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From Earth Observation Access to Spatial Evidence Literacy: Evidentiary Alignment in General-Education Geoscience Communication

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Abstract

As environmental challenges become increasingly complex, general education in higher education faces the challenge of preparing students to interpret and communicate environmental information across disciplinary boundaries. Earth Observation (EO) data and geospatial technologies are increasingly available through open archives, cloud platforms, and web maps. However, the expansion of access to spatial data does not automatically enable learners to understand how such data are interpreted, evaluated, and transformed into evidence. This study examines how EO-integrated general education curricula function as sites of curriculum-based geoscience communication, where expert EO and geospatial knowledge is transformed into accessible, communicable, and assessable forms of spatial evidence for non-specialist undergraduates. Using qualitative document analysis, we examine publicly available curriculum materials from 20 undergraduate EO-integrated general education courses in selected APEC higher-education contexts. We analyze the transformation of EO and geospatial knowledge across six curricular dimensions, namely course positioning, learning outcomes, project tasks, scaffolding, assessment, and evidentiary expectations, as well as the role of evidentiary alignment in shaping this transformation. The analysis identifies four patterns of evidentiary alignment, ranging from courses that primarily introduce satellite imagery and geospatial applications to those that require evidence-based reasoning with spatial data. Most sampled courses demonstrate intermediate levels of evidentiary alignment, asking students to interpret spatial patterns or produce maps and Story Maps. These tasks connect EO and geospatial data to climate, sustainability, hazards, urban change, Digital Earth, or geospatial literacy, but evidentiary expectations remain rarely explicit in publicly available documents, especially regarding data quality, uncertainty, scale, validation, and limitations. By extending the understanding of geoscience communication beyond the transmission of scientific information, this study highlights evidentiary alignment as a curriculum-level perspective for examining how curricula transform EO and geospatial knowledge into spatial evidence and create opportunities for developing spatial evidence literacy among non-specialist learners.

Keywords: EO-integrated general education; geoscience communication; spatial evidence literacy; evidentiary alignment; curriculum recontextualization

1. Introduction

The IPCC (2023)[1] and UNDRR (2022)[2] identify the intensification of climate-related

[1] Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (H. Lee & J. Romero, Eds.). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

[2] Global assessment report on disaster risk reduction 2022: Our world at risk- transforming governance for a resilient future. United Nations Office for Disaster Risk Reduction.

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and systemic risks, from extreme weather and sea-level rise to food, water, and ecosystem insecurity. Because these risks are unevenly distributed across places and communities, environmental governance and decision-making increasingly require spatial evidence to understand environmental changes, vulnerabilities, and resource-management challenges (Wilhelmi et al., 2024). These forms of evidence are often derived from spatial information, including satellite imagery, Earth Observation (EO) datasets, and geospatial products used in climate resilience assessment and resource management (Codyre et al., 2025; Kumar et al., 2024). However, the growing availability of EO and geospatial data does not automatically translate into meaningful evidence. Beyond access and visualization, such data must be accompanied by contextual interpretation, critical evaluation, and responsible communication to support evidence-based reasoning. Addressing this challenge requires spatial evidence literacy, defined in this study as the capacity to interpret, evaluate, and communicate spatial data as evidence rather than merely as visual representations. Such literacy is particularly relevant for undergraduates who will encounter spatial information in civic, professional, and environmental contexts. General education (GE) courses provide an important context for developing this capacity because they can extend foundational spatial literacy beyond specialist geoscience or geospatial technology training, while connecting EO and geospatial knowledge with broader undergraduate learning and societal concerns (Tsou & Yanow, 2010). This broader educational role is also important because geoscientific evidence now circulates beyond specialist communities through public discussions, media representations, and environmental decision-making processes (Illingworth et al., 2018; Onstad & van der Flier-Keller, 2025).

While the expansion of EO infrastructures has created new opportunities for higher-education teaching, it has also raised questions about how learners develop the capacity to interpret and reason with increasingly complex EO and geospatial data as evidence. Open EO infrastructures and platforms, such as the Copernicus Data Space Ecosystem [3]and Digital Earth Pacific[4], have expanded access to satellite imagery, geospatial datasets, and decision-ready products. Existing research has shown that cloud-based learning environments and structured instructional modules can support students, including non-specialist undergraduates, in engaging with EO and geospatial data as well as remote sensing applications (Wagemann et al., 2022; Callejas et al., 2023). However, meaningful engagement with EO and geospatial data involves more than obtaining and processing datasets; as research on geospatial data literacy and non-specialist use of satellite data suggests, it also requires learners to interpret data, evaluate uncertainty, and reason with spatial information as evidence (Juergens & Redecker, 2023; Gaddipati et al., 2025). Developing spatial evidence literacy

https://www.undrr.org/gar/gar2022-our-world-risk-gar
[3] Copernicus Data Space Ecosystem. (2025). Copernicus Data Space Ecosystem annual report 2024. https://dataspace.copernicus.eu
[4] Digital Earth Pacific. (2025). Digital Earth Pacific factsheet. https://unfccc.int/sites/default/files/resource/Digital%20Eath%20Pacific%20Factsheet.pdf

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therefore depends on curriculum structures that make evidentiary expectations explicit, including how students interpret EO and geospatial data, consider uncertainty, justify spatial claims, and communicate evidentiary limitations. Yet limited attention has been paid to how GE curricula organize opportunities for students to interpret, evaluate, and communicate spatial evidence.

