha, including: 700, 450, 300, 100 and 50 Mha for alley cropping (including $A_{GRO}F_{RST}$), SPS, protective AFS (e.g., windbreaks, riparian buffers), multi-strata and disperse trees in agro-systems, respectively (Somarriba et al., 2012). Particularly, SPS have a remarkable C_{SEQ} capacity reaching 1.8-6.1 Mg ha^{-1} y^{-1} (Alonso, 2011; Udawatta and Jose, 2011; Feliciano et al., 2018), which is about 25% more than $A_{GRO}F_{RST}$ (Nair, 2012). Such increase in soil organic matter reservoirs

(SOC) or “SOC fertilization”, is of ecological relevance since it modifies different soil properties, ultimately controlling major edaphic processes (e.g., water and nutrient availability) (Sollins, 1996; Blanco-Canqui and Lal, 2008; Juhos et al., 2021).

Multiple benefits of SOC pool improvement allow sustainability in the long-term animal and plant productivity, water and air quality, supporting human health improvement, which is collectively known as *Soil Quality* (SQ) (Karlen et al., 1997; Arshad and Martin, 2002). Soil properties sensitive to spatio-temporal variations due to land use changes or management are potentially useful tools to estimate SQ indexes (SQI) and designed as SQ indicators (SI_{ND}) (Doran and Jones, 1997). However, it is desirable that SQI determination include physical, chemical and biological SI_{ND}, since each express different aspects of soil productivity (e.g., fertility status) and time-lapses in which soil has undergone changes (Doran and Jones, 1997; Tale and Ingole, 2015; Li et al., 2020). In addition, a SI_{ND} should be easily measured and replicated to be eventually integrated into databases in order to: i) define, implement and monitor local strategies of conservation and ii) identify regional ecosystem patterns (e.g., acidification, flooding) (Karlen et al., 2001, Drobnik et al., 2018). In Chile, mainly because of anthropogenic activities, 37.8 % of the national territory is under moderate to severe land degradation (Flores et al., 2010; Casanova et al., 2013a), where the Andean foothills are the most susceptible areas due high erosive potential of the soils, which endanger their key role as genetic reservoirs and the regulation of the water cycle.

In this respect, at least 44% (8.1 Mha) of the native forest in southern Chile has been partially replaced due to the implementation of different land uses, including: i) 0.5 Mha of urban areas, ii) 2.8 Mha of croplands, iii) the expansion of about 3 Mha of grasslands and, iv) 2.1 Mha to forest plantations, being the *Nothofagus* genus the most strongly affected (70% of its original area) (Lara et al., 2012). However, considering the extensively reported benefits of AFS, very few but relevant experiences by using AFS in temperate native forests have been reported in Chile. For instance, it has been observed that these systems promote a range of 30-50% of solar radiation, which enhances the plant diversity of the understory, increase prairie productivity and reduce wind speed by up to 200% in Ñirre forests (*Nothofagus antartica*) (Schmidt et al., 2013; Sotomayor et al., 2016), promote greater SOC Q_{SEQ} accumulation rates than observed in *Nothofagus obliqua* forests (Ortiz et al., 2020) and doubling the SOC Q_{SEQ} capacity compared to commercial forestry plantations (Dube et al, 2011).

Therefore, the aim of this study was to evaluate the comparative effect of two principal AFS (SPS and $A_{GRO}F_{RST}$) on C_{SEQ} and SQ by different physical, chemical and microbiological or early response SQ_{IND} after 5 years of agroforestry in a degraded *Nothofagus* native forest.

3.2 Materials & Methods

In this section, a description of the study systems, sampling procedures and analysis techniques employed in the determination of SQ are described.

3.2.1 *Site description and experimental design*

Historically, Ranchillo Alto, a 635-ha property consigned to the Universidad de Concepción in the Ñuble Region (120 Km east of Concepcion City, 1200–2000 m.a.s.l) and in general the native forest to which it belongs, has been under severe degradation processes, resulting from: i) over logging (e.g., uncontrolled woodlots), ii) overgrazing, iii) cattle browsing of arboreal vegetation, and iii) allotment and over-utilization of areas destined to agriculture. To address this situation, two different AFS were established in 2016, a SPS and a $A_{GRO}F_{RST}$ (Dube et al., 2016; Dube et al., 2018) (Table 3.1). At present, the AGROFRST is used exclusively as a protein bank for the cattle (Red Angus) of the SPS, and the biomass yields reach up to 24 t ha^{-1} yr^{-1} (dry basis) (2017-2018), which are stored in bundles to be used mostly during winter as a staple food. Regarding the grazing season, up to 12 cows remain foraging for a 11-15 day-periods within each plot of the SPS.

Table 3.1 General information for each tree cover condition in SPS-RA

System	**Location**	**Area (ha)**	**Woody species**	**Tree density (stems ha^{-1})**	**Tree cover description**	**Ground cover species**
SPS$_p$	37° 14' 51'' S, 72° 26' 30'' O 1290 msnm	6	a) Oak (*Nothofagus obliqua*) and b) Coihue *Nothofagus dombeyi*	173.3 (a: 133.3; b:40)	Soil with 65-75% of external light (average area)	Vicia (*Fabaceae purpurea*), clover (*Trifolium incarnatum*, *T. subterraneum* y *T. vesiculosum*), *Lolium multiflorum westerwoldicum*, *Phalaris acuatica*, *Lolium perenne*, *Festuca arundinacea*, *Dactylis glomerata*, Quila *(Chusquea quila)* and the re-sprouting of Radal *(Lomatia hirsuta)*
AGROFRST	37° 14' 49'' S, 72° 26' 30'' O 1260 msnm	6	Oak (*Nothofagus obliqua*)	446.6	Soil with 35-45% of external light (average area)	Oats (*Avena sativa*) and vetch (*Vicia atropurpurea*)

*Each system was divided into three plots of equal area (2 ha)

The soils were classified as medial, amorphic, mesic Typic Haploxerands corresponding to "Santa Barbara" Series according to USDA (2014) and Stolpe (2006). Andisols are of key ecological and economic importance in Chile (particularly at 35°-49°S), not only supporting about 60% of national cropland area (Besoain and Sepulveda, 1985), but also covering 60-70% of Andean foothills (CIREN, 1999; Stolpe, 2006).

3.2.2 Soil sampling and characterization

In January 2019, both SPS and $A_{GRO}F_{RST}$ were divided into three plots of 2 ha each. Within each plot, six composite samples were taken, in triplicate at 0-5 and 5-20 cm. Thereafter the samples were air-dried and mixed then ground and passed the 2 mm sieve for later analysis, except for biological trials, where in such case the samples were stored unaltered under cold conditions. Soil physical determinations were performed as follows: **a**) Bulk density was determined according to Stone (1991), and samples were taken with a cylindrical soil core (211 cm^3), and were dried at 105 °C until reaching a constant weight, **b**) Soil particle density (PD) was estimated using the pycnometer method (Blake and Hartge, 1986), **c**) net pore space (P_{OR}) was calculated from BD and PD values as follow:

$$P_{OR} = [PD - BD/PD] \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

d) penetration resistance ($P_{EN}R$) was evaluated using a penetrometer model Soil Compaction Tester Dickey-John (Auburn, IL, USA). A total of 60 measurements in each plot were taken across longitudinal transects with the aim to achieve acceptable representativeness, **e**) water-stable aggregates (WSA) (%) was determined according to the method proposed by Kemper and Rosenau (1986). Every sample was placed in a 0.250 mm sieve, then immersed for 3 min (35 rep min^{-1}) into an aluminum chamber containing distilled water. Dispersed soil was dried at 105°C, while remaining soil was placed into another aluminum chamber containing sodium hexametaphosphate (2 g L^{-1}) for 15 min (35 rep min^{-1}) and the dispersed soil was dried at 105°C. After both procedures, samples were weighed in order to determine each proportion compared to the original sample, **f**) hydraulic conductivity (unsaturated) (K) trial was conducted using an infiltrometer model Mini Disk Infiltrometer S (Pullman, WA, USA). The determination of K (cm day^{-1}) was estimated according to Zhang (1997), by a sequence of cumulative infiltration measurements, **g**) water holding capacity (WHC) was tested based on the method proposed by Zagal et al. (2003). Each sample was placed into a plastic cone (1:2 soil water ratio), which was previously sealed at the bottom with adhesive tape for 12 hr. After that, the tape was carefully perforated allowing the soil solution to drain, which was collected in a plastic bottle and eventually measured.

Regarding chemical characterization (pH $_{[water]}$, NH_4^+, NO_3^-, P, K^+, Ca^{2+}, Mg^{2+}, effective cation-exchange capacity [ECEC], Na^+, S, Al_{EXCH} and % Al_{SAT}), this was conducted at the Agricultural Research Institute of Chile (INIA-Quilamapu) according to the methods proposed by Sadzawka et al. (2006). Total N and SOC content determinations were performed at the Soil and Natural Resources Laboratory (Faculty of Agronomy, University of Concepcion) according to Wright and Bailey (2001).

