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Soil research, management, and policy priorities in Chile

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1. Soils of Chile

Given the diversity of soil types in Chile, soil scientists face complex challenges to prioritize across different regions. Chile is located at the south-western extreme of South America and is characterized by its well-marked latitudinal climate segmentation along 4300 km from 18° S to 56° S, spanning diverse transversal geomorphologic units across a narrow 180-km wide landscape from the Andes mountains, Andean foothills, Central Valley, and Coastal Range to the coastal plains. Chilean soils formed in geographic isolation flanked by the Pacific Ocean, Atacama Desert and the Andes mountains (Casanova et al., 2013). From the extreme hyperarid north to central Mediterranean Chile, Aridisols and Entisols dominate, with Histosols in only a few areas of the northern Altiplano highlands. Residual and colluvial soils coexist with soils derived from volcanic ashes, which in the temperate and rainy south-central Chile allow Andisols to develop. Alluvial, glacial and fluvio-glacial soils occur primarily along the Central Valley and southern Patagonia plains. The southern volcanic zones of the Andes influence central-southern Chile, which is dominated from 35° S to 49° S by soils derived from volcanic ashes, mainly Andisols and Ultisols, where about 70% of agricultural activities are carried out. All remaining Soil Taxonomy Orders are also found, except Oxisols. Quantitative and qualitative anthropogenic soil degradation due to land use change and agricultural management has been an old and serious problem in Chile as far back as the mid-eighteenth century, with adverse impacts on agricultural productivity, rural livelihoods, biodiversity, and on food security in some places. Numerous connections to local and global environmental problems such as climate change and ongoing drought call for action-oriented science to inform management and decision making. We identified five soil priorities of particular importance in Chile.

2. Soil priorities in Chile

2.1. Soil information system

A comprehensive understanding of soils' distribution and a permanently updated open-access virtual soil library database are fundamental for future research, management, and decision-making. Chile has mapped an important proportion of its soils that are used for crop, livestock, and forestry production, and thus only central-southern Chile has continuous soil surveys (Fig. 1). Chilean territory has been covered by

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detailed and semi-detailed soil cartography scale, normally 1:20,000 and in more remote areas 1:500,000 (Casanova et al., 2013), using USDA Soil Taxonomy as the official classification system since the 1960s. Most soil data available are from these managed ecosystems, with only 25% of the country having legacy soil survey data, which mainly corresponds to compilations of past studies going back up to 1941, some of which are not properly referenced (Pfeiffer et al., 2020). Therefore, traceability of the official data is difficult, making the reported soil properties unreliable in relation to the sampling date. Additionally, legacy soil surveys are expensive and difficult to access, making mapping efforts from previous decades underutilized and almost unknown outside academic research and consultant companies Many of these surveys are now several decades old, not updated, and do not contain the data required to build current soil priorities such as an updated national map on the status of anthropogenic soil degradation. The scarce efforts on digital soil mapping are mainly based on this legacy data (Padarian et al., 2017; Reyes Rojas et al., 2018), and a recent effort on soil data compilation that covered 13,612 data points in the entire country showed that obtaining data outside of the traditional sampling area is extremely difficult (Pfeiffer et al., 2020). A national level discussion regarding the need for a comprehensive soil survey program to increase soil mapping coverage and soil sampling in these underrepresented areas is urgent, where soil maps should be developed at different scales as a function of the region or national requirements. This information must be freely available in easy-to-access platforms, which the creation of a National Soil Service would facilitate.

2.2. Land use change and soil resource fragility

Land use change has been recognized as a critical issue in keeping our planet within a safe operating space for humanity. While the main tendencies and drivers of land use change vary locally, most of them are catalyzed by human activity and result in soil degradation (Manuschevich et al., n.d., in press). In Chile, a lack of regulations and policies that consider both the fragility and the potential of soils makes the creation of a legal framework that regulates land use planning imperative (Pfeiffer et al., 2018). Neoliberal policies and an extractive-based economy during the last four decades favored land use change; for instance, there are subsidies for monoculture forest plantations in areas formerly covered by native forests (Heilmayr et al., 2020), subsidies for irrigated orchards that replaced native forest in steep slopes with soils not suitable for agriculture, and to a lesser extent, leaf litter harvesting under sclerophyllous forests of central Chile for use in landscaping and gardening. All these activities affect soil biodiversity and hydrological functioning. Other concerning issues of land use change are soil sealing by urban expansion on scarce premium agricultural land, driven by an urban-centric view of land planning (Silva, 2020), and de facto urbanization over rural lands driven by land subdivision for second homes for which there is no regulation if subdivided lots are over 0.5 ha (Pfeiffer et al., 2018). Land use planning should balance productive needs such as agriculture, forestry, mining, and human use with other soil functions and ecosystem services such as hydrological regulation, carbon sequestration, and biodiversity conservation.