To address this gap, this study examines how EO and geospatial data are recontextualized as spatial evidence within GE curricula for non-specialist undergraduates, focusing on how curricula transform accessible spatial information into opportunities for evidence-based reasoning. This study treats EO-integrated GE as a form of curriculum-based geoscience communication, in which EO and geospatial data are selected, organized, and communicated for broader undergraduate audiences. It focuses on selected APEC higher-education settings as an exploratory context for examining how EO and geospatial knowledge are incorporated into GE curricula addressing climate, sustainability, and related societal challenges. This regional focus is also consistent with APEC's emphasis on higher education, sustainability, and evidence-informed decision-making across disciplines (APEC, 2025). Publicly available curriculum documents, including syllabi, handbooks, and official course catalog pages, provide visible representations of the formal intended curriculum through course aims, learning outcomes, tasks, and assessment descriptions. The analysis therefore focuses on intended curriculum design rather than classroom practice.

Guided by this focus, the study addresses the following research questions:
(1) How do publicly documented GE curricula recontextualize EO and geospatial data for non-specialist undergraduates?
(2) How do they align learning outcomes, tasks, scaffolding, and assessment to support spatial evidence literacy?
(3) What patterns of evidentiary alignment are visible across the sampled courses?

By examining GE curricula, this study shifts attention in geoscience communication and EO education research from access to EO and geospatial data toward the curricular processes through which such data are transformed into spatial evidence for non-specialist learners. It asks not only whether non-specialist undergraduates encounter such data, but how curricula make visible the standards by which they are interpreted, claims are justified, and limitations are acknowledged.

2. Literature Review and Theoretical Framework

2.1 Literature Review

Research on geoscience communication and geospatial education progressively emphasizes the need to communicate geospatial knowledge beyond specialist communities, particularly as these forms of knowledge become more connected with

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environmental and societal challenges (Rodrigues et al., 2023). GE provides an important curricular setting for engaging students from diverse disciplinary backgrounds and connecting learning with broader socio-environmental concerns (AAC&U, 2025; Nusche, 2024). Within this broader educational context, EO and geospatial data can extend geospatial learning opportunities across disciplinary boundaries and support interdisciplinary engagement with environmental issues (Maganini et al., 2025). Such resources serve not only as sources of geospatial data but also as learning resources through which students explore environmental change and develop capacities to interpret spatial evidence (Juergens & Redecker, 2023). Accordingly, EO-integrated GE can be understood as a form of geoscience communication that recontextualizes disciplinary knowledge into forms accessible to broader undergraduate audiences.

EO and Geoscience Communication Beyond Specialist Audiences

The rapid growth of cloud platforms, open EO data, and e-learning infrastructures has made EO and geospatial data more accessible for university teaching (Kovács et al., 2026; Crowley et al., 2023; Bauer et al., 2021). This expansion illustrates a broader trend in geoscience communication, in which such geospatial resources is no longer limited to specialist communities and is increasingly communicated to broader audiences through evidence-based communication (Illingworth et al., 2018; Onstad & van der Flier-Keller, 2025). For general education, this broader communication of EO and geospatial data is important because non-specialist undergraduates encounter environmental and climate issues as citizens, professionals, and decision-makers who must learn how spatial evidence supports public reasoning. Although technical access once limited EO-based teaching, cloud-based platforms and structured learning tools are making access-related barriers less prominent in higher education (Wagemann et al., 2022; Callejas et al., 2023). The more persistent challenge, especially in GE curricula, lies in guiding non-specialist undergraduates who are not trained as geoscientists to interpret and communicate geospatial evidence (Juergens & Redecker, 2023).

EO and geospatial data often gain educational meaning when connected to substantive issues such as environmental change, sustainability, disaster risk, and regional vulnerability. Existing studies show that sustainability and disaster risk topics can be integrated into curricula through place-based problems, local hazard profiles, learning outcome alignment, and geospatial teaching resources (Hurlimann et al., 2024; Smith, 2025; Tyas et al., 2025). However, much of this work remains situated in K-12, teacher education, disciplinary, professional, or skill-intensive contexts, including fields such as engineering, planning, public health, environmental science, and built-environment education (Choudhury & Wu, 2023). From a general education perspective, less is known about how environmental, sustainability, and risk-related issues are pedagogically reformulated into spatial evidence tasks through which non-specialist undergraduates learn to interpret EO and geospatial data as evidence.

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Spatial Data, Maps, and Satellite Imagery as Evidence Communication

To understand how spatial evidence tasks are designed, it is necessary to examine the forms through which students encounter EO and geospatial data. In GE contexts, students often work with maps, satellite imagery, dashboards, and other visual tools rather than raw datasets. These representations serve as communicative artifacts rather than neutral outputs. Choices about scale, projection, classification, and symbolization influence which evidence becomes visible and how it can be interpreted (MacEachren & Kraak, 2001; Monmonier, 2018; Prestby, 2023). Because EO and geospatial data are typically encountered through such mediated representations, students need to understand how these data are generated, selected, and categorized, as well as how visualizations can highlight, simplify, or obscure specific spatial claims (Juergens & Redecker, 2023).