Microbiological parameters were conducted as follows: **a**) soil microbial respiration (S_{RESP}) and microbial biomass C (C_{MICR}) were determined by using the substrate induced method according to Anderson and Domsch (1978), where 10 g of dry soil were incubated for 24 hrs, then placed into gas tight container where liquid glucose amendments were added (Horwath and Paul, 1994) to bring slightly dried soil to 60% of water filled pore space) (Linn and Doran, 1984), and subsequent CO_2 measurement using a CO_2 analyzer (LI-COR LI-820, Lincoln, USA). The minimal concentration of glucose (able to produce the maximal respiratory rates) was added to each sample (5 and 10 µMole g^{-1} at 0-5 and 5-

20 cm depths, respectively). The C_{MICR} was determined according to the equation proposed by Anderson and Domsch (1978):

$$x = 40.4y + 0.37 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where: x means the total microbial biomass C ($\mu C\ g^{-1}$ dry soil) and y is the maximum initial rate of CO_2 respiration.

b) potential N-mineralization (N_{MIN}) trial and nitrification (N_{NIT}) estimation were conducted according to Linn and Doran (1984), where three subsamples were incubated at 22°C for 10 days at 60% moisture, including another three subsamples consisting of 5 g dry soil used as controls. After that, each sample was put into 150 mL plastic flasks with 25 mL of K_2SO_4 (0.5M) solution, subsequently shaken for 1 h at 180 rpm. The resulting extract was decanted and filtered, thereafter analyzed by colorimetry using a UV-visible spectrophotometer (AA3, BRAN+LUEBBE, Norderstedt, Germany). The nessler and sulfosalicylic reagents were utilized in order to determine the N mineralization as $NH_4^+$and NO_3^- according to Alef (1995). Finally, N_{MIN} and N_{NIT} were calculated using the following equations:

$$N_{MIN} = [N\text{-}NH_4^+ + N\text{-}NO_3^-]_f - (N\text{-}\ NH_4^+ + N\ \text{-}\ NO_3^-)_i]/Td \ \ldots(3)$$

$$N_{NIT} = [(N\text{-}NO_3^-]_f - (N\text{-}\ NO_3^-)_i]/Td \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where: f and i subscripts refer to concentrations measured before and after incubation, respectively; Td indicates the incubation time in days. Both parameters are expressed as $\mu gN \cdot g^{-1}$dry soil$\cdot$ d^{-1}.

Three enzymatic activities were determined as follows: **c)** the β-glucosidase activity was conducted by the method proposed by Tabatabai (1994), where after an incubation period of soil samples in a buffer solution (pH 6), there was a subsequent determination of p-nitrophenol released using the colorimetric at 400 nm; **d)** urease activity was determined by the incubation of soil samples into urea solution (0.72M) for 2 h at 37°C, according to the method proposed by Kandeler et al. (2011), **e)** phosphatase trial conducted according to Tabatabai (1994) and Bremner (1969) and Trasar-Cepeda et al. (2003), where to a 1 g of soil, 4 mL of buffer solution (pH4) were added to adjust the pH to 6.5, then 0.25 mL of toluene and 1 mL of 0.115M disodium *p*-nitrophenylphosphate tetrahydrate were incorporated and mixed and eventually incubated at 37°C for 1 h. Then 1 mL of 0.5M calcium chloride and 4 mL of 0,5M sodium hydroxide were added to each sample. The resulted mixed suspension was filtered for further colorimetric at 420 nm; **g)** the fluorescein diacetate hydrolysis (FDA) was assayed by the method of Alef, (1995) and Green et al. (2006), where 50 mL of 60mM Na-phosphate solution (buffered at pH 7.5) was added to 1.0 g of soil and then incubated at 37°C for 3 h. Then, 20 mL of acetone was added in order to stop the reaction until a 50% v/v ratio was reached. Shortly thereafter, the suspension of each sample was centrifuged at 4000 rpm for 10-15 min and in the clear supernatant, the FDA hydrolysis was determined by spectrophotometry (at 490 nm). Both enzyme activities and FDA absorbance were measured using a UV-visible spectrophotometer (AA3, BRAN+LUEBBE, Norderstedt, Germany).

3.2.3 *SQI estimation*

Each S_{IND} was selected on the basis of projected goals in both SPS and $A_{GRO}F_{RST}$ (soil reclamation, gradual improvement of soil fertility, C_{SEQ}). After the analytical characterization of any single S_{IND}, a numerical value (normalized in a scale 0-100) or sub-index was assigned depending on its relevance to the overall SQ, from optimal to critical ranges (Appendixes A, B and C). Prior to SQ estimation, this was divided into chemical (SQ_{CHE}), physical (SQ_{PHY}) and biological (SQ_{BIOL}) in order to elucidate the contribution of a particular group of pedogenetic processes. Therefore, the SQI_{PHY} was estimated as follows:

$$SQI_{PHY} = \Sigma\ [I_{NF}V + \%WSA + WHC + P_{EN}R + BD + PD + P_{OR}] \qquad (5)$$

where $SQI_{PHYSICAL}$ is the physical soil quality index, $I_{NF}V$, is infiltration, %WSA is the water stable aggregates %, WHC is the water holding capacity, $P_{EN}R$ is the penetration resistance, BD is the bulk density, PD is the particle density, and P_{OR} is the total porosity.

SQ_{CHE} was calculated as follows:

$$SQI_{CHE} = \Sigma\ [pH + \%SOC + C{:}N + N + NH_4^+ + NO_3^- + CEC + P + K + Ca^{2+} + Mg^{2+} + Na + S + Al_{EXCH} + Al_{SAT}] \qquad (6)$$

where [SQI_{CHEM} : chemical soil quality index; pH : soil reaction; %SOC: percentage of SOC; C/N : C:N ratio; N : total N (%); NH_4^+: available ammonium; NO_3 : available nitrate; ECEC : effective cation-exchange capacity, P : available phosphorus; K^+ : potassium content; Ca^{2+} : calcium content; Mg^{2+} : magnesium content; Na : sodium content; Al_{EXCH} : exchangeable aluminum, and Al_{SAT} : aluminum saturation (%)].

The SQ_{BIOL} was calculated as follows:

$$SQI_{MBIOL} = \Sigma\ [M_{BIOMSS} + M_{SOC} + M_N + MR_{ESP} + N_{MIN} + \beta\text{-}_{GLU} + U_{RS} + P_{HOSP} + FDA] \qquad (7)$$

where SQI_{MBIOL} is the microbiological soil quality index; M_{BIOMSS} : microbial biomass; M_C : microbial C; M_N : microbial N; MR_{ESP} : microbial respiration; N_{MIN} : N mineralization; $\beta\text{-}_{GLU}$: β-Glucosidase; Urease : U_{RSE}; P_{HOSP} : Phosphatase, FDA: fluorescein diacetate hydrolysis

The overall SQI for each system (SPS and $A_{GRO}F_{RST}$) was calculated as follows:

$$SQI_{\ TOTAL} = \Sigma\ [SQI_{CHEM} + SQI_{PHYSICAL} + SQ_{MBIOL}]/3 \qquad (8)$$

Finally, the percentage of % S_{IND} at critical levels (%SQ) was determined as:

$$\%\ SQ = [\text{number of } S_{IND} \text{ at critical level/number of } S_{IND} \text{ estimated}] \times 100 \qquad (9)$$

3.2.4 Statistical Analysis

The dataset resulting from the transformation of analytical results of every S_{IND} into sub-indexes (Appendixes A, B and C) and the estimation of the partial SQ indexes (SQI_{CHEM} + $SQI_{PHYSICAL}$ + SQ_{BIOL}) and SQI $_{TOTAL}$ were performed using Microsoft Excel. In addition, a completely randomized design in both systems and depths were considered. A one-way ANOVA's analysis was performed, if a source variation presented significant effect ($p \leq 0.05$), a means separation by Tukey's test was used to elucidate differences among the means of every S_{IND}. Thereafter, a Pearson's correlation was conducted with the aim to find potential interactions between the different S_{IND} ($r \geq \pm 0.7$). The data and their graphical representation were conducted using R (statistical software V4.1.0, the R Core Team 2021).

3.3 Results and discussion

3.3.1 Soil characterization

The results after the analytical procedures are shown below. The different S_{IND} were grouped according to the type of functions they perform, as well as their effect and interpretation respecting C_{SEQ} and SQ.

3.3.1.1 Physical properties as SI_{ND}

There were no significant differences found in any of physical SI_{ND} that were performed ($p \leq 0.05$) except for the $A_{GRO}F_{RST}$ > SPS (0.60,0.71), and the estimated differences were probably due to the greater previous intensive-mechanized management leading to lower tree ha^{-1} stocking, which is also still mirrored in the low WSA means <50% in all cases (48.78 and 49.05 for $A_{GRO}F_{RST}$ and SPS 0-20 cm). The SI_{ND} [BD, PD and P_{OR}] resulted in optimal values within both, systems and depths (Table 3.2, Appendix A –Table 3.7-), ranging [(0.60, 0.71 g cm^{-3}); (2.05, 2.12 g cm^{-3}); (70.69, 66.60%)] for SPS and $A_{GRO}F_{RST}$ (0-20 cm), respectively. Particularly, BD was in the typical range for [low-nonallophanic /C rich (SOC ≥ 6%)] volcanic soils (≤0.9 g cm^{-3}), which is consistent with the PD estimations, where all the values that were observed were similar to the reported mean for PD of condensed SOC (1.5 g cm^{-3}), and consequently with a wide range of P_{OR} (Nanzyo, 2002).

Table 3.2. Characterization results of physical SI_{ND}

S_{IND}	System			
	SPS 0–5	SPS 5–20	$A_{GRO}F_{RST}$ 0–5	$A_{GRO}F_{RST}$ 5–20
$I_{NF}Vk$ (cm d^{-1})	19.41	19.41	13.08	13.08
WHC (%)	70.83 a	65.97 a	74.44 a	65.97 a
BD (g cm^{-3})	0.57 a	0.61 a	0.65 b	0.73 b
PD (g cm^{-3})	1.91 a	2.09 a	2.0 a	2.16 a
*P_{OR} (%)	70.21 a	70.83 a	67.09 a	66.21 a
WSA (%)	49.20 a	48.65 a	49.74 a	48.82 a
PEN_{RES} (PSI)	100-200 a	100-200 a	100-200 a	100-200 a

*Estimated through the formula (1)

Similar findings were reported in Nissen et al. (2005) and Ortiz et al. (2020), who estimated ranges from 1.95-2.1 (0-15 cm) and 1.9-2.0 (0-20 cm) for PD and 73.9; 68.3-74.2 for P_{OR} (%), respectively, in volcanic soil from a native forest and under SPS management, both in South Central Chile. The SI_{ND} related to soil hydraulic capacities showed similar WHC values (0-20 cm) of 67.19 and 68.09 $A_{GRO}F_{RST}$>SPS, whilst there was a remarkable difference for $I_{NF}Vk$ 19.41 and 13.8, (SPS >$A_{GRO}F_{RST}$), and PEN_{RES} 100-200 psi (except for $A_{GRO}F_{RST}$ 0-5), which means a probable structural degradation / net disaggregation due to past anthropogenic disturbances, which however did not affect water entrance to soil, and storage and movement within the soil matrix because of the distinctive properties of Andisols, in addition to the successive re-aggregation processes expected to occur due to the constant C inputs in both systems.

