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RESEARCH ARTICLE

How much instruction do Chilean students receive in Soil Science? Bibliometric evaluation of elementary and high school curricula

Rocío E. Gallardo Jara[1], Juan Ortiz[1*], Marcelo Panichini[2*], Mathias Kuschel-Otárola[1], Pedro M. de Souza Campos[2], Pablo Neira[3], Benjamín Sandoval-Leal[4], Tatiana Escobar[1], Winfred Espejo[1], Eliana Pereyra[5], Silvia Patricia Paredes-Carrera[6], Inés Figueroa-Cares[1], Erik Zagal[1], Mauricio Schoebitz[1], Analí Rosas[1], Marco Sandoval[1], Manuel Casanova[7], and Neal Stolpe[1]

[1]Universidad de Concepción, Facultad de Agronomía, Chillán, Chile.
[2]Instituto de Investigaciones Agropecuarias, INIA Carillanca, Temuco, Chile.
[3]Universidad de Barcelona, Instituto de Investigación de la Biodiversidad (IRBio), España.
[4]Universidad de Concepción; Facultad de Arquitectura, Geografía y Urbanismo, Concepción, Chile.
[5]Universidad Nacional del Sur, Facultad de Agronomía, Bahía Blanca, Argentina.
[6]Instituto Politécnico Nacional, Escuela Superior de Ingeniería Química e Industrias Extractivas, Ciudad de México, México.
[7]Universidad de Chile, Facultad de Ciencias Agronómicas, Santiago, Chile.
[*]Corresponding authors (jortizc@udec.cl; marcelo.panichini@inia.cl)
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ABSTRACT

In spite of the unquestionable role of soil in regulating countless natural processes and satisfying human demands (e.g., climate change mitigation), such relevance is virtually unnoticed. Arguably, a limited inclusion of soil science into early education is a critical driver. Accordingly, we compiled and synthesized soil science information into official textbooks provided by the Ministry of Education (MINEDUC) in Chile for elementary (ES) and high school (HS) levels for the years 2018 and 2023. We detected 173 and 232 topics from 56 and 71 textbooks enclosing "soil" and among other 36 adjacent terms (e.g., ecosystem, agriculture) for 2018 and 2023. Once categorizing the data into information into the pedagogic objectives: Knowledge, comprehension, application, and others, we observed a distribution of 30.64%-32.76%; 31.79%-25.00%; 25.43%-33.19% and 12.14%-9.05% for 2018 and 2023. After weighting the data into eleven soil educational goals (e.g., soil genesis), we observed a dominance of environmental awareness concepts, where the educational goal soil degradation and protection temporally varied from 23.64% to 27.27% of core curricula, whereas a decline of ~ 52% in soil functions and ~ 47% agricultural usefulness were detected. However, a temporal overall improvement over time and more equal distribution of topics into soil science disciplines reflects an institutional concern for improving the quality of programs.

Key words: Basic school, scholar textbooks, scientific education, soil science teaching, soil security.

INTRODUCTION

Virtually, all cultures across time have shown interest in understanding soil (Churchman, 2010; Katikas et al., 2024). However, early soil studies (1800s), which were fundamentally descriptive, developed alongside distinct disciplines such as geology and agro-chemistry until systematized soil knowledge was published (Churchman, 2010; Hartemink and McBratney, 2025). Once consolidated as a science, the core body of soil science has been primarily divided into six main sub-disciplines: Pedology, soil mineralogy, soil chemistry, soil physics, soil biology and soil fertility, all of them fundamentally oriented to agriculture (Churchman, 2010). Over the past few decades, experimental evidence has disclosed: i) The interconnectedness of a myriad of edaphic processes linked to ecological integrity and those disturbing human activities underlying land degradation (e.g., organic matter decay, nutrient depletion, microbiota shifts, compaction, erosion), conducive to the ongoing global environmental crisis (Olsson et al., 2019), and ii) to prioritize soil variability: Forming factors + processes → taxonomic classes → properties (e.g., minerals, nutrients, organic composition, microbiome), in any land use recommendation/adoption to avoid socio-economic and environmental costs associated with mere land use requirement-based decisions (Beillouin et al., 2022). Soil ecological principles embody the basis of human life and provide non-ecological assets that support worldwide socio-economic roles, such as technical (e.g., source of raw materials), industrial, settlement (e.g., urbanization), recreational (e.g., sports), geogenic, cultural heritage (e.g., paleontological, archaeological), and transport (e.g., infrastructure), among others (Blum, 2005).

Therefore, soil research has moved up to the international agenda as main Sustainable Development Goals, then adopting a multidisciplinary approach (e.g., economists, engineers, medical staff, biotechnologists, anthropologists), to address the contemporary broad spectrum of soil related issues (e.g., food and water security, biofuels-energy harnessing, ecosystems services provision, gene reservoir, human health) (Bock and Wickings, 2025), which is mirrored for instance, by the rising number of publications and impact factor on soil science journals (Havlin et al., 2014). Consequently, public understanding of soil principles is potentially imperative for any person, regardless of age and education type/level, to develop intellectual abilities-criteria and ultimately values-social responsibility for any soil-related experience whatever it may be. Formal early education probably constitutes the main alternative, since it deals professionally with knowledge by using methods that promote a quality of understanding, new mental perspectives, and the development of critical faculties (e.g., judgement) (Adesemowo and Sotonade, 2022).

Despite the aforementioned, awareness pointing up the need to include soil related topics into all-grade educational systems dates back from about 70 yr ago, since soil science learning is in essence up to present, restricted to students-professionals enrolled within life and environmental sciences (Hillel, 2007). For instance, in North America, only ~ 30% of Forestry Schools include geology-geomorphology courses (~ 15% as elective) and despite soil science is present in ~ 90% of the cases, only ~ 50% require forests soils, both critical in professional operations such as define erosion risks/conservation actions and determine soil tolerance to mechanical stresses and therefore harvesting period election, respectively (Fisher et al., 2005). Although comprehensive and integrative research remains crucial (particularly in areas that are still scarcely studied, such as agrology), current soil science research is increasingly dominated by applied, technology-oriented approaches that focus on a limited subset of soil properties and functions (Churchman, 2010).

Respecting soil science oriented to children, core curricula for elementary school (ES) and high school (HS) grade levels, differ from country to country and even within different Regions, States or Provinces (e.g., Canada; Hayhoe et al., 2016), as well the focus of soil in these curricula, and teachers soil science background also varies. However, despite a general agreement indicating that soil science is a major syllabus requirement for both life and environmental science curricula, particularly at the elementary school level, there is limited literature addressing this topic (Hillel, 2007). In a recent study related to literature contents in soil science for ES and HS from 43 countries (involving 62% of worldwide population), Chile ranked among the latest countries regarding knowledge-understanding processes (soil fundamentals), whereas leading soil degradation-protection awareness concepts, in relation to nationwide available pedagogical tools-information (Charzyński et al., 2022).

In the following, we revise historic soil science occurrence-evolution and systematize soil science contents into official literary resources of Chile for the ES and HS. We also compare and discuss the temporal analysis 2018 and 2023, to depict possible thematic updates.

MATERIALS AND METHODS

Data analysis

An extensive literature review to detect the presence of soil science in Chile was conducted within elementary and high school textbooks provided to Ministry of Education (MINEDUC) for the years 2018 and 2023 (to ensure re-editions/updates of core curricula) and available complementary resources.

The keywords (along with soil) that were used for data acquisition were: Geography, landscape, land, nature, plant, agriculture, culture, cultivation, forest, ecosystem, tree, animal, pollution, pasture, livestock, food, river, hill, natural resources, mineral, rock, environment, jungle, sediment, root, organism, habitat, ecology, agronomy, diversity, climate, vegetables, and crops. To avoid vagueness, we discriminated these results where soils were not present in an implicit or explicit way.

Subsequently, the results were categorized into the following four progressively acquired student skills/educational goals according to Charzyński et al. (2022): a) Knowledge, b) comprehension, c) application, and d) others. The main soil science disciplines were grouped as follows: a) Knowledge (soil genesis, soil profile, soils of the country, world soils, climatic-soil-vegetation zones), b) comprehension (soil processes, soil functions, agricultural usefulness), c) application (soil management, soil degradation and protection), and d) others.

To transform descriptive-qualitative data into quantitative terms, we assigned the values: 0-no available information; 1-scarce information; 2-some information; 3-complete information. When the information was linked more than one topic or concept considered within different categories, the score was divided equally.

Finally, a soil information coefficient (SIC) to estimate the combined effect of individual scores to each educational goal:

$$SIC = \sqrt{(S_w/S_w max) \times S_w \times S_w max} \qquad (1)$$

where S_w is the weighted sum of scores of particular educational goals, $S_w$max is maximum weighted sum of scores related to particular educational goals.