Building on the idea that students need to interpret EO datasets and their visualizations, map-based argumentation explains how maps can act as evidence for spatial claims by connecting spatial representations to warrants (Kunze et al., 2025). Empirical studies of students training to become geography teachers indicate that this evidentiary role is not always recognized. Learners often focus on fundamental map skills and spatial orientation, while paying less attention to the argumentative purpose of maps (Kunze & Budke, 2025). Extensive research on evidence-based reasoning supports this finding, indicating that learners require structured guidance to connect evidence, reasoning, and claims, especially when dealing with complex socioscientific issues (Jimenez et al., 2024).

These studies suggest that EO and geospatial data do not inherently function as evidence. Rather, they become evidence only when learners are supported to interpret their meaning, limitations, and uncertainty. This requires the development of spatial evidence literacy, enabling students to evaluate claims and communicate interpretations grounded in spatial evidence.

Curriculum Recontextualization and Assessment in Geoscience Education

When EO and geospatial data enter undergraduate curricula for non-specialists, they are selectively relocated, refocused, and pedagogically recoded. Bernstein (2000) refers to this process as recontextualization. In geoscience communication, this involves more than just simplifying technical information. It transforms how evidence is presented, scrutinized, and justified for audiences lacking specialized knowledge (Onstad & van der Flier-Keller, 2025).

Studies of Google Earth Engine and modular EO-based learning show that students, including those without extensive technical backgrounds, can engage with EO-based tasks when supported by structured learning environments such as pre-built templates,

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guided exercises, computational notebooks, peer interaction, and feedback (Callejas et al., 2023; Wagemann et al., 2022). Yet procedural scaffolding alone does not guarantee the development of spatial evidence literacy. Students may learn how to follow an EO-based workflow, but still struggle to interpret spatial patterns, justify evidentiary claims, or communicate uncertainty and limitations. Recent work on cross-disciplinary geospatial learning points to the importance of epistemic support alongside procedural support. Ferrara et al. (2024), for example, conceptualize geospatial epistemic discomfort as a productive tension that can arise when learners from different disciplinary backgrounds work with spatial data. Taken together, these studies suggest that non-specialist learners need structured opportunities not only to complete EO-related procedures, but also to understand what counts as appropriate evidence, justified interpretation, and qualified claims.

If EO-integrated GE aims to go beyond mere technical procedures, then designing learning outcomes, tasks, and assessments with evidence-based interpretation is essential. Research on GIS-and remote sensing-supported learning indicates that geospatial technologies can enhance higher-order thinking when integrated into engaging and well-aligned teaching strategies (Yang et al., 2024; Moldamurat et al., 2025). However, this work often focuses on disciplinary or technical aspects, paying less attention to how non-specialists learn to justify claims with spatial evidence.

Assessment plays a crucial role in this transition from technical production to evidence-based interpretation. Vlachopoulos and Makri (2024), in a systematic review of authentic assessment in higher education, contend that traditional testing methods often fail to effectively measure critical thinking or the practical application of knowledge. Zhu et al. (2025) also demonstrate that even within a disciplinary GIS&T capstone, competency-based reflection journals can reveal overlooked abilities such as geospatial thinking, critical reasoning, and formal communication. These findings imply that assessment in EO-integrated GE should go beyond just assessing students' ability to create maps or perform technical tasks. It should also ask whether students can explain what spatial evidence shows, what remains uncertain, and how far a claim based on that evidence can reasonably go.

Existing research indicates that access to EO and geospatial data, environmental and risk-related contexts, and scaffolding can facilitate EO-enabled learning. However, these studies largely focus on technical skills, visualization practices, or disciplinary applications, rather than on how spatial data are transformed into communicable and assessable evidence in general education. As a result, there is limited understanding of how general-education curricula structure EO learning through coordinated learning outcomes, tasks, scaffolding, and assessment to support spatial evidence literacy for non-specialist students. This gap is particularly important from a geoscience communication perspective, where maps, satellite imagery, and geospatial dashboards function not only as instructional tools but also as evidence-bearing communication devices.

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2.2 Theoretical Framework

This study develops the Evidentiary Alignment Framework for Curriculum-Based Geoscience Communication (EAF-CGC), drawing on three complementary perspectives: pedagogic recontextualization (Bernstein, 2000), constructive alignment (Biggs, 1996), and epistemic scaffolding (Reiser, 2004; Quintana et al., 2004). It conceptualizes EO-integrated GE as a process of evidentiary alignment through which EO and geospatial data is transformed into curricularly organized forms of spatial evidence for non-specialist undergraduates. This alignment operates through three interrelated mechanisms: Knowledge Transformation, Task Transformation and Evidence Transformation (see Table 1), which together describe how EO and geospatial data is recontextualized, organized into learning tasks, and scaffolded to support the development of spatial evidence literacy.