For instance, Panichini (personal communication, May 2020), determined similar means for WHC (70.69%) in conterminous Andisols to our study site (same series) for wheat production that was managed during 4 years under stubble incorporation (10 t $ha^{-1}yr^{-1}$).

3.3.1.2 Chemical properties as S_{IND}

From the 15 chemical S_{IND} analyzed, pH, C:N, N, Na, and Al_{EXCH} showed no statistical differences ($p \leq 0.05$) at any condition (Table 3.3). In the case of pH, the low differences that were observed (5.54, 6.06) for $A_{GRO}F_{RST}$ and SPS respectively (0-20 cm) (weighted), could be explained by the narrow divergence in precipitation regimes (North>South), and basic cations scavenging by plants (Sadzawka and Carrasco, 1985).

Table 3.3. Characterization results of chemical SI_{ND}

S_{IND}	System			
	SPS 0–5	SPS 5–20	$A_{GRO}F_{RST}$ 0–5	$A_{GRO}F_{RST}$ 5–20
pH	6.04 a	6.07 a	5.62 a	5.51 a
SOC (%)*	13.94 a	10.65 b	14.63 c	11.95 d
C:N	12.73 a	13.48 a	10.47 a	10.90 a
N (%)*	1.10 a	0.80 a	1.40 a	1.10 a
P^{+} (ppm) **	3.02 ab	1.92 a	5.19 b	2.05 a
NH_4^{+} (ppm) **	12.13 a	9.30 b	11.62 ab	9.59 ab
NO_3^{-} (ppm) **	3.33 a	2.46 a	28.70 b	22.70 b
K_{TOT} (mg kg^{-1}) **	47.37 ab	30.72 c	51.33 a	37.58 bc
Ca^{2++}(mg kg^{-1}) **	2.19 a	0.39 b	2.67 a	0.63 b
Mg^{2+} (mg kg^{-1}) **	0.20 a	0.08 b	0.36 c	0.15 ab
S (ppm) **	7.71 ab	2.10 c	7.80 a	2.87 c
ECEC (cmol(+) kg^{-1}) ***	9.22 a	1.77 c	7.69 a	3.19 bc
Na (%)*	1.61E-6 a	1.61E-6 a	1.38E-6 a	1.38E-6 a
Al_{EXCH} ($cmol^{(+)}$ kg^{-1}) ***	0.09 a	0.18 a	0.15 a	0.30 a
Al_{SAT} (%)*	1.01 a	10.34 b	1.91 a	9.31 c

n:18; *p* < 0.05; *: %; ** : mg $kg^{-1:}$; *** : cmol (+) kg^{-1}), S_{IND} : Soil indicator

Respecting total N (0.88, 1.18%) and C:N ratios (13.30, 10.80) (0-20 cm) for SPS and $A_{GRO}F_{RST}$ respectively, the comparative greater values that were observed in $A_{GRO}F_{RST}$ (also by depth) expressed a potentially faster SOM cycling than SPS, which probably reflects both the differences in N fertilization practices and labile C inputs, as it occurs with P (2.20 / 2.84 ppm 0-20 cm for SPS and $A_{GRO}F_{RST}$), which varied both in depth and system, and was accentuated within $A_{GRO}F_{RST}$. Regarding available N forms, the SI_{ND} NH_4^+ had average weighted values (0-20 cm) of 10.01 and 10.10 ppm for SPS and $A_{GRO}F_{RST}$, respectively, and showed significant differences ($p \leq 0.05$) only in the SPS (by depth). Such differences were probably associated to urine inputs from the animal component and a lower intake by the herbaceous plant mosaic, which was composed of both annual and perennial species, contrary to $A_{GRO}F_{RST}$, although the $A_{GRO}F_{RST}$ means were intermediate between those of the SPS. In the case of NO_3^-, significant differences ($p \leq 0.05$) were estimated between systems having SPS:$A_{GRO}F_{RST}$ ratios of 1:8.6 and 1:9.2 for 0-5 cm and 5-20 cm depths respectively, since NO_3^- is highly mobile; those remarkable differences could be attributed to both, the high fertilization practices and a net NH_4^+ consumption by herbaceous component (intensive oats and vetch production) due to its preference intake within the $A_{GRO}F_{RST}$. Contrary to our results, Ortiz et al. (2020) found C:R ratios of 26.3/25.37 (0-5/5-20 cm) in a 5 year-old SPS established over a degraded forest with *Nothofagus obliqua* (134 stems ha^{-1}), and those differences with respect to these results could be explained by variations of litter quantity-quality and root exudates that are related tree-specific and vegetation/ understorey types, environmental factors such as temperature and precipitation, topography (e.g., latitude, elevation), and soil texture as stated in Qi et al. (2020). The uniformly low and Na^+ values (0.07, 0.06 cmol (+) kg^{-1}) are related to the relatively high precipitation level, which is able to leach out basic cations, as previously stated (Sadzawka and Carrasco, 1985). A similar condition may explain the moderate $\mathrm{Al_{EXCH}}$ concentrations (0-20 cm) of 0.26 and 0.16 $\mathrm{cmol^{(+)}\ kg^{-1}}$ for $\mathrm{A_{GRO}F_{RST}}$ and SPS respectively, despite doubling the concentration at 5-20 cm depth (regardless of the similar pH values), as it also occurs to the basic cations $\mathrm{Ca^{+2}}$, $\mathrm{Mg^{+2}}$, $\mathrm{K^{+}}$ and CEC, all of which varied significantly ($p \leq 0.05$); this is probably due to remarkable higher SOC content at 0-5 cm in both systems. The last value was confirmed by the 3.7:1, 2.7:1 S (ppm) (0-5:5-20 cm) ratios because of the very leachable condition of this anion, which was also highly correlated to the presence of SOM, which regulates the retention of S ($\mathrm{SO_4^{2-}}$) via organic mineralization and immobilization, apart from inorganic adsorption-desorption mechanisms (Fasth et al., 1990). With respect to $\mathrm{Al_{SAT}}$, the means of 4.42 and 6.01 (%) at 0-20 cm depth were observed for SPS and $\mathrm{A_{GRO}F_{RST}}$, respectively, and significant differences were observed only between depths of both systems. Since this $\mathrm{SI_{ND}}$ express the percentual $\mathrm{Al_{EXCH}}$: CEC ratio, it can provide insights of periodic variations on acidification/potential Al toxicity risks and nutrient depletion/enlargement processes that may ultimately affect crop yield, biomass production and $\mathrm{C_{SEQ}}$ potential (Jones, 1984).

3.3.1.3 Microbiological properties as S_{IND}

No significant differences ($p \leq 0.05$) were found in any microbiological $\mathrm{SI_{ND}}$ that were analyzed (except for $\beta\text{-}_{\mathrm{GLU}}$ and $\mathrm{N_{MIN}}$); however, a noticeable vertical variability was observed in all the $\mathrm{SI_{ND}}$ (Table 3.4). The $\mathrm{N_{MIN}}$, $\mathrm{MR_{ESP}}$ and $\mathrm{M_{SOC}}$ means were remarkable higher than those estimated by Alfaro et al. (2021) in: i) the same SPS that was analyzed in our study (estimates made in 2015) averaging 1.01 / 0.20 $\mathrm{\mu gNgdw^{-1}d^{-1}}$; 0.067 /0.040 mg $\mathrm{CO_2}$ g $\mathrm{dw^{-1}}$ and 1450.95 / 881.76 µg C g $\mathrm{dw^{-1}}$ and ii) a conterminous SPS to our study site $\mathrm{A_{GRO}F_{RST}}$, both under the *Nothofagus obliqua* as a tree component, with means of 1.67 / 0.48 µg N $\mathrm{gdw^{-1}}$ $\mathrm{d^{-1}}$; 0.081 /

0.048 mg CO_2 g dw^{-1} and 1774.15 / 1042.98 µg C g $dw^{-1}$for 0-5 cm / 5-20 cm depths in both systems (i,ii) respectively.