RESULTS AND DISCUSSION

Tracking evolution of soil science in Chile to understand current educational status

Early soil knowledge consists on traditional-indigenous practices (e.g., ethnopedology), such as terracing and resting between productive cycles, mediated by northern and south-central cultures respectively, both involving a deep understanding of soil and ecosystem dynamics (Casanova et al., 2013). Starting in the 19th century, soil instruction transitioned from purely agricultural-experimental application to the sequential consolidation of the first farmer association (1838), the first experimental station (1876), the first Technical and Superior Agricultural Schools in 1851 and 1904, respectively, National Agricultural Research Institute (1964), the first master in soil science (1973) and the foundation of Chilean Society of Soil Science (1973), also organizing various world-class events related to the discipline (del Pozo et al., 2021). This institutional evolution probably occurred along with historic global trends of intensive agriculture systems, prioritizing high yield crops and consequently exerting high ecological pressures, which is particularly critical in Chile due to only ~ 5% of national territory is suitable for those practices (MMA, 2018) and a high dependence on hillside-high slope agriculture (50%-60% of total) in areas which support important native forest ecosystems, resulting on ~ 49% of degraded lands (Salazar et al., 2022; Aguirre et al., 2023). This gave rise to new techniques of food production and associated scientific research oriented to the protection and optimal use of natural resources, such as precision agriculture or the monitoring of soil organic C (SOC) inventories (Pfeiffer et al., 2020).

Accordingly, Salazar et al. (2022) defined five key priorities concerning soil security in Chile: Soil information systems, land use change and soil resource fragility, soil management for sustainability and resilience, soil policy and soil education. Regarding the last topic, Casanova (2013) and Salazar et al. (2022) reported that at the bachelor's level, diverse soil science departments around faculties-universities nationwide have been removed or at least consolidated into other disciplines; consequently, losing literacy across soil science spectrum, as well as the soil science lessons required in other careers (Brevik et al., 2022a; 2022b) which is extensive to basic education due to a limited connectivity between soil scientist and schools.

Nationwide curricular structure for elementary and high school

To address the presence of soil science into basic schooling, firstly, is relevant to outline that the educational system in Chile is divided into two main stages according to age range: i) Elementary School (ES) (8 grade levels from 6-14 yr old), and ii) High School (HS) (4 grade levels from 14-18 yr old), having a unique curricular program nationwide, which is contained in the textbooks provided by MINEDUC. Basic education enrollment nationwide reaching 3 631 025 totals students in 2023 (67.8% and 32.2% for ES and HS, respectively), representing a net increase in matriculation of 117 855 students for the 2018-2023 period (except for ES1, ES2, and ES4), which are primarily based in urban areas such as Santiago and Concepción (Arias et al., 2023).

The system is divided into five categories of educational centers (Figure 1). i) Public (39%): Institutions under municipal administration, financed mainly by the State; ii) subsidized (49.3%): Private institutes that receive financing from both the State and parents; iii) private education (5.5%): Schools financed exclusively from parents; iv) delegated administration corporations (0.6%): Educational establishments administered by private corporations, but financed and supervised by the State; v) local education services (5.7%): A public administration model that manages educational establishments under previous municipal management. Consequently, ~ 94.5% and ~ 92.0% of institutions and students rely on didactic materials provided by the MINEDUC, respectively (excluding private education) (Arias et al., 2023).

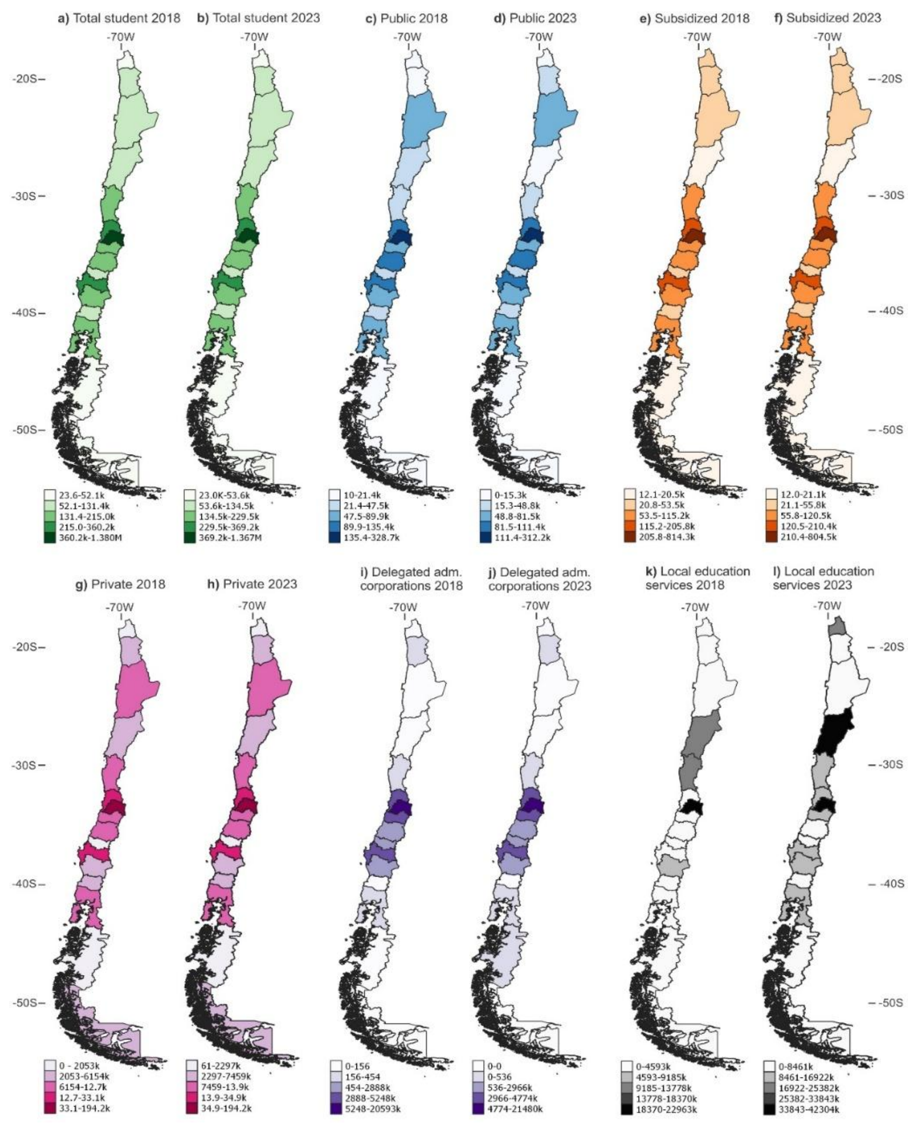


Figure 1. Updated database on national school enrollment. Total number of students nationwide by 2018 (a) and 2023 (b). Regional distribution of students by education establishment: Public/municipal 2018 (c), public/municipal 2023 (d), subsidized 2018 (e), subsidized 2023 (f), private 2018 (g), private 2023 (h), delegated administration corporations 2018 (i), delegated administration corporations 2023 (j), local education services 2018 (k), local education services 2023 (l). Source: Centro de Estudios MINEDUC, https://centroestudios.mineduc.cl/.

Recognition and categorization of soil science occurrence into core curricula

After a thorough review on the presence of soil science within MINEDUC literature resources for 2018 and 2023, in this section we analyze and grouped key aspects of identified information within educational goals and categories, under different approaches.

Soil science into academic objectives, courses and their associated textbooks. We observed the presence of soil science within both ES and HS; however, it varied markedly both in the volume of information and specificity (e.g., lessons in which soil was a principal or secondary subject of study) even within individual grades of each level. Concerning query periods, a total of 56 and 71 official textbooks enclosing the term "soil" and adjacent terms were identified, for 2018 and 2023, respectively (Table 1).

Table 1. Presence of soil information within main and particular scholar objectives by courses. NC: Natural Science; B: biology; HGSC: history geography and social sciences; CHEM: chemistry; PHYS: physics; SciCitz: science for citizenship; CitzEdu: citizenship education. Note: In some cases, soil term/topics are mentioned in units different from the cited above. Source: National curriculum, available at https://www.curriculumnacional.cl/portal/Documentos-Curriculares/Programas/#doc_general.