Table 1: Evidentiary Alignment Framework for Curriculum-Based Geoscience Communication (EAF-CGC)

Theoretical foundation	Analytical mechanism	Curriculum transformation focus	Coding dimensions
Pedagogic recontextualization	Knowledge transformation	Transformation of disciplinary EO and geospatial data into pedagogically accessible forms of spatial evidence for non-specialist undergraduates	EO course positioning; EO and geospatial integration; contextual framing of environmental themes (e.g., climate change, sustainability, hazards, urban systems, Digital Earth)
Constructive alignment	Task transformation	Alignment of learning outcomes, instructional tasks, and assessment to organize students' engagement with spatial evidence	Learning outcome orientation; task design orientation; assessment alignment toward spatial evidence interpretation and explanation
Epistemic scaffolding	Evidence transformation	Development of epistemic support that enables students to work with spatial evidence under conditions of uncertainty, scale variation, and interpretive limitations	Scaffolding for spatial reasoning; attention to uncertainty, scale, and limitations in spatial evidence interpretation

The EAF-CGC conceptualizes Knowledge Transformation as the curriculum process through which disciplinary EO and geospatial knowledge is recontextualized into pedagogically accessible forms of spatial evidence for non-specialist learners. This transformation reflects Bernstein's (2000) concept of pedagogic recontextualization, in which disciplinary knowledge is selected, reorganized, and reframed within pedagogical discourse rather than directly transferred into classrooms. Drawing on curriculum theorization, the framework further conceptualizes recontextualization as an epistemic process through which curriculum designers negotiate what knowledge is selected, how it is structured, and how it becomes accessible to learners (Hordern, 2021; Hudson et al., 2023; Bratland & El Ghami, 2023).

In EO-integrated GE, this transformation is visible in how satellite imagery, spatial datasets, and remote sensing outputs are reframed as spatial evidence rather than purely technical artifacts. In the context of EO-integrated education, Knowledge Transformation requires that meaningful engagement with EO and geospatial data depends on learners' understanding of data provenance, uncertainty, and interpretive constraints rather than mere exposure to visualization outputs (Juergens & Redecker, 2023; Goodchild, 2004; Keller & Siegmund, 2026). Accordingly, Knowledge Transformation captures how EO and geospatial knowledge is repositioned within curriculum structures. This repositioning transforms EO from disciplinary knowledge into spatial evidence with explicit expectations regarding uncertainty, provenance, and interpretive limitations. Once EO and geospatial knowledge is reframed as spatial evidence, curriculum design must further determine how learners engage with such evidence through learning activities and assessment.

The Framework operationalizes Task Transformation as the curriculum mechanism through which recontextualized EO and geospatial knowledge is structured into learning outcomes, tasks, and assessment designs that require students to engage with spatial evidence. This mechanism builds on constructive alignment theory, which emphasizes coherence between learning outcomes, teaching activities, and assessment as a foundation for effective learning (Biggs, 1996; Biggs & Tang, 2011). However, Constructive alignment alone does not guarantee epistemic engagement with disciplinary knowledge. Within this framework, meaningful learning is understood as requiring students not only to complete aligned tasks but also to participate in the practices of interpreting, evaluating, and using knowledge in contextually meaningful ways (Pazicni et al., 2026; Nieminen & Ketonen, 2024).

From an assessment perspective, Task Transformation incorporates principles of authentic assessment, where learning tasks require students to apply, evaluate, and use knowledge in contextually meaningful situations (Villarroel et al., 2018; Ashford-Rowe et al., 2014; Ajjawi et al., 2024). In addition, Task Transformation incorporates evaluative judgement and student agency as important dimensions of authentic assessment practices in higher education (Zhan et al., 2025). Within EO-integrated curricula, Task Transformation captures whether the alignment of learning outcomes, tasks, and assessment requires evidence-based reasoning with spatial data. Beyond structural coherence, evidentiary alignment requires that learning outcomes, tasks, and assessments make explicit what counts as valid spatial interpretation, justified analytical decisions, and responsible communication of uncertainty.

The final mechanism, Evidence Transformation, focuses on how instructional design provides epistemic support for students to work with spatial evidence under conditions of uncertainty, scale variation, and representational complexity. This mechanism is grounded in epistemic scaffolding theory, which conceptualizes scaffolding as structured support that enables learners to participate in disciplinary reasoning practices beyond their independent capability (Reiser, 2004; Quintana et al., 2004; Lin & Puntambekar, 2025). Rather than functioning as task simplification, scaffolding operates as a mechanism for organizing learners' engagement with core epistemic practices such as interpretation, evaluation, and explanation.

For Evidence Transformation, spatial reasoning is understood as involving more than technical exposure to GIS tools; it requires learners to develop competencies for interpreting spatial representations, reasoning across scales, and applying spatial concepts to analytical problems (Duarte et al., 2022; Hickman, 2023). Accordingly, Evidence Transformation captures how instructional scaffolds support the development of spatial evidence literacy by enabling students to evaluate spatial evidence, interpret data limitations, and construct justified claims based on spatial evidence. It emphasizes that spatial evidence literacy is not an automatic outcome of data exposure but a product of structured epistemic support through which learners develop the capacity to work with spatial evidence.