Table 3. 4. Characterization results of microbiological SI_{ND}

	System			
S_{IND}	SPS 0–5	SPS 5–20	AGROFRST 5–20	AGROFRST 5–20
M_{SOC}	1325.50 a	315.23 a	463.43 a	69.60 a
M_N	196.67 a	46.77 a	68.77 a	10.30 a
MR_{ESP}	0.18 a	0.13 a	0.14 a	0.13 a
β-$_{GLU}$	338.03 a	159.97 b	186.40 b	130.76 b
U_{RS}	1247.55 a	994.69 a	1063.50 a	650.07 a
P_{HOSP}	713.62 a	699.71 a	759.52 a	740.05 a
FDA	55.85 a	56.74 a	54.64 a	39.93 a
N_{MIN}	19.36 ab	1.78 a	18.21 ab	8.41 ab

Measuring units: **$M_{SOC:}$** $µgCgdw^{-1}$; **M_N** : $µgNgdw^{-1}$; **MR_{ESP}** mg : CO_2gdw^{-1}; **β-$_{GLU}$** : $µgPNFgdw^{-1}h^{-1}$; **U_{RS}** : µg N-NH4 $gdw^{-1}h^{-1}$; **P_{HOSP}** : µg $PNFgdw^{-1}h^{-1}$) ; **FDA** : $µgFgdw^{-1}$; **N_{MIN}** :$µgNgdw^{-1}d^{-1}$. Where dsw : grams dry weight; PNF: p-nitrophenol ; F: fluorescence

The last data suggest a temporal enhancement of microbial activity (in the case of the same SPS); with respect to depth-differences, they may be due to greater amounts of fresh substrates / relative proportion of labile organic materials (e.g., M_{SOC}), whereas between the two systems, it might be caused by substrate quality differences including: variations on substrate inputs, chemical /physical leaf composition, since deciduous leaf litter has relatively lower lignin content and consequently lower C:N ratios (Dube et al., 2009), which is consistent with Decker and Boerner (2003), who determined lignin N ratios of 21.7 and 27.1 for *N. obliqua* and *N. dombeyi*, respectively. The latter could also explain the significantly higher N_{MIN} values ($p \leq$

0.05) at the 5-20 depth in $A_{GRO}F_{RST}$ compared with their counterpart in the SPS, and was probably due to the historic evolution of litter quality inputs, mineralization-immobilization processes (e.g., differences on M_N), fertilization practices and species preferences for available N forms, where the NO_3^- ratio was 1:3.39 at the 5-20 cm depth, favoring the uptake of this chemical species by the herbaceous component, then promoting the N_{MIN}.

Regarding enzymatic activities, the greater β-$_{GLU}$ activity in SPS could be explained by the continuous closed canopy sectors given by the evergreen trees (compared to the total deciduous condition in $A_{GRO}F_{RST}$), that limited solar radiation entrance, then helped preserve the moisture and temperature conditions in leaf-litter for subsequent fungal proliferation (also correlated with FDA) (Schnürer and Rosswall, 1982), and consequently the occurrence of ligninolytic enzymes (e.g., manganese peroxidase), which may influence positively other SI_{ND} such as M_{SOC} and MR_{ESP} as in the case of our results (Table 4). Despite the U_{RS} activity being well correlated to the presence of labile N forms and a combination of high temperatures-low moisture conditions, the higher biomass activity found in SPS (e.g., M_{SOC} and MR_{ESP}), may explain the higher U_{RS} values because it was able to release this enzyme (Kang et al., 2009). The P_{HOSP} exhibited greater activity in $A_{GRO}F_{RST}$, which was probably related to a combination of the more acidic conditions and greater water retention capacity in this system (e.g., SI_{ND} pH, WHC and $I_{NF}Vk$) .

In the case of FDA, the factor controlling increases of activity of this SI_{ND} were directly proportional to pH, temperature and ECEC (Green et al., 2006), however as it occured in the case of U_{RS}, the higher C and N biomass in SPS (M_{SOC} M_N) may stimulate the FDA activity (Alvear et al. 2007), which may explain the differences that were observed mainly at 5-20 depth between systems. In Andisols (0-15cm), from a relict-native forest consisting of the plant associations:

Aextoxicon punctatum, Nothofagus obliqua, Eucryphia cordifolia, Laurelia sempervirens and *Persea lingue* in Temuco, Chile, Reyes et al. (2011) observed similar trends to our findings in M_{SOC} (1245 µgCgdw^{-1}), M_N (99.5 µgNgdw^{-1}) and FDA (51.5 µgFgdw^{-1}), although there were remarkable differences for β-$_{GLU}$ and P_{HOSP} activities, which means 7.3 and 68.2 µmol gdw^{-1} h^{-1} PNF, respectively, virtually tripling and exceeding by a 10 order magnitude our estimations; this may be related to the maturity stage of the forest, compared to our study sites)

3.3.2 *Interactions among soil quality indicators (S_{IND})*

A total of 73 interactions with correlations $R= \geq 0.7$ were detected (8 inverse) as follows: 57, 14 and 2 for chemical, microbiological and physical S_{IND}., respectively (Figure 3.1). The SOC was the most interactive S_{IND}, and was correlated with total N (R= 0.70) and available N (NH_4^+ R=0.76), and other relevant plant nutrients such as P (R=0.71), K (R=0.90), Ca^{2+} (R=0.91), Mg^{2+} (R=0.90), S (R=0.84), including the CEC (R=0.89), that also influences N_{MIN} (R=0.77),

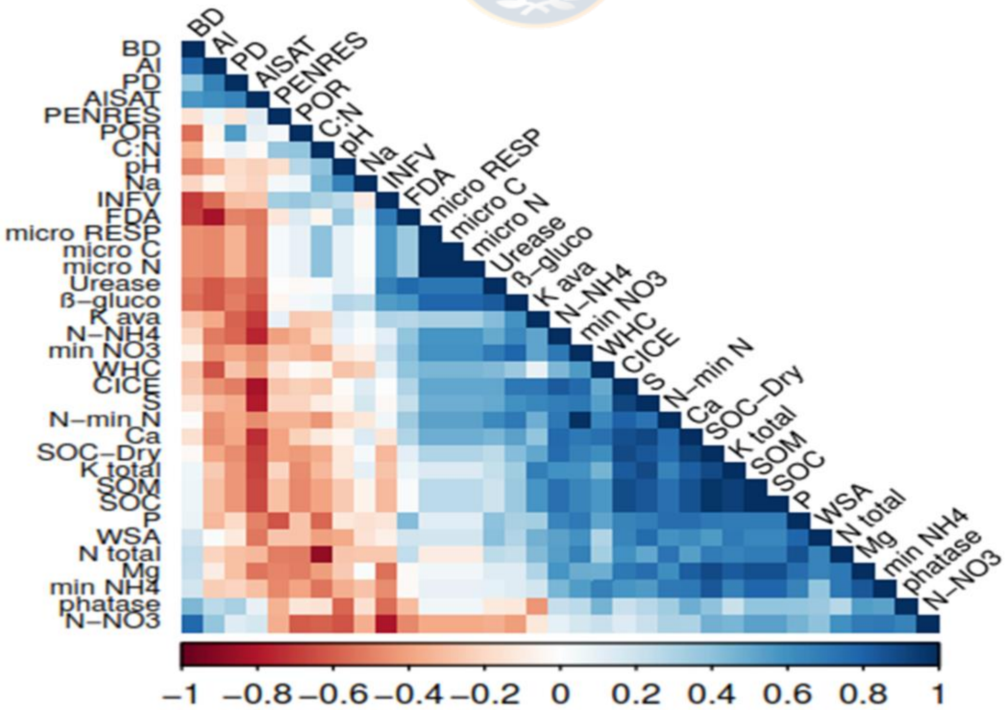

Figure 3.1 Heat map representing Pearson's correlation coefficients for the different S_{IND} analyzed. Significant interactions were considered for coefficients with values $R= \geq 0.7$

demonstrating the pivotal role of SOM in mediating nutrient storage and supply, contrary to Al, where increases in soil solution may lead to nutrient deficiencies (e.g., CEC-Al, R= -0.83; NH_4^+-Al_{SAT}, R=-0.83). Most of the microbial S_{IND} were strongly correlated: for instance i) MR_{ESP} - M_{SOC} (R=1.0), MR_{ESP} - β-$_{GLU}$ (R=0.8) and M_{SOC}- β-$_{GLU}$ (R=0.8) which are responsible for C cycling and ii) Indicators related to N cycle, including N- N_{MIN} (R=0.74), M_N - U_{RS} (R=0.72) and MR_{ESP} - M_N (R=1.0).

3.3 *Carbon sequestration*

Based on previous on-site studies, it was possible to determine temporal changes in SOC concentrations and stocks (0-20 cm) and their respective accumulation rates (Table 3.5). Both SOC density and accumulation were greater in $A_{GRO}F_{RST}$ than SPS, which is reflected in SOC stock variations: SPS 21.93 Mg C ha^{-1} (5 yr period), whilst 27.52 Mg C ha^{-1} for the $A_{GRO}F_{RST}$ (4 yr period). The latter could be related to the record-periodicity of fertilization and the presence of more labile plant residues in $A_{GRO}F_{RST}$, promoting a faster cycling of plant detritus into the soil matix (ultimately meaning larger inputs of soil organic matter).

Table 3.5 Temporal Variation of SOC density, stocks and C_{SEQ}

	System	
	SPS 0–20	$A_{GRO}F_{RST}$ 0–20
Previous SOC (%)	8.5*	9.2**
SOC_{2019}	11.5	12.6
Previous SOC stock (Mg ha^{-1})	61.09*	79.92**
SOC stock 2019 (Mg ha^{-1})	83.02	107.44
Theoretical annual C_{SEQ}	5.48	5.50

All the data reported correspond to weighted values from 0-5 and 5-20 cm depths. * For the year 2015, source: Alfaro et al. (2020) and ** year 2014 source: Dube et al. (2016).

In nearby areas to our study site that were devoted to conservation agriculture (Andisols), Muñoz et al. (2012), reported positive variations of SOC (33.1 to 35.5 Mg ha^{-1}) after 16 year of no tillage, while Panichini (personal communication, June 2020), estimated a SOC stock mean of 106.83 Mg ha^{-1} in systems with stubble incorporation for wheat production. Regarding C_{SEQ}, our estimates were in accordance with Ortiz et al. (2020), who determined positive variations of C_{SEQ} of + 4.83, + 7.5 and 1.6 Mg C $ha^{-1}yr^{-1}$ during the period 2015-2018 in three different SPS within a native *Nothofagus obliqua* degraded forest over Andisols in South Central Chile, having three tree densities of 60, 134 and 258 steams ha^{-1} (corresponding to 85-95%, 65-75% and 45-55% of solar radiation), respectively.