Course	Core curricula general objective	Year	Grade (didactic unit/specific objective related to soil)
NC	This course group various disciplines - Biology, Chemistry, Physics, Botany, Geology and Astronomy - dealing with a wide variety of natural phenomena: Living beings, matter, energy and its transformations, along the Solar System and the Earth	2018	ES1: Unit 2 - Characteristics of living beings ES1: Unit 3 - Animals and plants of nature ES2: Unit 3 - Human activity and environment ES3: Unit 3 - Importance of plants ES3: Unit 4 - Protection of plants and environment ES4: Unit 2 - Life in ecosystems ES4: Unit 4 - Chilean ecosystems ES5: Unit 1 - Water cycle and agriculture ES6: Unit 2 - Living beings and the soil the inhabit ES6: Unit 5 - Soil formation, living beings and the soil they inhabit ES7: Unit 1 - Microorganisms reservoir and soil ES7: Unit 6 - Role of soil in natural processes (e.g., climate changes, aquifer recharge) ES8: Unit 2 - Interactions soil – plants
		2023	ES1: Unit 2 - Living beings and their environment ES1: Unit 3 - Animals and plants of nature ES2: Unit 3 - Human activity and environment ES2: Unit 5 - Seasonal changes weather and plants growth ES3: Unit 3 - Importance of plants ES4: Unit 1 - Human activity on environment ES4: Unit 4 - Living beings and their environment ES5: Unit 1 - Water cycle and soil proprieties ES5: Unit 3 - Pollution, organisms, ecosystem and sustainability ES6: Unit 1 - Soil formation, living beings and the soil the inhabit ES6: Unit 2 - Plant nutrients ES7: Unit 1 - Soils and natural regions ES8: Unit 2 - Nutrients transport on plant ES8: Unit 4 - Institutions related to the study of soil
B	Offer opportunity to learn how and why things happen in nature, to understand phenomena of the natural world with the laws and theories that best explain them, besides positive and negative impacts of technological phenomena	2018	HS1: Unit 1 - Evolution and biodiversity HS1: Unit 2 - Organisms and ecosystems HS1: Unit 3 - Matter and energy in ecosystem HS1: Unit 4 - Impacts in ecosystem and sustainability
		2023	HS1: Unit 1 - Conditions to soil formation HS1: Unit 2 - Organisms and ecosystems

			HS1: Unit 3 - Matter and energy in ecosystem
HGSC	This course allows the student to achieve a better understanding of society and his role in it. It is composed of the disciplines - History, Geography, Economics, Demography, Sociology and Political Science - that study both, the human being as individual and as a member of society from different perspectives	2018	ES2: Unit 1 - Using maps and learning about our country ES2: Unit 3 - Chilean society and its origins ES2: Unit 4 - Chilean traditions, culture and heritage ES3: Unit 3 and 4 - Daily life in ancient time and the legacy of Greek/Roman civilization, respectively ES4: Unit 2 and Unit 3 - The cultural legacy of Mayas-Aztecs/and Incas, respectively ES5: Unit 1 - Geographic diversity of Chile ES6: Unit 2 - The process of Chilean independence and nation building ES6: Unit 4 - Chile from different geographical visions ES8: Unit 4 - Society and territory: The region in Chile and America HS1: Unit 3 - Conformation of Chilean territory HS1: Unit 4 - Citizenship and responsible consumption HS2: Unit 4 - Citizen development: Rule of law, society and diversity HS3: Unit 1 - Transformation of the state's role and modernization of society in the first half of 20th century. HS3: Unit 4 - Restoring democracy. Political, social and cultural transformations: Chile since the 1990's HS4: Unit 2 - Civic actions and responsibilities HS4: Unit 3 - The challenges of enrolling in a globalized world: Chile facing the economic-global threats
		2023	ES2: Unit 3 - Chilean society and its origins ES3: Unit 1 - Climatic zones and agriculture, consequences of deforestation ES3: Unit 2 - Daily life in ancient time and the legacy of Greek civilization ES4: Unit 1 - Degradation and erosion processes on soils, water reservoirs ES4: Unit 2 and 3 - The cultural legacy of Mayas-Aztecs/and Incas, respectively. ES5: Unit 1 - Degradation and erosion processes on soils, geographic diversity of Chile ES6: Unit 2 - The process of Chilean independence and nation building ES6: Unit 4 - Chile from different geographical visions, deforestation of soils, geologic/socio-natural disasters on soils ES7: Unit 1 and 3 - Agriculture innovations related to ancient Mesoamerican civilization ES8: Unit 1 and 3 - Society and territory: The region in Chile and America ES8: Unit 2 - Agriculture innovation in central region of Chile HS1: Unit 1 and 2 - Contradictions of progress and its consequences on ecosystems HS1: Unit 2 and 3 - Redefined of Chilean territory, German immigration, relocation of Mapuche culture
CHEM	Investigate and elucidate phenomena in the natural world, understand principles of thermodynamics and chemical kinetics that help explain the Earth and the Universe. Discuss the impacts produced by climate change at the level of bio-geochemical cycles	2018	HS1: Unit 1 - Soil and saltpeter formation (fertilizers), human activity over the ecosystem HS1: Unit 2 – Lifecycle's plants, photosynthesis and growth, desertification, soil as part of ecosystem, fertilization for agriculture HS2: Unit 1 - Carbon cycle (carbon fixation), soil fertilization HS3: Units 1 and 2 – Lifecycle's plants HS3: Unit 3 - Bio-physicochemical soil properties, acidification of soil HS3: Unit 5 - Use of isotopes in agriculture
		2023	HS1: Unit 1 - Acid rain and erosion of soil, nutrient uptake, consequences of fires and deforestation on soils HS1: Unit 3 - Fertilization of soil for agriculture HS1: Unit 4 - Cycle of the matter and energy in ecosystem, effect of drought in agriculture and soils

			HS2: Unit 1 - Consequence of climatic change, pollution, and degradation of soil
PHYS	It explores the subjects of classic mechanics, modern physics, the Universe and Earth sciences	2018	HS1: Unit 3 - Earth dynamics and benefits effects of volcanic eruptions HS3: Unit 1 - Physicochemical mechanisms that affect the lithosphere, regulation of terrestrial climate, dynamics of the hydrosphere HS3: Unit 2 - Cycle of the matter and energy in ecosystem
SciCitz	Explore skills and attitudes necessary for scientific studies, understanding core knowledge of science, relating science and technology to society and the environment	2023	HS3: Wellness and health, Unit 1: Factors and medicine, composting for land productivity HS3: Safety, prevention and self-care, Unit 1: Emergencies, risks, and geologic/socio-natural disaster in soil HS3: Safety, prevention and self-care, Unit 2: Threats and risks on the environment due human activity (e.g., pesticides) HS3: Environment and sustainability, Unit 1: Effect of local and global climate change on landscape and people HS3: Environment and sustainability, Unit 2: Sustainable consumption and environmental awareness, degradation and erosion processes on soils, carbon footprint, bioremediation HS3: Technology and society, Unit 2: Technology development and applications in land use changes, sustainable consumption strategies (e.g., drought in agriculture)
CitzEdu	Offer essential resources for living in a democratic society, enhancing critical thinking to contribute for the collective good	2023	HS3: Unit 3 - Citizens as part of the territory: Territory transformation, land use changes and its effect in the soil, family farming in the ancestral people (e.g., Lickanantai culture) HS4: Unit 1 - Social participations: Territory transformation, land use changes and its effect in the soil HS4: Unit 4 - Labor rights and development models: Human activity over the ecosystem, carbon footprint, and sustainable land use

i) 2018. Natural Sciences (NC) (1^{st} to 8^{th} ES grades); Biology and Natural Sciences Biology (B) (3^{rd} and 4^{th} HS grades), History Geography and Social Sciences (HGSC) (1^{st} to 8^{th} ES and 1^{st} to 4^{th} HS grades); Chemistry (CHEM) (1^{st} to 4^{th} HS grades); and Physics (PHYS) (1^{st}, 3^{rd} and 4^{th} HS grades). The identified resources included both, student textbooks (STB) and teacher's guides -or teaching programs- (TG) for each grade of main levels.

ii) 2023. For ES, NC (1^{st} to 8^{th} grades); for HS, B (1^{st} and 2^{nd} grades), also contained within STB and TG; the inclusion of supplementary resources to NC course titled activity books (ACB) was noticed. For ES and HS, HGSC (2^{nd} to 8^{th}, and 1^{st} and 2^{nd} grades, respectively); Chemistry (CHEM) (1^{st} to 2^{nd} HS grades); Science for Citizenship (SciCitz) (3^{rd} and 4^{th} HS grades); Citizenship Education (CitzEdu) (3^{rd} and 4^{th} HS grades). Similar to 2018, STB and TG in all grades contained soils knowledge.

In terms of educational goals distribution at each level by course (Table 2), we detected a consistent presence of soil science lessons in all grades along basic education curricula. By 2023, the number of topics examined across almost all courses has increased, with a consistent prevalence of lessons within ES over HS content. For instance, there was a higher count of textbooks for NC (mainly in TG) than for HGSC and B (in the HS) during the analyzed years. However, the lack of contents for PHYS-2023, SciCitz-2018 and CitzEdu-2018, was due to curricular adjustments, which resulted in the removal or addition of courses.