Taken together, the EAF-CGC conceptualizes evidentiary alignment as a curriculum-level process. Through Knowledge Transformation, Task Transformation, and Evidence Transformation, disciplinary EO and geospatial knowledge is progressively transformed into teachable content, assessable tasks, and learning experiences centered on spatial evidence. These transformations establish explicit expectations for engaging with spatial evidence, structure learning tasks around evidence-based reasoning, and provide epistemic scaffolding for attending to uncertainty, evidence limitations, and justified spatial claims. By coordinating these three transformations, the framework offers an analytical lens for examining how GE curricula organize geoscience communication for non-specialist learners.

3. Methodology

3.1 Research Design

This study adopts qualitative multiple-case study methods and documentary analysis to explore how EO and geospatial data are recontextualized within general education courses for non-specialist undergraduates. The analyzed curriculum materials reveal connections between course positioning, learning outcomes, tasks, assessment, and spatial evidence requirements. We chose publicly available curriculum materials for analysis, as they document formal curriculum planning and assessment arrangements at the institutional level (Bowen, 2009; Yin, 2018). Accordingly, the analysis focuses on intended curriculum rather than classroom delivery or student learning outcomes (Bohm et al., 2024).

All analyses adopt the three-layer model proposed in our theoretical framework, encompassing Knowledge Transformation, Task Transformation, and Evidence Transformation. Using this model as a guideline, we examine how EO and geospatial knowledge is recontextualized, organized into learning tasks, and supported through instructional scaffolding for spatial evidence interpretation and justification.

3.2 Sampling Strategy, Search Procedure, and Case Selection

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A purposive multiple-case sampling strategy was used to identify information-rich GE courses that illuminate how EO and geospatial knowledge are incorporated into curricular structures in selected APEC higher-education contexts (Patton, 2015; Yin, 2018). The sample was drawn from publicly available curriculum documents, including official syllabus, university catalogues, course webpages, teaching handbooks, and general education course lists. Only records with sufficient EO/geospatial content, activities, or assessment information were included.

Case identification combined two complementary procedures: exploratory search and known-item verification (Path A), and systematic keyword searching with staged screening (Path B). Final verification confirmed institutional affiliation, course identity, and sufficient public documentation for qualitative analysis (Bowen, 2009; Booth et al., 2021; Morgan, 2022).

In the exploratory stage, preliminary searches through Google and university websites identified 13 verified course candidates. In the systematic stage, targeted Google searches combining EO and geospatial terms with general education and syllabus-related keywords were conducted on 27-28 April 2026. Retrieved records were manually screened against predefined inclusion criteria: undergraduate-level provision, broad-access/general education orientation, relevance to EO/geospatial learning, APEC-based higher-education delivery, and sufficient public documentation for qualitative analysis.

Courses were excluded if they were major-specific training programmes, lacked substantive geospatial components, provided only overly brief catalogue descriptions, or duplicated records already identified through cross-listing or different academic cycles. Following deduplication and eligibility validation, the final sample consisted of 20 courses: 13 identified through exploratory searching and 7 retained through systematic keyword screening. Detailed search procedures, screening records, and inclusion criteria are provided in Supplement Sect. S1.

Figure 1. Search, screening, and final case-selection workflow

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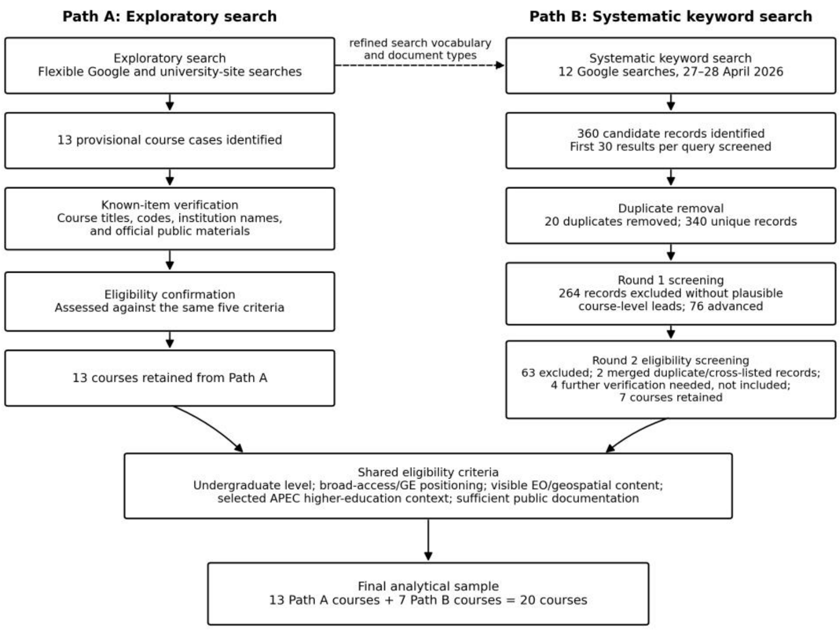

3.3 Coding Framework

Each course serves as the unit of analysis, with coding based primarily on the syllabus and extended by other public documents where available. The three mechanisms were operationalized into coding indicators (Table 2), covering course positioning, EO and geospatial integration, task design and alignment, and scaffolding and evidence rigor.