3.4 *Determination of SQI*

After the estimation of all the sub-indexes (Figure 1), different trends were observed by type of S_{IND}: i) physically, all the indicators in all conditions (between systems and depths) were in adequate to optimal conditions for plant growth (except for $I_{NF}Vk$ and WSA), representing the highest SQI type (Table 3.6). However, the critical status for the aggregation is the limit with a higher category, whilst water movement is in a similar level from acceptable near to optimal, based on the fact that this occurs in both cases, evidencing the historic degradation processes, although gradual changes will probably be observed due to the ongoing SOM inputs. Chemical SQI presented the highest variation among the systems and depths, having accentuated critical levels that were mostly related to nutrient availability in all conditions (e.g., NH_4^+, P, K, Ca^{+2}), however the SPS presented differences in percent of -19.7 and -15.2 for 0-5 and 5-20 cm, respectively, probably due to a combination of natural (e.g., base cation leaching) and anthropogenic (e.g., acid reaction fertilizers use) processes. A lightly Al^{3+} toxic risk was observed, where despite exchangeable Al^{3+} (Al_{EXCH}) was in moderate concentrations in all conditions except for SPS at 0-5 cm depth (optimal); Al saturation (Al_{SAT}) was critical and at high level risk for SPS and $A_{GRO}F_{RST}$ at 5-20 cm, respectively, which also corresponded to the condition with high nutrient depletion), alluding to the previous statement. Accordingly, Casanova et al. (2013b) mentions that acidification processes reduce ECEC values, which were lower than 2 cmol kg^{-1} and associated not only to limited bio-availability of certain nutrients, but Al^{3+} availability since the exchange complex releases cation to buffer H^+ ion production via leaching.

Table 3.6. Soil quality indexes (%) by condition

	Systems			
	SPS 0–5	SPS 5–20	$A_{GRO}F_{RST}$ 0–5	$A_{GRO}F_{RST}$ 5–20
(5) Physical SQI	64.26	64.26	64.26	64.26
(6) Chemical SQI	9.09	1.52	28.79	16.67
(7) Microbiological SQI	41.86	25.58	41.86	23.26
(8) Global SQI	38.41	30.46	44.98	34.74
(9) % SQI	37.9	44.8	31.0	37.9

The number inside each parenthesis corresponds to the equation from which the values were calculated.

Microbiological activity had equivalent SQI at 0-5 depth of both systems, whereby the S_{IND} M_N M_{SOC}, MR_{ESP} and $\beta\text{-}_{GLU}$ had critical status while the U_{RS} P_{HOSP} was optimum, and the N_{MIN} in FDA was acceptable. Similar trends were observed at 5-20 depth except for FDA in $A_{GRO}F_{RST}$ which was in a limited range, whilst N_{MIN} was critical in both systems.

The critical category that was common to all conditions could be related to substrate quality of fresh input organic material, meantime the optimal category may depict P and N mining, generating a net immobilization processes, linked to their chemical S_{IND} concentrations- counterparts.

Specifically, the limited FDA activity that was previously discussed indicates a less diverse microbial community that was less able to produce proteases, lipases and esterases (responsible to hydrolize the fluorescein diacetate or FDA), while critical N_{MIN} at 5-20 depth, may be caused by a combination of lower N concentrations (S_{IND} N%), focal compaction generating lower aeration limiting O^+ availability, thus slowing the nitrification processes (transformation of NH_4^+ into NO_2^-/NO_3^-) and/or due to higher lignin (S_{IND} C:N).

The estimated overall SQI by system (0-20 cm) was 31% for SPS and 37.8 for $A_{GRO}F_{RST}$, while SQI% reached 41.4% and 31.5% respectively; this was probably due to a combination of greater leaf-litter production and fertilization practices. However, a pattern showing higher SQI in the upper depths of both systems were observed, if fewer S_{IND} were in a critical state, which may evidence the positive effects of AFS management - SOC generation.

Broadly, although the general SQI could be explained mainly by native SQ (e.g., distinctive properties of Andisols) and possibly to a lesser extent by the effects of anthropogenic activities, the differences in SOM and most of S_{IND} that were evaluated between the upper and lower depths (both systems) finally resulted in a positive change over SQI and showed a sensitiveness to AFS management.

Moreover, in order to establish comparative advantages between AFS and i) natural regeneration – secondary ecological succession after degradation processes merely in terms of soil properties, in plots that were adjacent but outside of our study sites (with the same historical record of pure extractive practices), estimated the following values: WHC: 40.4 /38.6 %; WSA 42.63/41.53%; PEN_{RES} 200->300 PSI; SOC: 11.26 / 7.63% (0-5/5-20 cm), and ii) plots with 50 year old secondary forest SOC: 10.2 / 9.7%, WSA 52.5/50.8%; WHC: 39.3 /34.9 % (0-5/5-20 cm), PEN_{RES} 100->200 PSI (both cases noticeably lower than those observed for the SPS and $A_{GRO}F_{RST}$.), but also a dense undergrowth was observed, dominated almost entirely by *Chusquea quila*, which is considered a species of indirect medical importance (e.g., habitat of the longtailed lobster *Oligoryzomys longicaudatus*, vector of the hantavirus *Bunyaviridae*), also having opportunistic habits, persistence and of low potential nutritional value, besides the high presence of the locally denominated “blond scorpion” *Brachystostenus negrei*, of a certain medical importance.

a)

	SPS 0-5 cm	SPS 5-20 cm	$A_{GRO}F_{RST}$ 0-5 cm	$A_{GRO}F_{RST}$ 5-20 cm
pH	🟢 2/2	🟢 2/2	🟢 2/2	🟢 2/2
SOC (%)	🟩 10/20	🟩 10/20	🟩 10/20	🟩 10/20
C:N	🟡 1/2	🟡 1/2	🟡 1/2	🟡 1/2
N (%)	🟢 2/2	🟢 2/2	🟢 2/2	🟢 2/2
P (ppm)	🔴 -5/10	🔴 -5/10	🔴 -5/10	🔴 -5/10
NH_4^+ (ppm)	🔴 -5/10	🔴 -5/10	🔴 -5/10	🔴 -5/10
NO_3^- (ppm)	🔴 -5/10	🔴 -5/10	🟩 5/10	🟩 5/10

K_{TOT} (mg kg^{-1})	🔴 0/2	🔴 0/2	🔴 0/2	🔴 0/2
Ca^{2+}	🔴 -1/1	🔴 -1/1	🔴 -1/1	🔴 -1/1
Mg^{2+}	🔴 0/2	🔴 0/2	🔴 0/2	🔴 0/2
S (ppm)	🟢 1/1	🟢 1/1	🟢 1/1	🟢 1/1
ECEC (cmol(+) kg^{-1})	🟢 10/10	🟡 10/10	🟢 10/10	🟡 10/10
Na (%)	🟢 1/1	🟢 1/1	🟢 1/1	🟢 1/1
Al_{EXCH} (cmol$^{(+)}$ kg^{-1})	🟢 0/0	🟡 -1/0	🟡 -1/0	🟡 -1/0
Al_{SAT} (%)	🟢 0/0	🔴 -5/0	🟡 -1/0	🟢 0/0

b)

	SPS 0-5 cm	SPS 5-20 cm	$A_{GRO}F_{RST}$ 0-5 cm	$A_{GRO}F_{RST}$ 5-20 cm
I_{NF}Vk (cm d^{-1})	🟡 0/5	🟡 0/5	🟡 0/5	🟡 0/5
WHC (%)	🟢 10/10	🟢 10/10	🟢 10/10	🟢 10/10
BD (g cm^{-3})	🟢 2/2	🟢 2/2	🟢 2/2	🟢 2/2
PD (g cm^{-3})	🟢 1/1	🟢 1/1	🟢 1/1	🟢 1/1
*P_{OR} (%)	🟢 5/5	🟢 5/5	🟢 5/5	🟢 5/5
WSA (%)	🟤 0/3	🟤 0/3	🟤 0/3	🟤 0/3
PEN_{RES} (PSI)	🟢 2/2	🟢 2/2	🟢 2/2	🟢 2/2

c)

	SPS 0-5 cm	SPS 5-20 cm	$A_{GRO}F_{RST}$ 0-5 cm	$A_{GRO}F_{RST}$ 5-20 cm
M_{SOC} (µgCgdw^{-1})	🔴 1/3	🔴 1/3	🔴 1/3	🔴 1/3
M_N (µgNgdw^{-1})	🔴 1/2	🔴 1/2	🔴 1/2	🔴 1/2
MR_{ESP} (mgCO$_2$gdw^{-1})	🔴 1/10	🔴	🔴	🔴
β-$_{GLU}$ (µgPNFgdw-1h^{-1})	🔴	🔴	🔴	🔴
U_{RS} (µg N-NH4 gdw-1h^{-1})	🟢 2/2	🟢 2/2	🟢 2/2	🟢 2/2
P_{HOSP} (µg PNFgdw-1h^{-1})	🟢 3/3	🟢 3/3	🟢 3/3	🟢 3/3
FDA (µgFgdw^{-1})	🟩 2/3	🟩 2/3	🟩 2/3	🟡 1/3
N_{MIN} (µgNgdw^{-1}d^{-1})	🟩 8/10	🔴 3/10	🟩 8/10	🔴 3/10

Figure 3.2 Bi-indicative illustration of S_{IND} sub-indexes through dots for the estimation of SQI. The combination of each color and diameter ranges represents the spectrum defined in the Appendixes. Larger diameters-greenish hues corresponding to acceptable-optimal ranges (distinguishable by minor to main intensity, respectively), yellowish tone – medium diameters point out intermediated to limiting soil quality values. Finally orangey-reddish colors and smaller diameters correspond to undesirable to critical levels. The values adjacent to each circle (x/y) symbolize the quality sub-index score (x) and the maximum possible sub-index value (y) (Appendixes A, B and C). a), b), c) refer to chemical, physical and microbiological S_{IND} scores.