Table 2. Frame-up of soil science into textbooks by educational levels type and courses. N(STB)[Tt]; where N: total books; (STB): number of student books; [Tt]: total of topics; *textbooks for both 1^{st} and 2^{nd} levels, **textbooks for both 3^{rd} and 4^{th} levels; ***textbooks for 1^{st}, 3^{rd} and 4^{th} levels. ES: elementary school; HS: high school.

Education level	Natural Science		Biology		History Geography and Social Sciences		Chemistry		Physics		Science for Citizenship		Citizenship Education	
	2018	2023	2018	2023	2018	2023	2018	2023	2018	2023	2018	2023	2018	2023
ES	$19^{(8)[67]}$	$32^{(8)[99]}$	-	-	$13^{(6)[41]}$	$21^{(7)[60]}$	-	-	-	-	-	-	-	-
HS	-	-	$5^{(2)[18]**}$	$5^{(1)[29]*}$	$9^{(4)[18]}$	$3^{(2)[4]*}$	$8^{(3)[16]}$	$5^{(1)[14]*}$	$2^{(1)[13]***}$	-	-	-	$2^{(1)[14]**}$	$3^{(1)[12]**}$

Availability and distribution of educational goals and relevant concepts by courses. The main contributions of each academic course are described as follows (Table 3, Figures 2a, 2b):

Table 3. Soil science content within MINEDUC collaborative educational resources. Note: Two resources were detected, having notable differences between them. Textbook [(A)] does not address the educational goal related to world soils, whereas Textbook [(B)] lacks content in the category "others" and does not include topics on world soils or climatic-soil-vegetation zones.

Source	Contents according to evaluated topics and categories	Comments
Soil issues "Unraveling soil dilemmas"[(A)]	The educational contents were structured around four main dimensions. **Knowledge** included fundamental concepts of soil genesis and the rock cycle, soil profiles and horizons, national soil distribution and associated issues, and climate-soil-vegetation relationships through practical simulations. **Comprehension** addressed key soil processes and functions, focusing on land cover, substrate-dependent properties, water retention, and agricultural sustainability. **Application** emphasized soil management practices, including the impacts of monoculture, intensive agriculture, fertilization, and water quality, as well as soil degradation and protection linked to human activities. **Additional topics** incorporated interdisciplinary soil definitions, the effects of armed conflicts on soils, and social integration through collaborative, family-involved learning activities.	This book constitutes a valuable scientific-inquest pedagogical tool that provides detailed information about concepts, methodologies and didactic techniques useful for soil science comprehension fundamentals, focused on the soil environmental issues. This handbook is divided into five parts: i) Introduction, ii) didactic strategies, iii) teacher mentoring, iv) learning experiences
Modules with an investigative approach - SOIL [(B)]	Educational contents were organized into three main dimensions. **Knowledge** focused on biotic and abiotic soil components, the role of soil organisms and human activities in soil formation, soil profile characteristics influencing water infiltration and bioturbation, and regional examples of erosion-prone areas. **Comprehension** addressed key soil processes and functions, including texture-controlled water dynamics, decomposer activity, nutrient (N and P) cycles, and ecosystem services, as well as comparative assessments of substrate fertility and water-holding capacity. **Application** emphasized soil management and degradation, highlighting erosion processes, rainfall effects on bare soils, composting and organic residue use, soil remediation strategies, soil health, land-use change impacts, waste disposal effects, and soil–climate change interactions.	This pedagogical resource, adapted from a governmental guide on soil health recovery, presents an inquiry-based framework to address soil-related environmental issues across scales, from pot experiments to local settings. The handbook progresses from core soil properties and nutrient cycles to land degradation processes, including erosion and chemical impacts on water retention and germination, and concludes with land reclamation by framing soil as an ecosystem and exploring restoration strategies.

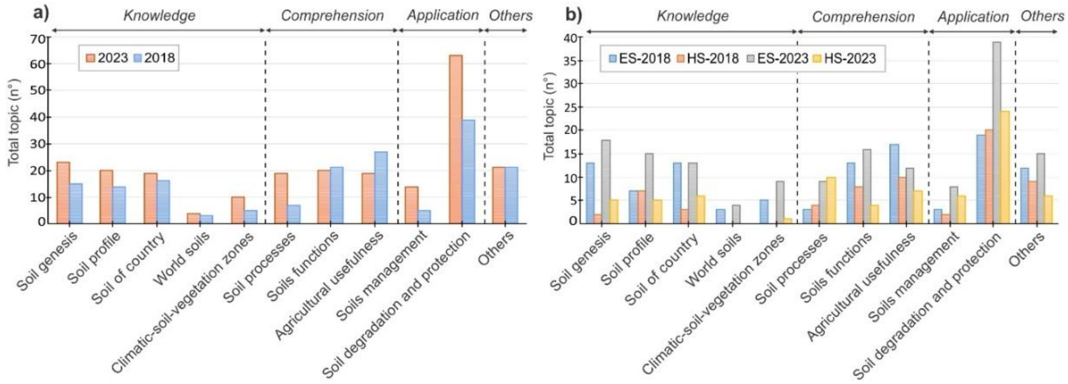


Figure 2. Graphical results for total education goals detected by category between 2018-2023 (a) and total recognized education goals by categories related to elementary school (ES) and high school (HS) level (b).

NC: It represents the most relevant for ES, main topics (more of them addressed in TG) are soil formation (weathering of rocks, and transport of sediments), generalities of soil profile description, main bio-physico-chemical soil properties, agricultural usefulness, threats of erosion and soil degradation-reclamation. Emphasizing the 6^{th} grade in the academic curricula is crucial, as it offers the most specific and consistent information about soil science for both 2018 and 2023 dedicating approximately 48 class-hours.

B: It offers the broadest perspective to HS students about essential soil functions related to matter and energy cycling. Particularly, from natural C and water biogeochemical or N biological cycles, to anthropogenic effects on soil, including: Water cycling (e.g., "green water"), soil degradation, pollution effects, climate change and food security.

HGSC: This is offered for ES and HS, the contents are oriented to land use transition from native cultures and colonization processes to present, mentioning in some cases soils types and climate-vegetational conditions (e.g., soil occupation in Southern regions). However, despite this course included less amount of explicit to merely mentioned soil science issues, thus the relevance, focusing and background in the knowledge transmitted to the student, depends on the criteria of each teacher.

CHEM: The importance of soils as a part of terrestrial ecosystems and plant development (e.g., nutrient uptake), main soil properties and some practical determinations are enounced (e.g., texture, pH). Critical agricultural issues are also discussed, including: i) Fertilization and plant growth, such as the use of antifreeze, as well as drought and salinity (case of Lluta and Azapa valleys in Northern Chile); mining for fertilizer production (e.g., the case of saltpeter- "caliche"), sustainable fertilization approach (e.g., use of radioisotopes and isotopes in agriculture), ii) acid rain and soil acidification; iii) combustion processes (e.g., wildfires), iv) other anthropogenic activities responsible for land degradation (e.g., deforestation, hydrocarbon contamination), and v) C footprint focusing on global warming and the relevance of C cycle management (e.g., sustainable land uses) SOC stabilization (e.g., C sequestration) for climate change mitigation.

PHYS: Lessons deal with some earth-shape aspects such as of volcanic ash derived pedogenesis, rock weathering, sediment transport, natural or anthropogenic soil erosion agents (e.g., acid rain) also affecting coastal areas are approached. A second broad thematic discussed interactions between soils, plants, and water, and how when they altered by uncontrolled human actions, social economy evolution, lead to soil degradation; particular points discussed are: Deforestation, desertification, soil pollution, soil acidification, industrial human activities, urbanization, climatic change.

SciCitz and CitzEdu: In these courses, the relevance of soils as a major component of terrestrial ecosystems, plant development, water cycle, and food chain web are highlighted. Subsequently, adequate management of agricultural or other land-use changes is crucial. Particular related subjects detected adjacent to climate change were addressed, including massive deforestation, excessive use of pesticides, soil pollution, agricultural burning, water-drought management, desertification, and enlargement of C footprint, among other non-agricultural human activities (e.g., urbanization). Additionally, SciCitz considers other relevant subjects, including soil decontamination by bioremediation techniques, composting, and risks from geologic-based disasters.