Table 2: Operationalized coding framework

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Analytical mechanism	Coding dimensions	Analytical focus	Rating criteria
Knowledge transformation	Course positioning; EO and geospatial integration; application context	How EO and geospatial data are recontextualized as general-education content for non-specialist learners.	Strong: explicit GE status and EO/geospatial integration; Partial: implied but not formalized; Not evident: absent or unclear
Task transformation	Learning outcomes; task design; task–assessment alignment	How course design asks students to use EO and geospatial data in evidence-oriented learning tasks.	Strong: explicit spatial evidence interpretation or justification required; Partial: tasks visible but evidence use implied; Not evident: no task or project evidence
Evidence transformation	Scaffolding; evidence reasoning support	How courses support students in interpreting, justifying, qualifying, and communicating spatial evidence.	Strong: explicit scaffolding for uncertainty, interpretation, and evidence justification; Partial: some support implied; Not evident: no support mechanism visible

We applied a three-level rating system: strong, partial, and not evident. For each mechanism, the overall rating reflects the weakest dimension across its coding indicators. Mechanism ratings combine into profiles based on conservative decision rules. Following Biggs (1996), alignment requires coherence across all components; pattern assignment reflects the sequential dependency of knowledge recontextualization, task design, and instructional scaffolding. This produces four observable combinations (see Table 6). Coding decisions were based on documentary evidence, with interpretations grounded in the materials. Detailed coding criteria, decision rules, and analytical matrices are provided in Supplement Sect. S3 (Table S5).

3.4 Coding Procedure and Analysis

This study adopted qualitative content analysis for document coding. We first established a preliminary codebook to clarify coding dimensions and corresponding judgment rules (Schreier, 2012; Saldaña, 2021). All 20 courses were coded by a single researcher through two rounds of analysis. An external expert in geoscience education and curriculum studies reviewed the codebook and sample coding to strengthen consistency and refine decision rules (Reyes et al., 2024). The second round revisited ambiguous and partial cases against the original documents. Given the uneven depth of public course documentation, features not visible in available records were coded as not evident rather than inferred from course titles or general descriptions. Analytic memos maintained an audit trail linking source documents to coding decisions

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(Ahmed, 2024).

We organized all coded data into a matrix to facilitate cross-course comparison. We conducted within-case and cross-case analyses. Within-case analysis examined how individual courses organized content, tasks, scaffolding, and assessment, while cross-case analysis identified common patterns and variations across the sample. We also conducted additional checks to examine whether the four-pattern structure remained stable when partial and not-evident ratings were combined, and cases with limited documentation were excluded.

3.5Trustworthiness and Limitations

Methodological quality was strengthened through transparent coding, conservative evidence assessment, and source archiving. A verification log recorded source links, screening decisions, and final selections to support traceability (Adler, 2022). While these measures strengthen the credibility of the analysis, the research is inherently limited by its exclusive reliance on publicly available curriculum resources. As official archival materials, these documents only outline formal curriculum design intentions, rather than capturing in-class instructional practices or tangible student learning performance. For this reason, the results of this study offer targeted analytical observations of the sampled EO-integrated courses, rather than generalizable conclusions regarding geospatial and EO-related GE across the broader APEC region.

4. Results

4.1 Sample description

The final dataset consists of 20 EO-integrated GE courses drawn from public documents of universities in selected APEC higher-education contexts, with a concentration in the United States (12 courses) and Hong Kong (China) (4 courses); Japan, New Zealand, and Canada each contribute one course. This distribution reflects the purposive sampling strategy and the availability of publicly accessible course documents, rather than representative coverage of APEC higher education. Table 3 provides a complete overview of the sampled courses.

Table 3. Overview of sampled courses

Sample ID	University	Country/Region	Course Title	Pattern
C01	The Hong Kong University of Science and Technology	Hong Kong, China	Monitoring Changing Climate from Space	4
C02	University of Hong Kong	Hong Kong, China	Earth as Seen by Satellite	3
C03	The Chinese University of Hong Kong	Hong Kong, China	Earth as Seen from Space	2
C04	Salem State University	USA	Remote Sensing: Studying the Earth from Space	1
C05	University of Iowa	USA	Our Digital Earth	2
C06	University of Oregon	USA	Our Digital Earth	2
C07	Penn State University	USA	Mapping Our Changing World	3
C08	University of Maryland	USA	Earth from Space	3

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Sample ID	University	Country/Region	Course Title	Pattern
C09	Hong Kong Polytechnic University	Hong Kong, China	Big Earth Data and Geospatial AI	3
C10	San Diego State University	USA	Geographic Information Science and Spatial Reasoning	3
C11	The University of Texas at Dallas	USA	Spatial Thinking and Data Analytics	3
C12	San José State University	USA	Mapping the World	3
C13	NC State University	USA	Earth from Space	1
C14	Hirosaki University	Japan	The World of Engineering-Remote Sensing	2
C15	University of Auckland	New Zealand	Digital Earth	3
C16	University of Victoria	Canada	Our Digital Earth	3
C17	University of Washington	USA	Critical Remote Sensing	3
C18	University of Washington	USA	Digital Earth	3
C19	The University of Texas at Dallas	USA	Digital Earth	3
C20	Missouri State University	USA	Exploring Our Digital Earth	2

Note. The complete list of sampled courses and documentary sources, including institutional records, course documents, and source links, is provided in Supplement Sect. S2.