Although it is beyond the scope of the present work to prove its occurrence and distribution in that site due to natural regeneration, it is possible to state that no specimens were found in any other of the study sites and that it could be a future line of research (Juan Ortiz, Personal Communication, Nov. 2020). Therefore, it is possible to conclude that under the described scenarios, AFS are able not only to improve soil conditions in shorter periods, but also to prevent the massive developed of undesirable species.

4. Conclusions

After the assessment of the proposed 30 S_{IND}, it was established that 79.3% did not vary under any condition; in fact, 41% were in the acceptable-optimal interval, while 6.9% were ranked as intermediate-limiting and 31.0% to restrictive-critical levels, revealing an overall SQI (0-20 cm) of 34.5 and 41.4% for SPS and $A_{GRO}F_{RST,}$ respectively. Physical SQI ranged within optimal status, except for two S_{IND} (WSA and $I_{NF}Vk$), however both in ranges that were still near to desirable, thus ensuring water storage-movement and adequate structure for root exploration and developed. On the contrary, a high variability and more critical aspects were observed in chemical SQI, where the SI_{ND} related to cationic nutrients (K^+, Mg^{2+}) and P^+ in critical levels, both attributable to the inherent properties of Andisols, as well as the underlying risk of Al^{3+} toxicity; deficiencies of assimilable N referable to net N immobilization, limited microbial activity (e.g., critical levels for the S_{IND} M_N, M_{SOC}, M_{RESP}), which creates certain tendencies in microbial SQI, also as a result of the combined effects of fertilization patterns, substrate quality and labile C provided by the herbaceous component (e.g., amount of rhizodepositions), revealing some comparative advantages of $A_{GRO}F_{RST.}$ but also, a dependence on external inputs. Unlike the above, positive changes on nutrient status and microbial dynamics could be expected to be enhanced in SPS in the medium-term due to manure contribution. Moreover, since 5.48 and 5.50 Mg C ha yr^{-1} are added to the SPS and $A_{GRO}F_{RST}$, respectively, virtually all the SI_{ND} were improved significantly ($p \leq 0.05$) or simply in magnitude in the upper depth studied (0-5 cm), which shows the pivotal role of SOM in influencing pedogenic processes and functions. Our results, in addition to being in line with the growing scientific evidence supporting the widely recognized aptitudes of AFS to confront major world challenges as global warming and food security, also evidence the complementarity of these systems in forested areas for native forest reclamation-conservation and multi-purpose land managements for food production that are focused on smallholder agriculture. Future research should include the periodical-seasonal quantification and characterization of leaf-litter stock-input, microbial communities (e.g., key groups related to metabolic activity) and SOC fractionation to assess the C stabilization processes involved and the particular contribution of each C pool to the estimated C_{SEQ}, and also a general C balance in order to determine comparative ecological parameters.

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DISCUSION GENERAL

En el Capítulo I se consultaron 233 fuentes con el fin de conocer el estado actual de la degradación de la tierra y las potencialidades que los AFS (particularmente los SPS) representan para su remediación. Este fenómeno modifica negativamente las funciones y capacidades biofísicas del colectivo tierra:" suelo-atmosfera circundante, agua, vegetación especies", debido uso normalmente al uso extractivo de recursos naturales y/o manejo de sitios inviables / vulnerables para la agricultura convencional, descrito a través de 24 principales procesos, de los cuales 15 se relacionan directa y/o exclusivamente con el suelo (degradación del suelo). La degradación del suelo comprende: remoción de la cobertura vegetal, ii) modificaciones en su arreglo espacial natural y/o iii) desplazamiento sus componentes que en suma generan una alteración de sus procesos internos, minado de nutrien tes y en consecuencia, su capacidad de provisión de servicios ambientales (e.g., pérdidas en la producción primaria neta, cambios en los patrones vegetacionales, biodiversidad), amenazando seriamente la seguridad alimentaria.

Adicionalmente, las perturbaciones al suelo generan una masiva desestabilización del C almacenado, así como de otras sustancias de importancia medio ambiental como en N_2O, favoreciendo una generalizada emisión de GHG, causante del calentamiento global. Se estima que alrededor del 20% de la población mundial se ve directamente afectada por procesos de degradación, teniendo impactos sin embargo en un porcentaje mucho mayor, pues el fenómeno de degradación genera tensiones sociales como el abandono y disputa de sitios, flujos migratorios, ciclos de pobreza-sobre explotación natural, inestabilidad económica y política.

Usos y manejos del suelo capaces de limitar a incrementar el contenido de C y con ello sus beneficios ambientales (denominados colectivamente calidad del suelo), son esperables en la remediación de sitios degradados, así como el monitoreo de distintas propiedades y procesos (que fungen como S_{IND} y habrán de integrarse pare establecer SQI) del suelo que permitan establecer variaciones en función del $C \rightarrow SOC$.

Los AFS ampliamente reconocidos en la literatura y con presencia a nivel mundial, representan posibles soluciones integrales ante la degradación de la tierra capaces no solo de preservar, sino recuperar sitios degradados, debido a que sus principios básicos son promover y consevar la mayor cantidad de interacciones biológicas y conservación de biomasa posibles con menores alteraciones al suelo. Los AFS suelen ser además tecnológicamente simples, con altos grados de auto-sustentabilidad, promoviendo la diversificación de bienes de consumo por unidad de superficie, la participación social inclusiva y gran adaptabilidad en función de las necesidades específicas de cada usuario y/o condiciones del medio biofísico.

En particular, los SPS, el segundo tipo de AFS con mayor presencia en el mundo, representan ciertos beneficios adicionales, no solo en términos del mayor rango de bienes de consumo (e.g., cárnicos, lácteos), sino también ambientales. En la literatura se menciona a los SPS como los de mayor capacidad de captura de C, tanto C→COS como en biomasa, pues a diferencia de otros AFS, éstos pueden soportar mayores densidades arbóreas (siempre y cuando se encuentren soluciones viables a la producción de forrajes bajo altas condiciones de sombra). A través de la consulta de diversas fuentes, se identificaron 25 mecanismos responsables de la alta capacidad de almacenamiento de C en los SPS, por ejemplo, destacan: i) limitando las pérdidas de nutrientes y C en forma disuelta por efecto de ciclajes internos a través de los sistemas radicales arbóreos, ii) aporte de nutrientes (e.g., P, K, Mg, Ca) a través de fecas, iii) N como NH_4^+, que estimula preferentemente el desarrollo de herbáceas, que a su vez, iv) generaran rizodepositaciones altas en C lábil que v) estimularan la actividad biológica aumentando la productividad del sistema. De acuerdo con lo anterior y en virtud de los alcances que la degradación del suelo que ha tenido en Chile (41% del territorio nacional afectado), donde además cerca de un tercio de las zonas agrícolas históricas se encuentran en condiciones de limitadas a inaptas. Este fenómeno ha creado una enorme presión sobre los bosques nativos (de alto valor como reservorios genéticos únicos). Paralelamente, los suelos volcánicos comprenden al 60% de la superficie y 30-70% en zonas precordilleranas, además de albergar a algunos de los bosques nativos más amenazados.

En el Capítulo II en sitios que reflejasen la realidad descrita (e.g., bosques nativos con rasgos evidentes de degradación, desarrollados sobre suelos volcánicos típicos), se propuso determinar el efecto de SPS de 5 años de antigüedad emplazados en bosques nativos de Roble (*Nothofagus obliqua*), bajo distintos niveles históricos sobre aprovechados (que corresponden a diferentes grados de cobertura arbórea) sobre índices físicos y químicos de calidad del suelo. Los resultados evidenciaron tanto la influencia de la cobertura arbórea sobre distintas propiedades físicas y químicas del suelo, destacando el SOC por su determinante rol e influencia en prácticamente el resto de ellas. En cuanto a las propiedades físicas, se esperan observar en el mediano plazo: i) variaciones positivas en el estado general de agregación y probablemente con ello en consecuencia, mayores incrementos de SOC, tanto en el contenido total como en las tasas anuales de almacenamiento, como consecuencia directa de modificaciones en la densidad aparente ii) mayor estructuración que genere simultáneamente ciertas variaciones positivas en el espacio poroso, capacidad de almacenamiento de agua, que habrían de impactar a la felicidad de infiltración, que es el único indicador en condiciones medianamente limítrofes. Tales efectos en suma representan un aporte significativo en términos de control y reversión de los procesos erosivos manifiestos a través de puntos con altas resistencias a la penetración (>300PSI) y redes de canalículos, al limitar el flujo superficial. En relación con los indicadores químicos, estos expresan un bajo status nutricional generalizado, que pudiera resultar de la combinación tanto de rasgos característicos de suelos volcánicos, como del historial de sobre aprovechamiento en el sitio. Por una parte, el lavado de cationes básicos (nativo) y su minado a través de remoción y/o cosecha de biomasa (antropogénico). La marcada insuficiencia de P podría atribuirse a la alta retención de fosfatos característica en Andisoles; la suficiencia pero indisponibilidad de N, obedecería a intermedias-altas relaciones C:N resultantes de sustratos con elevado contenido de lignina, que dan cuenta de la hojarasca-residuos leñosos como fuente principal en la etapas primarias del sistema, junto a una limitada expresión de los beneficios de los componentes herbáceo y animal. Lo anterior produce procesos de inmovilización (e.g., formación de N-orgánico para el crecimiento y reproducción celular de microorganismos a partir de N disponible del medio), que restringe el desarrollo vegetal. Se han observado mejoras importantes en el SQI total hacia las profundidades 0-5 cm (excepto por la condición semi-cerrada, que corresponde al sitio con apreciables menores niveles de perturbación previos), lo que indica evidencias en la recuperación de los procesos edáficos y niveles de productividad potencial (incluso por encima de los SQI observados para cualquier produndidad del sistema menos perturbado). Lo anterior se condice con el mayor numero de S_{IND} en condiciones criticas para las produndidades 5-20cm de los sistemas abierto y semi-abuerto (40.9 y 27.2 %), que corresponden a los historiales de mayor degradación. Se espera que en un periodo 5-10 años estos suelos bajo SPS superen algunas de las condiciones criticas de determinados S_{IND} y de los suelos volcánicos en general. Los resultados obtenidos difieren con expuesto por Blaser et al (2018), quienes afirman que en AFS con sombreados mayores a 30%, los beneficios de al menos uno de los componentes pudieran verse afectado.