Thematic integration of topics into educational goals and categories

Based on considered educational goals and pedagogic categories grouping soil knowledge across educational levels, core curricula are mainly offered in the 3rd and 6th grades of ES and 1st grade of HS, although virtually no soil-information is provided in the 2nd and 4th grades of HS (Figures 2 and 3). A description of key aspects addressed per educational goal is outlined as follows:

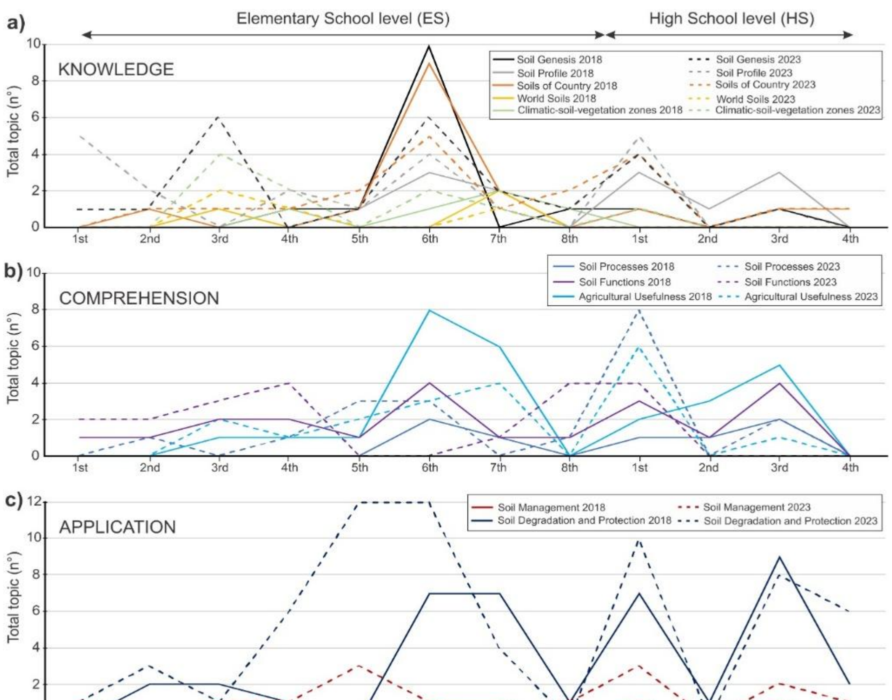


Figure 3. Topic distribution by grade and school level according to analyzed categories knowledge (a), comprehension (b), application (c), and others (d).

Knowledge. Fundamentals on soil science information represented 30.64% of the core curricula for 2018, which increased by 2.1% for 2023. Regarding educational goals within this basic category. i) Soil genesis: Base on the number of topics, the contents increased by +144.4% for the 2018-2023 period (+144.4% from now on for this section); major topics were soil concept, soil weathering and soil formation processes; multi-scale composition and relevance of soils; effects of anthropopedoturbation, zonal-azonal-intrazonal soils; generalities on pedogenesis of Andisols and Histosols. Moreover, despite no explicit soil classification system is quoted, the USDA soil taxonomy system was adopted since 1960 officially nationwide (Salazar et al., 2022) and the use of North American school concepts (e.g., Jenny's model, Klinka's organic horizons classification) are mentioned in textbooks, which is consistent with Chilean scientific literature and academia. ii) Soil profile (+53.9%): Main topics were plant anchorage; mineral composition of aridic based soils; soil profile description of main components; inherent properties of calcareous soils; main bio-physico-chemical soil properties: Color, texture, water holding capacity-permeability, organic matter, cation exchange capacity, including practical determinations of some of them (e.g., texture, pH); density fractionation of soil minerals. iii) Soils of the country (-18.8%): Principal subjects addresses were those linking the evolution of agricultural practices to social evolution from particular contexts of original societies (e.g., Mapuches and the Ñuke concept, involving soil rest periods between cultivation cycles and minimal soil disturbance by the use of hole-making tools named kalla for planting; soil conservation practices such as terracing by Atacameños and Quechua; crop associations/agroforestry based practices by Rapa Nui) to mechanized post-Hispanic period and the introduction of mechanization and intensive agriculture. iv) World soils (+33.3%): This educational goal remained as least addressed in the entire curricula, mentioned as secondary subject during lessons on the rise and agricultural implications for Greek, Roman, Aztec, Mayan, and Inca civilizations. v) Climatic-soil-vegetation zones (+100%): Despite the observed contents increased, still very limited information is provided on this educational goal. However, clear insights on the relationships between climatic variations across nationwide physical geography and ecosystems-natural resources, generating diverse agronomic possibilities are mentioned (e.g., agriculture in Mediterranean climate, effects of Andean volcanic activity on soils).

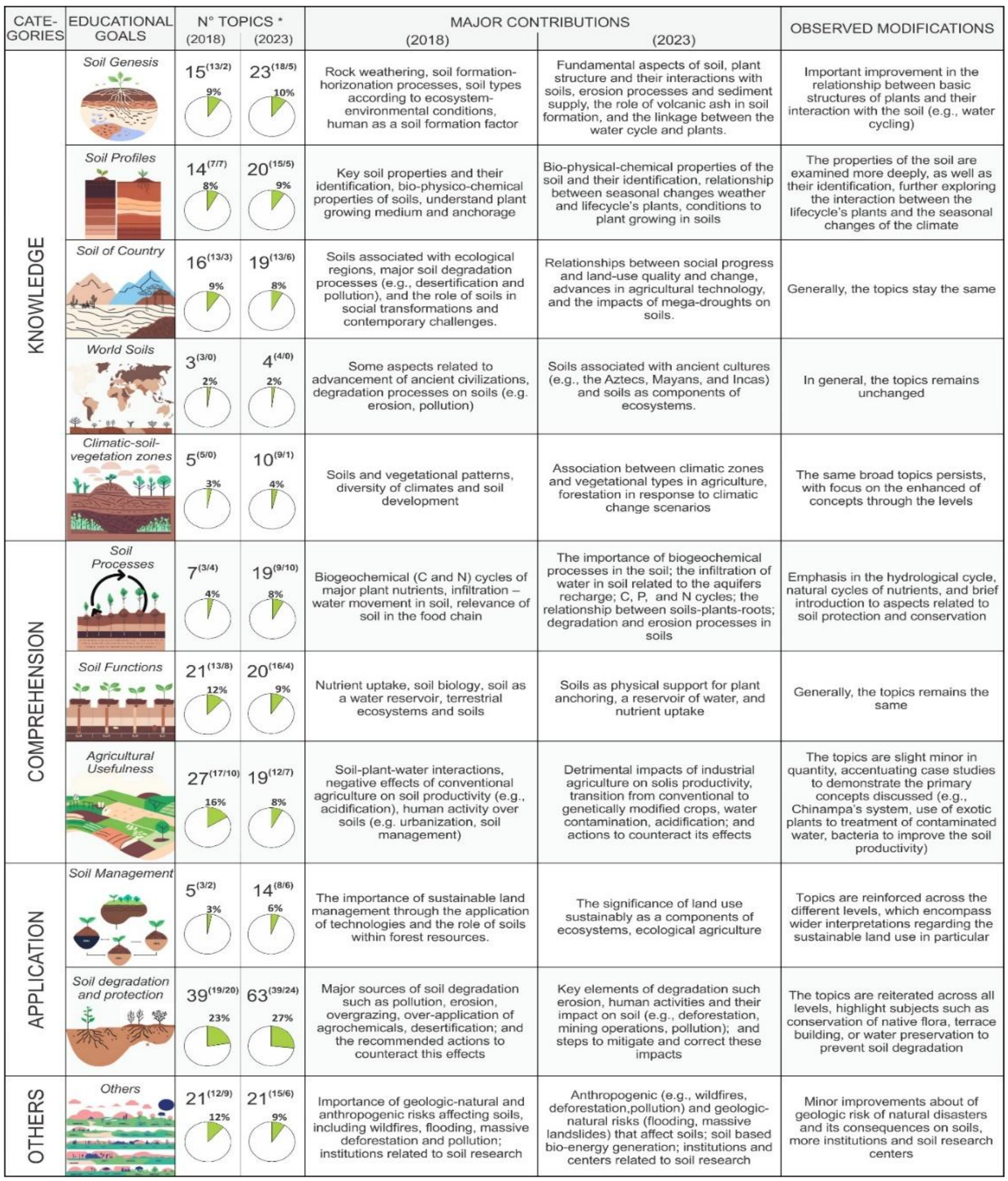
Comprehension. In this secondary category, educational goals significantly impact how students relate soil properties and variability to their ecosystem functions and productive capacities/limitations. Particular changes revealed a decrease in total concepts, passing from the most prevalent in 2018 curricula with 31.8% of total information to becoming last with 25% in 2023. Regarding educational goals in this category: vi) Soil processes (+171.4%): Primary topics were soil-plant-atmosphere relationships and the cycling of the most critical terrestrial nutrients. For instance, the importance of bioturbation on soil water storage-movement as a critical part of hydrologic cycle (e.g., groundwater recharge); relevance of photosynthesis/C-fixation as precursor of soil organic matter; N cycle/N-fixation and the earthbound nature of P cycle. vii) Soil functions (0%): Central concepts highlighted the crucial role of soils for terrestrial to agrosystem levels for biomass to plant production. Particular topics included the soil as physical medium for plant anchoring; linkage between vascular plant architecture and soils; root mechanisms for nutrient uptake and transport; animal habitat-shelter; water reservoir. viii) Agricultural usefulness (-29.6%): This educational goal largely concerned the evolution and expansion implications of agriculture as well as relevant legislative frame (e.g., National Agrarian Reform), agricultural Regions (e.g., central valley) and specific land management practices. Such contents include soil quality and the effects of intensive agriculture in soil nutrient management, composting, organic fertilizers, bio-fertilizers (e.g., bacterial inoculation or usage of *Lessonia spicata* algae), effects of variations of soil pH and crop type potentialities (e.g., saline soils, acid rain-soil acidification).