4.2 Knowledge Transformation: Recontextualizing EO and Geospatial Knowledge as Spatial Evidence

Across all 20 courses, the overall knowledge transformation rating is strong. Every course recontextualizes EO and geospatial Knowledge into pedagogically accessible forms for non-specialist learners, suggesting that knowledge recontextualization is a baseline condition for EO-integrated GE.
However, the application contexts vary considerably. Table 4 summarizes four dominant framing orientations: climate and environmental change, sustainability and urban development, Digital Earth and spatial literacy, and critical or interdisciplinary approaches. This contextual diversity indicates that knowledge transformation is not uniform. The sampled courses foreground different disciplinary aspects through their documented course positioning and application contexts.

Table 4. Knowledge Transformation: Application context classification

Category	Count	Cases	Consolidated Key Framing
Climate and environmental change	4	C01, C04, C08, C13	Satellite remote sensing for climate monitoring; orbital perspective on Earth systems; physics of light energy and satellite imaging mechanics
Sustainability and urban development	5	C02, C03, C05, C09, C15	SDG alignment; urban heat islands; human-environment interactions; climate justice; resource extraction and environmental degradation
Digital Earth and spatial literacy	8	C06, C07, C11, C12, C16, C18, C19, C20	Google Earth, mobile GIS, social media-based spatial data; foundational competencies in geospatial technologies; spatial thinking and quantitative reasoning
Critical and interdisciplinary	3	C10, C14, C17	Politics and limitations of remote sensing; integration of spatial statistics; EO and GeoAI integration; volunteered geographic information and geoweb ethics
Total	20		

4.3 Task Transformation: From Exposure to Structured Engagement

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Unlike Knowledge Transformation, Task Transformation reveals substantial variation across the sample (Table 5). This variation represents the main dimension along which sampled courses differentiate in curriculum design.

Table 5. Task Transformation summary

Task Transformation Rating	Number of Courses	Representative Cases
Strong	8	C01, C07, C08, C09, C10, C12, C16, C19
Partial	8	C02, C06, C05, C11, C14, C15, C17, C18
Not evident	4	C03, C04, C13, C20
Total	20	

Note. S = strong, P = partial, NE = not evident. The overall task-transformation rating is assigned according to the weakest dimension (i.e., a case receives the lowest rating across the three coding dimensions), reflecting the principle that constructive alignment holds only when coherence extends across learning outcomes, task design, and assessment alignment (Biggs, 1996).

Four courses exhibit limited task transformation and are classified as not evident. Although these courses connect EO and geospatial data to real-world issues spanning environment, sustainability, urban development, and social ecology, their publicly available documents provide limited evidence of structured learning tasks, assessment alignment, or explicit criteria for evaluating spatial outputs.C04, for example, is GPH 344 Remote Sensing: Studying the Earth From Space, a General Education course satisfying the Scientific Reasoning (non-laboratory) requirement. The course introduces remote sensing concepts, satellite imaging, and image analysis for environmental problem solving. Public documents do not lay out class activities, assessment rules, or formal benchmarks for evidence quality.

By contrast, eight courses demonstrate strong task transformation, requiring students to move beyond theoretical study into hands-on engagement with spatial data. C09 (LSGI1001 Big Earth Data and Geospatial AI) incorporates lab exercises involving “hands-on practices in solving real-world problems with geospatial analytics tasks,” accounting for 40% of total coursework within a 2-credit CAR (D) Science, Technology and Environment course. C12 (GEOG 107 Mapping the World) requires students to “weave factual scientific data with map layers, narratives, multimedia, imagery, and sounds” to create public-facing Story Maps about regional environmental issues, with weekly peer review and revision embedded into the learning process.

Eight courses fall into the partial task transformation category. These courses articulate learning outcomes or design tasks that engage students with EO and geospatial data, but assessment alignment remains partial, lacking explicit criteria for evidence quality, uncertainty, or analytical limitations.

4.4 Evidence Transformation: The Critical Gap and the Threshold to Alignment

Evidence Transformation is the dimension that most sharply distinguishes the four patterns of evidentiary alignment. Only one course achieves strong evidence transformation; the remaining nineteen courses fall within Patterns 1-3, with evidence

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transformation ratings remaining partial or not evident. This distribution reveals that evidence transformation, rather than knowledge or task transformation, is the critical bottleneck.
Pattern 3 demonstrates strong task transformation through labs, peer review, and Story Maps. However, the assessment criteria focus on deliverable formats rather than standards for evidence quality. No sampled course explicitly documented requirements for students to evaluate data quality, discuss uncertainty, validate analytical choices, or justify claims against alternative interpretations.