En el Capítulo III y debido a que en la zona existen sitios con asociaciones *N. dombeyi* – *N. obliqua*, se instalaron igualmente SPS bajo esta condición (173 árboles ha^{-1}, *N. obliqua :*133:, *N. dombeyi* :40), además de un banco de proteína- forraje consistiendo de (446 árboles ha^{-1}, *N. obliqua*) para la producción de avena (*Avena sativa*) y vicia (*Vicia atropurpurea*) en un predio contiguo destinado al consumo animal de los SPS en épocas invernales. En ambos casos se evaluaron igualmente la capacidad de C→SOC y SQI a través de S_{IND} físicos, químicos y se incluyeron, además, indicadores microbiológicos (a diferencia del Capitulo II). Los resultados mostraron tendencias similares para los S_{IND} físicos, ubicándose en su mayoria en niveles deseables de calidad (excepto también y con valores similares que el estado de agregación y la velocidad de infiltración como en el Capitulo II).

Los mayores C→SOC y SQI observados en el agrobosque se condicen con la alta productividad de forraje reportada y viceversa. En el caso de los incrementos periódicos de SOC, estos pueden ser directamente atribuidos a dos factores, la calidad-calidad de sustrato, en donde los aportes de hojarasca desde *N. obliqua* donde la densidad de árboles es mayor, pero adicionalmente por la propoción del desarrollo del componente herbáceo de rápido crecimiento, que haría aportes significativos en términos de SOC lábil, que estimula la productividad del sitio, sin embargo, lo anterior también expresa intrínsecamente una alta dependencia en este AFS de inputs externos, particularmente de fertilizantes.

En el caso del SPS, a pesar de que el C→SOC es menor, pudiendo asumirse que igualmente refleja los menores valores de SQI estimados y por lo tanto de los S_{IND} involucrados, es importante mencionar que es esperable que en mediano y largo plazos, las contribuciones en términos de nutrientes que aportará el componente vía deposiciones de cationes (Ca, Mg, K), nativamente limitantes, así como N disponible (NH_4^+), que a su vez estimularía el desarrollo del componente herbáceo y con ello la producción de exudados radicales, productividad del sistema y el apropiado desarrollo-bienestar animal. En relación con los S_{IND} microbiológicos, altamente sensibles al manejo / alteraciones del medio, no presentaron sin embargo diferencias significativas excepto para la N_{MIN} y $\beta\text{-}_{GLU,}$ aunque en comparación con reportes pasados para el sitio, los valores promedio para los S_{IND} N_{MIN}, MR_{ESP} and $_{-}M_{SOC}$, estimados en 2015 en épocas del año similares, resultaron en valores apreciablemente menores, lo que hace suponer un claro aumento en la actividad biológica y con ello una mayor productividad del sistema. En concordancia con lo antes planteado, los apreciables mayores valores no solo en la actividad microbiológica, sino también de S_{IND} químicos y físicos en la profundidad 0-5 cm (estas dos ultimas también observadas en el Capitulo II), evidenciar los atributos mencionados en la literatura relacionados con un mejoramiento generalizado de las aptitudes del suelo a través del manejo silvopasroril.

Cabe mencionar que con el fin de establecer diferencias en terminos de C→SOC y SQI entre los AFS y sucesion ecológica luego de la no intervención posterior a los procesos de degradación, aunque se estimaron contenidos de C (%) menores tanto para: un manejo pasivo de cero intervenciones durante 5 años, como para ii) lotes de renovales o bosques secundarios de *N. obliquia* de al menos 50 años. Los resultados preliminares establecieron que en el primer caso, se observaron valores inferiores en distintos S_{IND} como: WHC, WSA, PEN_{RES}, SOC, mientras que en el segundo caso, tendencias similares (excepto por un mayor grado de agregación WSA% > 50%), auque también se observó dominado por *Chusquea quila*, considerada una especie de indirecta importancia médica y marcada presencia de alacrán rubio *Brachystostenus negrei* (no presentes en otros sitios de estudio). Lo anterior podria establecer ventajas comparativas entre los AFS y los procesos de regeneración natural.

IV. CONCLUSIONES GENERALES

Mediante la evidencia mostrada, es posible rechazar la hipótesis planteada, pues si bien los SPS promovieron C→COS en todos los casos en niveles comparables reportados en la literatura, no se cumplió la condición de que la calidad del suelo seria mayor en todas las produndidades (0-5 cm) como consecuencia directa de estos aportes. No obstante, en la mayoría de los casos analizados, distintas funciones edáficas como la capacidad de almacenamiento de agua, aereación del suelo (e.g., capacidad de anclaje y desarrollo radical), estado nutricional y procesos de agregación se han visto mejoradas para la profundidad a 0-5 cm en las condiciones más degradadas. Por tanto, este estudio sugiere que los SPS posseen un gran potencial en la recuperación de bosques degradados pero también para su aprovechamiento. Particularmente, las coberturas (*Nothofagus obliqua*) intermedias-semi abiertas (134 arboles ha^{-1}) alcanzaron los mejores SQI y mayor productividad visible de *Poaceae*, potencialmente beneficiando la nutrición animal, aunque no el menor número de S_{IND} en condiciones críticas. En el caso de las coberturas con altas densidades- semi cerradas (258 arboles ha^{-1}), con menores perturbaciones históricas, éstas obtuvieron los mejores SQI, auque no necesariamente las mejores condiciones para expresar las potencialidades del SPS *per se*, debido a la alta proliferación y arraigo de especies tolerantes de sombra con bajos valores nutricionales / de palatabilidad frente a la potencial merma en establecimiento, proliferación, distribución y rendimiento de pasturas y especies fijadoras de N. Los SPS en condiciones abiertas (60 arboles ha^{-1}), a pesar de que presentaron valores de intermedios a altos SQI, también es donde existieron el mayor número de indicadores en condiciones criticas (%SQI) y visiblemente condiciones aun de degradación como mayores niveles de compactación, presencia de redes de canalículos y superficies desprovistas de vegetación, con lo cual se espera que la recuperación de estos sitios y el climax de los efectos del pastoreo se observen en el mediano plazo. Paralelamente al comparar un SPS mixto siempre verde - caducifolio (*N. dombeyi – N. obliqua*) con el AFS agrobosque bajo *N. obliqua*, utilizado como banco de proteína –forraje (ambos coetáneos entre si y con los SPS antes mencionados), se observó mayor capacidad de secuestro de C y SQI en el agrobosque, debido a periódicas enmiendas a la fertilidad de estos suelos, sin embargo, en todos los SPS es esperable una autonomiamayor, debido a las aportaciones nutricionales del componente animal, vía fecas y orina animales.

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ANEXOS

ANEXO 1.

Tablas utilizadas en el CAPÍTULO II para la evaluación de SQ.

2.5 Appendixes A and B and C

Subindices for each soil quality indicator (S_{IND}) considered for the soil quality index (SQI) estimation as well a summary if the terminology used in the chapter . Below are shown S_{IND} ranges or levels of soil quality and the correspondent sub-index values (modified from [34]), Appendix C correspond to a list of terms corresponding to the abbreviations included.

Table 2.8 Appendix A Soil quality levels and their associated sub-index values for physical $S_{IND.}$

PHYSICAL S_{IND}	Level	Interpretation	Subindex	Source
PD (g cm^{-3})	<2	Desirable	1	Nissen et al., 2005
	>2	Without effect	0	
BD (g cm^{-3})	<1.10	Optimum	2	Arshad et al., 1997
	1.10−1.47	Desirable	1	
	>1.47	Low	0	
P_{OR} (%)	<5	Critical	−5	Pagliai and Vognozzi, 2002
	5–10	Restrictive	0	
	10–25	Acceptable	1	
	25–40	Desirable	2	
	>40	Optimum	5	
WHC (%)	>60	Optimum	10	Vidal, 2007
	51–60	Acceptable	5	
	41–50	Low	0	
	<40	Critical	−10	
I_{NF}Vk (cm day^{-1})	<8.64	Undesirable	−5	Reynolds et al., 2003
	8.64–20	Acceptable	0	
	20–43.2	Optimum	5	
P_{EN}R (psi)	>300	Undesirable	0	Lal and Elliot, 1994; Carter , 2002
	200–300	Acceptable	1	
	100–200	Optimum	2	
WSA (%)	<50	Undesirable	0	Lal and Elliot, 1994
	50–70	Medium	1	
	70–90	High	2	
	>90	Optimum	3	

Table 2.9 Appendix B Soil quality levels and their associated sub-index values for chemical $S_{IND.}$