Application. In this set of tertiary educational goals, students understand environmental implications of soil. Over the analyzed period, this category became with the highest contribution to the total curriculum, rising from 25.4% in 2018, to 33.2% in 2023. Concerning the two educational goals: ix) Soil management (+ 180%): Central topics emphasize the importance of sustainable land uses, including organic agriculture (e.g., organic fertilizers utilization); the importance of appropriate fertilization plans to avoid adverse ecological issues (e.g., eutrophication); complementary practices for water acquisition in dryland farming systems by "mist catchers". x) Soil degradation and protection (+ 61.5%): This educational goal is substantial in the core curricula for both analyzed periods. The contents addressed comprise and overview of the combined effects of climatic emergence and land degradation through diverse cause-effect-possible solution thematic. Among the most recurrent, we observed associations of deforestation, mining, pollution and/or urbanization processes and the consequent losses of native flora and fauna, which may be protected through sustainable land uses and the disadvantages to awareness on the introduction of exotic species (e.g., *Castor canadensis* in Tierra del Fuego);

multidimensional causes of soil degradation (e.g., desertification) focused on erosive degradation types (e.g., overgrazing, monocultures, mechanization overloading) and soil conservation/reclamation practices (e.g., terracing); intensive agriculture in the context of climate change; effects of acid rain and over-fertilization on soils; wetlands protection; the concept of C-footprint.

Others. Information for this complementary category showed no variation; however, when weighted its curricular impact, a temporal decline of 3.1% was observed. However, different interdisciplinary or institutional aspects of soil science not previously discussed were included.

A summary highlighting the main curricular main contributions by category/educational goals and temporal shifts is presented in Figure 4.



CATEGORIES	EDUCATIONAL GOALS	N° TOPICS * (2018)	N° TOPICS * (2023)	MAJOR CONTRIBUTIONS (2018)	MAJOR CONTRIBUTIONS (2023)	OBSERVED MODIFICATIONS
KNOWLEDGE	Soil Genesis	$15^{(13/2)}$ 9%	$23^{(18/5)}$ 10%	Rock weathering, soil formation-horizonation processes, soil types according to ecosystem-environmental conditions, human as a soil formation factor	Fundamental aspects of soil, plant structure and their interactions with soils, erosion processes and sediment supply, the role of volcanic ash in soil formation, and the linkage between the water cycle and plants.	Important improvement in the relationship between basic structures of plants and their interaction with the soil (e.g., water cycling)
	Soil Profiles	$14^{(7/7)}$ 8%	$20^{(15/5)}$ 9%	Key soil properties and their identification, bio-physico-chemical properties of soils, understand plant growing medium and anchorage	Bio-physical-chemical properties of the soil and their identification, relationship between seasonal changes weather and lifecycle's plants, conditions to plant growing in soils	The properties of the soil are examined more deeply, as well as their identification, further exploring the interaction between the lifecycle's plants and the seasonal changes of the climate
	Soil of Country	$16^{(13/3)}$ 9%	$19^{(13/6)}$ 8%	Soils associated with ecological regions, major soil degradation processes (e.g., desertification and pollution), and the role of soils in social transformations and contemporary challenges.	Relationships between social progress and land-use quality and change, advances in agricultural technology, and the impacts of mega-droughts on soils.	Generally, the topics stay the same
	World Soils	$3^{(3/0)}$ 2%	$4^{(4/0)}$ 2%	Some aspects related to advancement of ancient civilizations, degradation processes on soils (e.g. erosion, pollution)	Soils associated with ancient cultures (e.g., the Aztecs, Mayans, and Incas) and soils as components of ecosystems.	In general, the topics remains unchanged
	Climatic-soil-vegetation zones	$5^{(5/0)}$ 3%	$10^{(9/1)}$ 4%	Soils and vegetational patterns, diversity of climates and soil development	Association between climatic zones and vegetational types in agriculture, forestation in response to climatic change scenarios	The same broad topics persists, with focus on the enhanced of concepts through the levels
COMPREHENSION	Soil Processes	$7^{(3/4)}$ 4%	$19^{(9/10)}$ 8%	Biogeochemical (C and N) cycles of major plant nutrients, infiltration – water movement in soil, relevance of soil in the food chain	The importance of biogeochemical processes in the soil; the infiltration of water in soil related to the aquifers recharge; C, P, and N cycles; the relationship between soils-plants-roots; degradation and erosion processes in soils	Emphasis in the hydrological cycle, natural cycles of nutrients, and brief introduction to aspects related to soil protection and conservation
	Soil Functions	$21^{(13/8)}$ 12%	$20^{(16/4)}$ 9%	Nutrient uptake, soil biology, soil as a water reservoir, terrestrial ecosystems and soils	Soils as physical support for plant anchoring, a reservoir of water, and nutrient uptake	Generally, the topics remains the same
	Agricultural Usefulness	$27^{(17/10)}$ 16%	$19^{(12/7)}$ 8%	Soil-plant-water interactions, negative effects of conventional agriculture on soil productivity (e.g., acidification), human activity over soils (e.g. urbanization, soil management)	Detrimental impacts of industrial agriculture on solis productivity, transition from conventional to genetically modified crops, water contamination, acidification; and actions to counteract its effects	The topics are slight minor in quantity, accentuating case studies to demonstrate the primary concepts discussed (e.g., Chinampa's system, use of exotic plants to treatment of contaminated water, bacteria to improve the soil productivity)
APPLICATION	Soil Management	$5^{(3/2)}$ 3%	$14^{(8/6)}$ 6%	The importance of sustainable land management through the application of technologies and the role of soils within forest resources.	The significance of land use sustainably as a components of ecosystems, ecological agriculture	Topics are reinforced across the different levels, which encompass wider interpretations regarding the sustainable land use in particular
	Soil degradation and protection	$39^{(19/20)}$ 23%	$63^{(39/24)}$ 27%	Major sources of soil degradation such as pollution, erosion, overgrazing, over-application of agrochemicals, desertification; and the recommended actions to counteract this effects	Key elements of degradation such erosion, human activities and their impact on soil (e.g., deforestation, mining operations, pollution); and steps to mitigate and correct these impacts	The topics are reiterated across all levels, highlight subjects such as conservation of native flora, terrace building, or water preservation to prevent soil degradation
OTHERS	Others	$21^{(12/9)}$ 12%	$21^{(15/6)}$ 9%	Importance of geologic-natural and anthropogenic risks affecting soils, including wildfires, flooding, massive deforestation and pollution; institutions related to soil research	Anthropogenic (e.g., wildfires, deforestation,pollution) and geologic-natural risks (flooding, massive landslides) that affect soils; soil based bio-energy generation; institutions and centers related to soil research	Minor improvements about of geologic risk of natural disasters and its consequences on soils, more institutions and soil research centers

Figure 4. Principal concepts and temporal differences observed by soil science branches-categories and educational goals. $N^{(ES/HS)}$; N: total books, ES: elementary school, HS: high school. The circular charts represent percentage of each total from total curricula for each respective year.

The results are in concordance with tendencies in different countries, according to Brevik et al., 2021, who analyzed soil science education in Brazil, Canada, Japan, and USA, and the results revealed that most programs remain dominated by a traditional classroom-laboratory based approach, often reflecting a mono-disciplinary perspective that limits a holistic understanding of soils and their functions. In contrast, to the recent implementation of innovative strategies such as problem-based learning and digital technology. This trend is particularly notable in Brazil, where those last initiatives have strengthened soil education curricula for scholars, ranking among the best worldwide (Charzyński et al., 2022).