2.3. Soil management for sustainability and resilience

Multifunctional soils that support resilient crop, livestock, and forestry production, while providing other ecosystem services such as climate modulation,water regulation, soil biodiversity conservation are key for working landscapes that operate within planetary environmental boundaries (Wittwer et al., 2021). Chile's climate action strategy was criticized for overreliance on forestry plantations as carbon sinks and requires diversification across a wider range of natural climate solutions (Hoyos-Santillan et al., 2021). This could include management to increase soil organic matter in grazing land and cropland soils which has already declined in Chile and is predicted to continue to do so (Ramírez

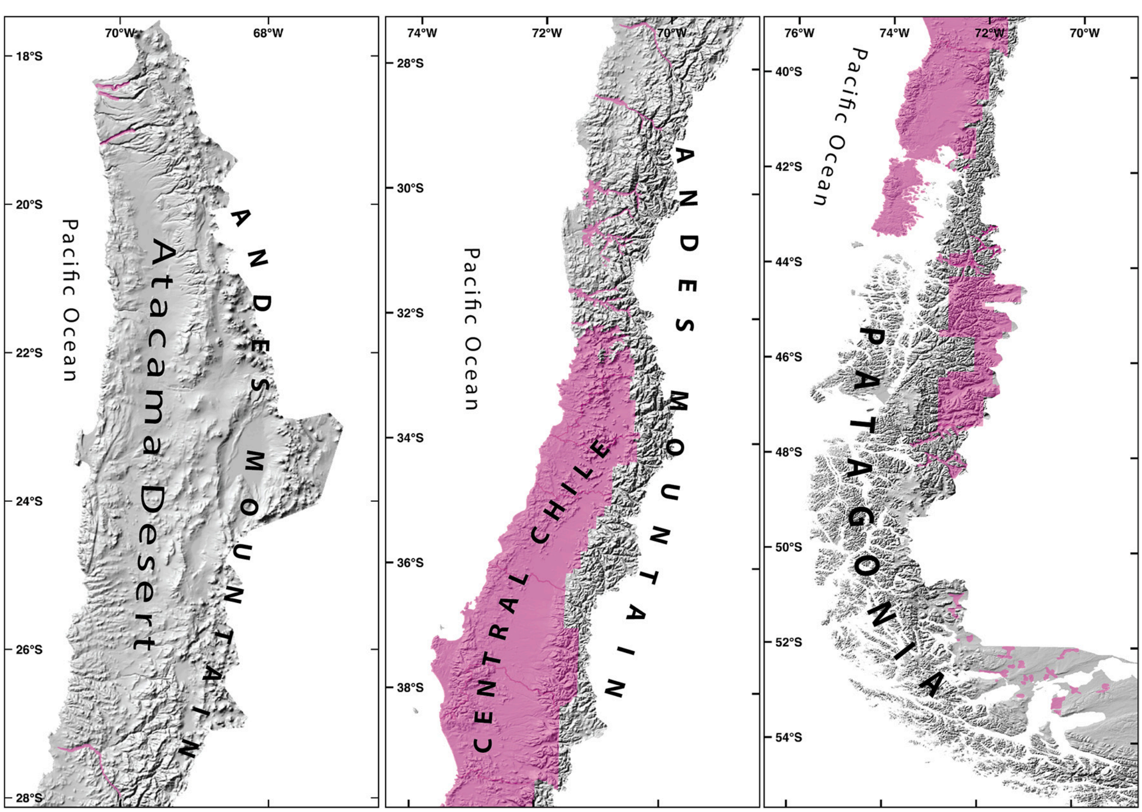

Fig. 1. Coverage of soil survey maps in Chile (in pink). The background relief map corresponds to a DEM (Digital Elevation Model) of Chile based on SRTM data. The map is splitted latitudinally from north (left) to south (right).

et al., 2019; Reyes Rojas et al., 2018). Land management for greater soil organic matter and soil health could help adaptation to Chile's current decade-long drought and future climate predictions of higher temperatures, lower precipitation, and reduced snowpack in many zones, by fostering crop resilience to drought and deficit irrigation (Jahanzad et al., 2020; Renwick et al., 2021). One soil health management practice, using crop residues and prunings as organic amendments, is an alternative to agricultural burning, which will be banned in Chile's Metropolitan Region in 2026, and offers additional climate adaptation co-benefits by reducing wildfire risks associated with agricultural burning in Chile. Quantifying land management outcomes for soil biological, physical, and chemical health versus degradation and incentivizing sustainable land management is critical.

2.4. Soil education

Soil education in Chile has followed a trajectory closely linked to the evolution of soil sciences at a global level, from a discipline with foundational roots in geology to an applied agricultural and environmental related discipline. Nevertheless, some soil science departments are being eliminated or combined with other departments, creating opportunities for integration across disciplines but concerns/risk of losing disciplinary identity. Soil science curriculum for future professionals and scientists in agriculture and the environment in Chile requires more up-to-date, innovative, evidence-based terminology and emerging concepts and technologies, including but not limited to advances in soil ecology and "omics" approaches, agroecology and sustainable agrifood systems, and data science. Educational frameworks should guide students toward knowledge integration, with the perspective that their future work will require facing complex problems and diverse scenarios as part of multidisciplinary and transdisciplinary teams (Casanova, 2013).

2.5. Soil policy

Among the OECD countries, Chile is the only one that does not have a specific legislation and regulations regarding soil use, conservation and management. To date, legislation in Chile refers to soil only as the base for urbanization and establishes rules for land use change from natural ecosystems to anthropogenic uses. After more than 20 years of efforts to achieve a specific legal structure for soil protection in Chile, a Framework Law for Soils (Ley Marco de Suelos) was proposed in the Chilean Senate in November 2021. It was unanimously approved in January 2022 to advance to the legislative stage in recognition of the need to legislate urgently on issues related to land degradation, climate change, land management, and the prevention of soil contamination, which impact the quality and quantity of food production, public health and welfare, and the country's economy. This initiative was the result of the joint efforts of the scientific societies of soil sciences and geology, a non-governmental organization, and congressional representatives. The proposed law includes guidelines for land use planning, soil degradation, climate change mitigation and adaptation, and education. We highlight the need for a legal framework for soils, to guarantee their protection and use according to their capacities with the aim of preserving this non-renewable natural resource for future generations and emphasizing soil's role in ensuring food security and mitigating climate change.

Declaration of Competing Interest

None.

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