CHEMICAL S_{IND}	Level	Interpretation	Sub-index	Source
pH	<3.0	Super critical	−1	Amacher et al., 2007
	3.01–4.0	Critical	0	
	4.01–5.5	Limiting	1	
	5.51–6.8	Desirable	2	
	6.81–7.2	Optimum	2	
	7.21–7.5	Acceptable	1	
	7.51–8.5	Limiting	1	
	>8.5	Critical	0	
SOC (%)	>15	Excellent	20	Vidal, 2007
	5–15	High	10	
	3–5	Moderate	1	
	<2	Low	−10	
N (%)	>0.5	Desirable	2	Amacher et al., 2007
	0.1–0.5	Adequate	1	
	<0.1	Insufficient	0	
NO_3^- (mg kg^{-1})	<10	Critical	−5	Vidal, 2007
	10–20.1	Insufficient	0	
	20.1–40	Adequate	5	
	>40	Desirable	10	
NH_4^+ (mg kg^{-1})	<25	Critical	−5	Vidal, 2007
	25–50	Insufficient	0	
	51–75	Adequate	5	
	>75	Desirable	10	
	20–20	Moderate	1	
	>20	Insufficient	0	
C:N ratio	1–10	Adequate	2	Amacher et al., 2007
	10–20	Moderate	1	
	>20	Insufficient	0	
P (mg kg^{-1})	>16	Adequate	10	Villarroel, 2000
	5–15	Moderate	1	
	<5	Insufficient	−5	
K (mg kg^{-1})	>500	Adequate	2	Amacher et al., 2007
	100–500	Moderate	1	
	<100	Insufficient	0	
S (mg kg^{-1})	>100	Insufficient	0	Amacher et al., 2007
	1–100	Adequate	1	
	<1	Insufficient	0	
Ca (mg kg^{-1})	>1000	Desirable	2	Amacher et al., 2007
	101–1000	Adequate	1	
	10–100	Insufficient	0	
	<10	Critical	−1	

Mg (mg kg^{-1})	>500	Adequate	2	Amacher et al., 2007
	50–500	Moderate	1	
	<50	Insufficient	0	
ECEC (cmol kg^{-1})	>6.27	Adequate	2	[62]
	1.65–6.27	Moderate	1	
	<1.65	Insufficient	0	
Exchangeable % Na	<15	Critical	0	Amacher et al., 2007
	≤15	Acceptable	1	
Al$_{EXCH}$ (cmol kg^{-1})	<0.1	Adequate	0	Villarroel, 1989
	0.11–0.51	Moderate	−1	
	0.51–0.81	Undesirable	−2	
	>0.81	Critical	−3	
Sat Al (%)	1.1–3.1	Adequate	0	Villarroel, 1989
	3.2–6.1	Moderate	−1	
	6.2–12	High	−2	
	>12	Critical	−5	

*Nota: Las referencias en extenso pertenecientes a cada número se encuentran a partir de la pagina

Table 2.10 Appendix C List of abbreviations.

ABBREVIATION	DESCRIPTION	ABBREVIATION	DESCRIPTION
Gg	Gigagrams	NO$_3^-$	Nitrate
Pg	Petagrams	P	Phosphorous
AFS	Agroforestry system	K$^+$	Potassium
SPS	Silvopastoral systems	Ca^{2+}	Calcium
SPS-RA	Silvopastoral systems Ranchillo Alto	Mg^{2+}	Magnesium
C	Carbon	Na$^+$	Sodium
CO$_{2eq}$	Carbon equivalent	S	Sulphur
SOM	Soil organic matter	Al$_{EXCH}$	Exchangeable Al
SOC	Soil organic carbon	%Al$_{SAT}$	% of Al saturation
C→SOC	Carbon sequestration	ECEC	Effective cation-exchange capacity
SQ	Soil quality	pH	Soil reactivity
SQI	Soil quality index	PD	Particle density
S$_{IND}$	Soil quality indicator	BD	Bulk density
O$_p$	Open condition	% (POR)	Total porosity
S$_{Op}$	Semi-open condition	WSA	% of water stable aggregates
SC	Semi-closed condition	INFV	Infiltration velocity
N	Nitrogen	WHC	Water holding capacity
C/N	Carbon-to-nitrogen ratio	P$_{EN}$R	Penetration resistance
NH$_4^+$	Ammonium		

ANEXO 2

Chapter III

Appendixes A, B and C

Subindices for each soil quality indicator (S_{IND}) considered for the soil quality index (SQI) estimation

Appendix A. Table 3.7 Soil quality levels and their associated sub-index values for physical S_{IND}

PHYSICAL S_{IND}	Level	Interpretation	Subindex	Source
PD (g cm^{-3})	<2	Desirable	1	[Nissen et al., 2005]
	>2	Without effect	0	
BD (g cm^{-3})	<1.10	Optimum	2	[Arshad et al., 2015]
	1.10−1.47	Desirable	1	
	>1.47	Low	0	
P_{OR} (%)	<5	Critical	−5	[Pagliai and Vignozzi, 2002]
	5–10	Restrictive	0	
	10–25	Acceptable	1	
	25–40	Desirable	2	
	>40	Optimum	5	
WHC (%)	>60	Optimum	10	[Vidal, 2007]
	51–60	Acceptable	5	
	41–50	Low	0	
	<40	Critical	−10	
I_{NF}Vk (cm day^{-1})	<8.64	Undesirable	−5	[Reynolds et al., 2003]
	8.64–20	Acceptable	0	
	20–43.2	Optimum	5	
P_{EN}R (psi)	>300	Undesirable	0	[Lal and Elliot, 1994; Carter, 2002]
	200–300	Acceptable	1	
	100–200	Optimum	2	
WSA (%)	<50	Undesirable	0	[Lal and Elliot, 1994]
	50–70	Medium	1	
	70–90	High	2	
	>90	Optimum	3	

Appendix B. Table 3.8 Soil quality levels and their associated sub-index values for chemical S_{IND}.

CHEMICAL S_{IND}	Level	Interpretation	Sub-index	Source
pH	<3.0	Super critical	−1	[Amacher et al., 2007]
	3.01–	Critical	0	
	4.01–	Limiting	1	
	5.51–	Desirable	2	
	6.81–	Optimum	2	
	7.21–	Acceptable	1	
	7.51–	Limiting	1	
	>8.5	Critical	0	
SOC (%)	>15	Excellent	20	[Vidal, 2007]
	5–15	High	10	
	3–5	Moderate	1	
	<2	Low	−10	
N (%)	>0.5	Desirable	2	[Amacher et al., 2007]
	0.1–0.5	Adequate	1	
	<0.1	Insufficient	0	
NO_3^- (mg kg^{-1})	<10	Critical	−5	[Vidal, 2007]
	10–20.1	Insufficient	0	
	20.1–40	Adequate	5	
	>40	Desirable	10	
NH_4^+ (mg kg^{-1})	<25	Critical	−5	[Vidal, 2007]
	25–50	Insufficient	0	
	51–75	Adequate	5	
	>75	Desirable	10	
C:N ratio	1–10	Adequate	2	[Amacher et al., 2007]
	10–20	Moderate	1	
	>20	Insufficient	0	
P (mg kg^{-1})	>15	Adequate	10	[Villarroel, 2000]
	5–15	Moderate	1	
	<5	Insufficient	−5	
K (mg kg^{-1})	>500	Adequate	2	[Amacher et al., 2007]
	100–500	Moderate	1	
	<100	Insufficient	0	
S (mg kg^{-1})	>100	Insufficient	0	[Amacher et al., 2007]
	1–100	Adequate	1	
	<1	Insufficient	0	
Ca (mg kg^{-1})	>1000	Desirable	2	[Amacher et al., 2007]

	101–1000	Adequate	1	
	10–100	Insufficient	0	
	<10	Critical	−1	
Mg (mg kg^{-1})	>500	Adequate	2	[Amacher et al., 2007]
	50–500	Moderate	1	
	<50	Insufficient	0	
ECEC (cmol kg^{-1})	>6.27	Adequate	10	[Villarroel, 1989; Casanova et al., 2013b]
	1.65–6.27	Moderate	5	
	<1.65	Insufficient	0	
Exchangeable % Na	<15	Critical	-10	[Amacher et al., 2007]
	≤15	Acceptable	1	
Al_{EXCH} (cmol kg^{-1})	<0.1	Adequate	0	[Villarroel, 1989]
	0.11–0.51	Moderate	−1	
	0.51–0.81	Undesirable	−2	
	>0.81	Critical	−3	
Sat Al (%)	1.1–3.1	Adequate	0	[Villarroel, 1989]
	3.2–6.1	Moderate	−1	
	6.2–12	High	−2	
	>12	Critical	−5	

Appendix C. Table 3.9 Soil quality levels and their associated sub-index values for biological S_{IND}

BIOLOGICAL S_{IND}	Level	Interpretation	Subindex	Source
M_N (μgNgdw^{-1})	>4067	Desirable	2	[Xu et al., 2013]
	<4067	Undesiderable	1	
M_{SOC} (μgCgdw^{-1})	>28608	Adequate	3	[Xu et al., 2013]
	2814 – 28608	Moderate	2	
	<2814	Low	1	
MR_{ESP} (mgCO$_2$gdw^{-1})	<0.3	Critical	1	[Moebius-Clune et al., 2016]
	0.3–0.5	Restrictive	3	
	0.5–0.65	Limited	5	
	0.65–0.85	Desirable	8	
	>0.85	Optimum	10	

N mineralization N-min N (μgNkgdw^{-1})	<9	Critical	1	[Moebius-Clune et al., 2016]
	9–13	Restrictive	3	
	13–17	Limited	5	
	17–21	Desirable	8	
	>21	Optimum	10	
β-GLU (μgPNFgdw^{-1}h^{-1})	<14304	Undesirable	0	[Stott et al., 2009]
	14304-28608	Acceptable	5	
	>28608	Optimum	10	
U_{RS} (μg N-NH4 gdw^{-1}h^{-1})	<28	Undesirable	0	[Nannipieri et al., 2002; Maulood and Darwesh, 2019]
	28-560	Acceptable	1	
	>560	Optimum	2	
P_{HOSP} (μg PNFgdw^{-1}h^{-1})	<60	Undesirable	0	[Eivazi and Tabatabai, 1977]
	60–170	Medium	1	
	>170	Optimum	3	
FDA (μgFgdw^{-1})	>66	Optimum	3	[Green et al., 2006]
	50-66	Adecuate	2	
	33-50	Average	1	
	< 33	Limited	0	