Soil information coefficients (SICs)

After a comprehensive information-quality assessment and the relevance to particular educational goals (Figures 5 and 6), we detected a high variability in conceptual weightiness. Therefore, it is quite relevant to mention that the frequency when "soil" and adjacent appeared does not necessarily imply a fully conceptual development, but different thematic impacts, from being a central subject or weakly significant to vaguely quoted (e.g., sea soil instead of seafloor; rock layer instead of outcrop, D horizon instead of R horizon), besides, some graphics such as soil profile (6th NC, 2023), which did not represent the central ideas expressed. The details of each information quality group are listed in Figure 5 as scores group (SG; min: 0, max: 3); Figures 6a-6b as soil information coefficients to ES and HS (SIC; min: 0 and max: 35), and Figures 6c and 6d as total soil information coefficients (SIC_T; min: 0 and max: 25). However, they did not appear until sixth and fifth grades of ES in 2018 and 2023, respectively (Figures 6a, 6b).

a) Score group to 2018

CATEGORIES	SCHOOL LEVELS	Score for ES								Score for HS			
	EDUCATIONAL GOALS	1st	2nd	3rd	4th	5th	6th	7th	8th	1st	2nd	3rd	4th
KNOWLEDGE	Soil Genesis	0	0	0	1	1	3	0	1	1	0	1	0
	Soil Profile	0	0	1	0	1	1	1	0	1	1	1	0
	Soils of Country	0	1	0	0	1	3	1	0	1	0	1	1
	World Soils	0	0	1	0	0	0	1	0	0	0	0	0
	Climatic soil-vegetation zones	0	0	0	1	0	1	1	1	0	0	0	0
COMPREHENSION	Soil Processes	0	0	0	0	0	1	1	0	1	1	1	0
	Soil Functions	1	1	1	1	1	2	1	1	1	1	2	0
	Agricultural Usefulness	0	0	1	1	1	2	2	0	1	1	2	0
APPLICATION	Soil Management	0	0	0	1	0	1	1	0	1	0	1	0
	Soil Degradation and Protection	0	1	1	1	0	2	2	1	2	1	3	1
OTHERS	Others	0	0	1	0	0	2	1	1	2	0	2	0
	sum	1	3	6	6	5	18	12	5	11	5	14	2
	min	0	0	0	0	0	0	0	0	0	0	0	0
	max	1	1	1	1	1	3	2	1	2	1	3	1
	mean	0.1	0.3	0.5	0.5	0.5	1.6	1.1	0.5	1	0.5	1.3	0.2

b) Score group to 2023

CATEGORIES	SCHOOL LEVELS	Score for ES								Score for HS			
	EDUCATIONAL GOALS	1st	2nd	3rd	4th	5th	6th	7th	8th	1st	2nd	3rd	4th
KNOWLEDGE	Soil Genesis	1	1	2	0	1	2	1	1	2	0	1	0
	Soil Profile	2	1	0	1	1	2	1	0	2	0	0	0
	Soils of Country	0	1	1	1	1	2	1	1	2	0	1	1
	World Soils	0	0	1	1	0	0	1	0	0	0	0	0
	Climatic soil-vegetation zones	0	0	2	1	0	1	1	0	1	0	0	0
COMPREHENSION	Soil Processes	0	1	0	1	1	1	0	1	2	0	1	0
	Soil Functions	1	1	1	2	0	0	1	2	2	0	0	0
	Agricultural Usefulness	0	0	1	1	1	1	2	0	2	0	1	0
APPLICATION	Soil Management	1	0	1	1	2	1	0	1	1	0	1	1
	Soil Degradation and Protection	1	1	1	2	3	3	2	0	3	0	3	2
OTHERS	Others	1	1	1	1	1	1	1	1	1	0	1	1
	sum	7	7	11	12	11	14	11	7	18	0	9	5
	min	0	0	0	0	0	0	0	0	0	0	0	0
	max	2	1	2	2	3	3	2	2	3	0	3	2
	mean	0.6	0.6	1	1.1	0.9	1.3	1	0.6	1.6	0	0.8	0.5

Score group of information-quality
0: no available information; **1**: scarce information; **2**: some information; **3**: complete information

Figure 5. Scores group (SG) attained according to occurrence and depth of categories and educational goals. ES: Elementary school levels; HS: high school levels.

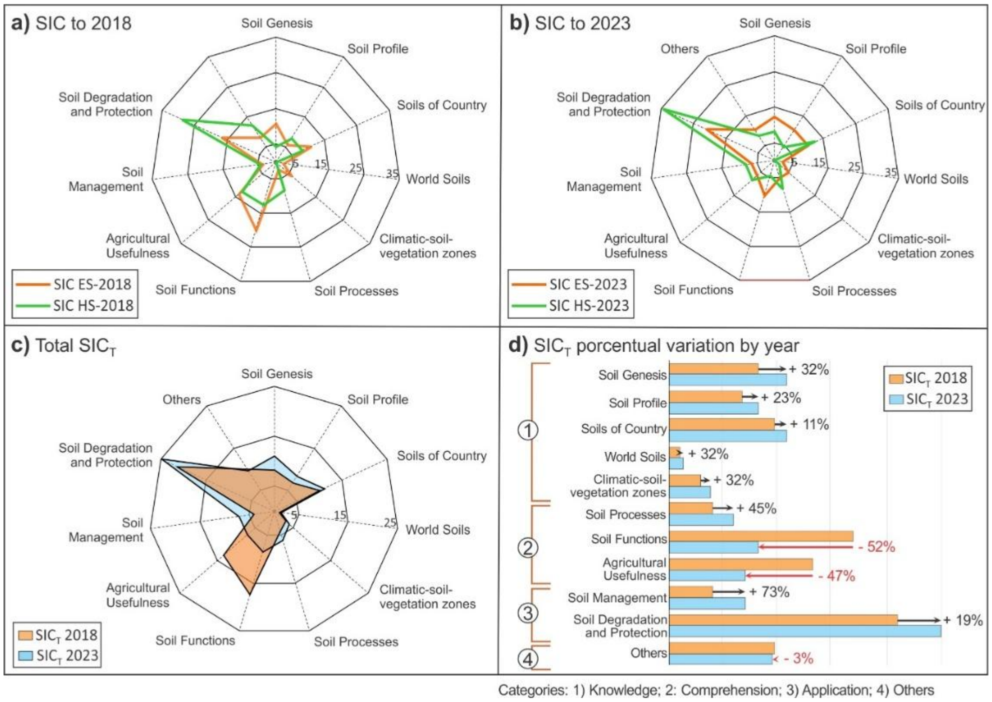


Figure 6. Graphic visualization of soil information coefficients (SICs) grouped by: SIC for 2018 (a), SIC for 2023 (b), Total SIC (SIC_T) (c) and temporary variation in SIC_T (d). ES: Elementary school levels; HS: high school levels. In figure d white circle with number represents categories; 1: knowledge, 2: comprehension, 3: application, 4: others.

First information-quality group may correspond in some extent to primary-central soil science classes-lectures-lessons reached only six thoroughly discussed topics (SG: 3). In addition, all these lessons concern only to the application category-soil degradation and protection educational goal (SIC_T: 22 to 2018, 25 to 2023), except for one in 6th ES 2018, related to knowledge category-soils of country educational goal (SIC_T: 10 to 2018, 11 to 2023), and soil genesis (SIC_T: 8 to 2018, 11 to 2023) (Figures 6c, 6d). The latter suggests a remarkable dominance of environmental climatic-emergence in the overall curricula, which is consistent with single topic recount (section 3.4). Second information-quality group, 30 educational goals were observed (SG: 2) (Figure 5). Although specific ideas related to soil science were developed, they complemented the central lesson-lecture, as: Agricultural usefulness (SIC_T: 14 to 2018, 7 to 2023), soil function (SIC_T: 17 to 2018, 8 to 2023), and soil profile (SIC_T: 7 to 2018, 8 to 2023) (Figures 6c, 6d). Third information-quality group (SG: 1, scarcely conducted soil concepts), reached 166 topics, mainly occurring as very specific-complementary mentions of particular soil aspects within other subjects (e.g., ecosystems, flora) (Figure 5, Figures 6c, 6d). Fourth quality-information group entailed less to no consistent conceptualization (SG: 0), where soil or adjacent terms searched were only mentioned without contributing directly to the main subject area (Figure 5, Figures 6c, 6d).

Another finding included: i) A widespread of quality-information along global curricula, ii) a consistent increase in topics ES 2018→2023 (except for 6th and 7th grades), iii) a virtual absence (≤ 3 topics) of soil science for grades 1st-2nd ES, 4th HS in 2018, and 2nd HS for 2023 (Figure 5, Figures 6a, 6b).

The findings concerning both the distribution of topics within educational goals and their clustering within their respective categories may reflect an inherent complexity of soil science. According to Yus Ramos and Rebollo Bueno (1993), there are some conceptual prerequisites to soil science comprehension, including: Chemical processes, the nature of matter, the concept of energy among other geological (e.g., external geological processes) and biological (notions of microbiology, the cycle of matter, plant nutrition) background. The last suggest a two principal learning stages: i) An empirical approach based on sensorial-perceptible aspects (e.g., Piaget Theory) in early education (1st-4th ES), previous to ii) formal soil science intellectual-learning processes per se, where students already acquired adequate scientific criteria (5th ES hereafter). Another relevant aspect related is the polysemy and vast lexicon of soil sciences and an observed lack of complementary experimental activities/in situ, limiting successful schooling goals.

External literary resources

Concerning complementary literature, four comprehensive external/complementary sources were detected: a) Soil issues “Unraveling soil dilemmas” (Jiménez et al., 2024); b) modules with an investigative approach – SOIL (Acuña et al., 2020); both intended for educators and students (Table 3), developed in collaboration between the MINEDUC and the Pontificia Universidad Católica de Valparaíso and Universidad de Tarapacá universities, respectively, c) “Adventures below ground” (Fuentes and Huerta, 2010) and “Eco-leaders: Innovative strategies to instill love for the environment” (Vliegenthart, 1998) (Table 4).

Particularly, alternative literature observed and examined in some detail part of the originally considered topics, also including complementary activities such as field trips, sample collection-handing and analytical determinations, thus becoming a significant complementary pedagogical tool in the soil teaching-learning processes for both ES and HS levels and even general audiences.

Table 4. External literary resources relevant to soil science. Note: Textbook [(A)] does not address soils of the country, world soils, climatic–soil–vegetation zones, or soil management, whereas Textbook [(B)] lacks content related to climatic–soil–vegetation zones.

Source	Contents according to evaluated topics and categories	Comments
Adventures below ground[(A)]	Educational contents were organized into four dimensions. **Knowledge** covered soil genesis, formation processes, the three-phase soil system, and master horizons. **Comprehension** emphasized soils as part of the critical zone, their functions as plant growth media and multiscalar habitats, and the role of soil organic matter. **Application** focused on soil degradation and protection, highlighting ecosystem services and soil buffering functions. **Additional topics** addressed analytical and field methodologies for soil characterization, biological assessment, and erosion evaluation, together with know-how activities such as soil microcosms and monoliths.	The textbook is divided into two parts: Soil concepts-properties and practical activities, where: i) Soil concepts-properties include a clear soil concept, soil forming factors, basic pedogenic processes and soil functions, and ii) practical activities: guide to promote know-how skill in both, abiotic and biological properties
Eco-leaders: innovative strategies to instill love for the environment[(B)]	Educational contents were structured into four dimensions. **Knowledge** covered soil formation, bioturbation, national and global soil contexts, and desertification. **Comprehension** emphasized texture-controlled nutrient and water dynamics, the role of organic matter, and links between agriculture, water stress, and desertification. **Application** focused on soil management and degradation, including reforestation, nitrogen fixation, composting, soil reclamation, and major drivers such as erosion, wildfires, urbanization, and compaction. **Additional topics** addressed soil–landscape relationships and urban and peri-urban land-use planning within administrative and legal frameworks.	This textbook chapter addresses historical legislative changes related to land use and management and their direct implications for soils. It also proposes a wide range of practical activities, including outdoor and recreational activities.

Recommended complementary activities

In addition to literary resources, the National Commission for Scientific and Technological Research (CONICYT) through its National Program for the Dissemination and Appreciation of Science and Technology (Explora Program), regularly conduct activities of scientific dissemination in coordination with research centers and their staff (e.g., postgraduate students). From this perspective, establishing permanent spaces for outreach, dialogue, and socio-territorial engagement is essential to foster territorial awareness and to integrate soil science education from early educational stages. Incorporating field-based and outdoor research activities, tailored to different age groups (Table 5), is particularly important. Within this framework, the use of contemporary digital tools—such as artificial intelligence, advances in geographic information systems, and multimedia resources including digital and 3D models—can enhance student engagement and support a more dynamic understanding of soil-related concepts. On the other hand, within educational curricula, soil science needs to align with contemporary environmental disciplines, adding critical aspects such as climate change effects and future perspectives, water cycles and aquifer recharge, alternative energy sources, and urban and industrial contamination. To address the limited integration of soil science topics into educational contexts and the broad social context (which certainly also depends on their low visibility in current legislative agendas), recent initiatives have aimed at the development of a Soil Framework Law (Cámara de Diputados y Diputadas, 2021) (https://www.camara.cl/legislacion/ProyectosDeLey/tramitacion.aspx?prmID=15204&prmBOLETIN=14714-01). Such government efforts will strengthen soil science education at all levels and eventually play a critical role in shaping future policies supporting the sustainable management of Chilean soils.

Table 5. Soil knowledge-oriented interactive and outdoor learning activities suggested by age range. Note 1: Although public access to natural areas is allowed nationwide, soil-related activities are best conducted in spring-summer due to restrictive winter weather conditions. Note 2: Potential health risks should be considered, including venomous spiders such as *Loxosceles laeta* (Canals and Solís, 2014), soil- and dust-borne pathogens transmitted via wounds, inhalation, or ingestion (Steffan et al., 2020), and ticks (*Ixodida*) associated with encephalitis and *Lyme borreliosis* (Goldstein et al., 2018).

Source	Contents according to evaluated topics and categories	Comments
5-10	Play based scheme as a key component of learning processes, including: Emulative or edible cooking activities illustrating soil environment, mud sensory bin (e.g., soil moisture and consistence)-dirt lab, seed sprouting with different soil based-substrates, stories, drama, songs, riddles, puzzles, board games, video games/media sources; excursions-observations (rocks and soil aggregates), simple experiments and art, creative artwork, gardening, assisted soil pit observations, observation of life forms and identification of bioturbation processes (e.g., krotovinas)	Vliegenthart, 1998; Lybrand, 2023; Jimenez et al., 2024
11-15	Gardening, recreation, painting, board games, media sources; assisted soil pit observations and exploration (soil description) and one-site measurements, handling and primary classification of textural classes and life forms, wormery, simple soil	Lybrand, 2023; Jiménez et al., 2024
> 16	Soil organic matter qualitative approach (e.g., Pfeiffer soil chromatograms), remote sensing principles, assisted soil pit observations, description, sampling, one-site measurements (e.g., color, texture) and the use of instruments for pedometrics, recognition and formal classification of life forms and soil classification principles, learning on soil analytical techniques, soil survey and soil mapping	Vliegenthart, 1998; Fisher et al., 2005; Jiménez et al., 2024

CONCLUSIONS

After examining the literature provided by Ministry of Education which is applicable to more than 90% of educational centers/students enrolled in elementary and high school, for the years 2018 and 2023, a total of 127 available textbooks concerning soil learning were detected. A remarkable increase of 26.71% in terms of literary resources (56 to 71, same period) was observed. After separating bulk information into knowledge, comprehension, application, and others categories and their associated particular educational goals (e.g., specific soil science topics) to discriminate learning competencies, we detected remarkable shifts on each period analyzed. In 2018, only soil degradation and protection, agricultural usefulness and soil functions reached 51% of core curricula, which suggests an extensive priority towards sensitizing young people on food and soil security issues. In contrast, in 2023, a diversification of content was observed, where seven educational goals reached ~ 9% of the total curricula, and soil degradation and protection were prevalent overall syllabus 27%, which probably indicates a new sustainable development approach in which fundamentals of soil science, essential to intellectualize soil variability to identify-discern specific capabilities-issues and more suitable management under specific contexts are outlined. Further research should include the monitoring soil-related programs over time, an analysis of literary sources in private education, to promote extensive teacher training courses, outdoor learning and workshops.

Author contribution

Conceptualization: R.G.J., J.O., M.P., E.P., M.S., M.C., N.S. Methodology: R.G.J., J.O., M.P., M.K-O., P.S.C., T.E., W.E., E.P., I.F-C., E.Z., MSc., A.R., M.S., M.C., N.S. Software: R.G.J., J.O., M.K-O., S.P-C. Validation: R.G.J., J.O., M.P., B.S-L., W.E., S.P-C., I.F-C., E.Z., MSc., A.R., M.S. Formal analysis: R.G.J., J.O., M.K-O., P.S.C., P.N., B.S-L., T.E., W.E., E.P., S.P-C., I.F-C., E.Z., MSc., A.R., M.S. Investigation: R.G.J., J.O., M.K-O., P.S.C., B.S-L., T.E., W.E., S.P-C., MSc., M.C., N.S. Resources: R.G.J., J.O., M.P. Data curation: R.G.J., J.O., M.P., M.K-O., P.S.C., P.N., B.S-L., T.E., W.E., E.P., S.P-C., I.F-C., E.Z., MSc., A.R., MS. Writing-original draft: R.G.J., J.O., M.K-O., W.E., MSc. Writing-review & editing: R.G.J., J.O., M.P., P.N., E.P., S.P-C., I.F-C., E.Z., MSc., A.R., MS., M.C., N.S. Visualization: R.G.J., J.O., P.N., MSc. Supervision: M.P., I.F-C., M.S., M.C., N.S. Project administration: R.G.J., J.O., M.S. Funding acquisition: M.P., M.S. All co-authors reviewed the final version and approved the manuscript before submission.

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