C01 (CIVL1180, HKUST) stands alone as Pattern 4. Its grading rubric operationalizes evidence-quality standards: Grade A requires students to "synthesize evidence masterfully" and "discuss limitations with exceptional critical insight and creativity"; Grade B requires "effectively using quantitative evidence to support conclusions" and "a good ability to evaluate policies and discuss project limitations." This clear articulation of evidence standards, data quality, uncertainty, validation, and critical insight sets C01 apart from all other courses.

The key distinction lies in whether assessment criteria operationalize evidence rigor or merely task completion. C01's rubric requires "critical insight" into limitations, whereas Pattern 3 assessments require students to create a Story Map or complete a lab exercise. These contrasting requirements illustrate how assessment criteria differ in their treatment of spatial evidence across patterns.

4.5 Synthesis: Four Patterns of Evidentiary Alignment

The three transformation mechanisms converge into four differentiated profiles of evidentiary alignment (Table 6). These profiles capture increasing levels of integration among knowledge recontextualization, task engagement, and evidence-oriented reasoning.

Table 6. Typology of evidentiary alignment in EO-enabled GE

Pattern	Pattern Label	Defining Features	Cases	Knowledge	Task	Evidence	Interpretive Implication
1	Contextualized EO Exposure	Strong knowledge; absent task design and evidence scaffolding	C04, C13	S	NE	NE	Disciplinary exposure without epistemic engagement. Students encounter EO content but are not required to reason with spatial data.
2	Application-Oriented Spatial Interpretation	Strong knowledge; application-oriented engagement with spatial information, but limited evidence of structured spatial evidence production and explicit	C03, C05, C06, C14, C20	S	P	P	Contextualized relevance without epistemic accountability. Students see why spatial data matters, but are not assessed on how they justify evidentiary claims.

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Pattern	Pattern Label	Defining Features	Cases	Knowledge	Task	Evidence	Interpretive Implication
		evidence-quality reasoning.					
3	Guided Spatial Evidence Production	Strong knowledge; structured hands-on tasks (projects, labs, spatial communication); partial evidence	C02, C07–C12, C15–C19	S	S	P	Productive activity without quality benchmarks. Students produce spatial outputs but face no criteria for data quality, uncertainty, or validation.
4	Integrated Spatial Evidence Reasoning	Strong knowledge, structured hands-on tasks, and explicit evidence-quality standards	C01	S	S	S	Triple transformation convergence: knowledge recontextualization, task-embedded reasoning, and explicit evidence-quality standards. Assessment operationalizes evidence rigor rather than merely task completion.

Note. Pattern assignment follows the decision rules described in Supplement Sect. S3 (Table S6), based on the combined profiles of knowledge transformation, task transformation, and evidence transformation.

Pattern1 represents the baseline: strong knowledge transformation without commensurate task or evidence transformation. Two courses fall into this pattern. EO and geospatial knowledge is recontextualized into general-education learning content, but students are not required to engage in structured tasks or evidence-based reasoning.

Pattern2 adds partial task transformation. Five courses exemplify this pattern. They connect EO and geospatial data to real-world problems spanning climate, sustainability, urban change, and environmental management. Application contexts are clear and pedagogically meaningful. However, task design remains partially visible, and evidence-quality standards are absent.

Pattern3 marks the mainstream: twelve courses require students to produce maps, reports, Story Maps, lab outputs, and presentations using real EO and geospatial datasets. Scaffolding is visible and structured, yet assessment criteria specify deliverable formats rather than evidence-quality benchmarks.

Pattern 4 is the only pattern in which all three transformation mechanisms are strong. C01 achieves this full integration by aligning course positioning, learning outcomes, tasks, scaffolding, assessment, and evidence-quality expectations around accountable spatial evidence use. Assessment criteria explicitly require students to synthesize evidence masterfully and discuss limitations with critical insight.

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Taken together, the four patterns reveal a systematic hierarchy. Knowledge transformation is universal, task transformation is common but uneven, and evidence transformation is rare and decisive. The majority of courses (13 of 20) demonstrate strong task transformation, while evidence transformation remains partial in most cases.

5. Discussion

5.1 From Data Access to Evidence Conditions

EO and geospatial data are widely recognized as valuable learning resources for non-specialists (Asimakopoulou et al., 2023). However, curricula in our sample reveal a structural asymmetry, with knowledge transformation being widespread while evidence transformation remains comparatively underdeveloped. This asymmetry suggests that curricula recognize the pedagogical potential of global-scale platforms while providing less visible support for translating expert spatial practices into learning experiences that make evidentiary conditions explicit (Crowley et al., 2023). When curricula make satellite imagery accessible without exposing its evidentiary conditions, learners encounter maps and visualizations as persuasive representations rather than constructed artifacts (Moser, 2025). Geospatial data literacy research highlights why this omission matters: meaningful engagement with geospatial data requires understanding not only their analytical power but also their constructed nature and interpretive limitations (Juergens & Redecker, 2023). Visualizations make patterns appear concrete and self-evident, yet their interpretation depends on representational choices and the capacity to evaluate what is shown and omitted (Franconeri et al., 2021).

The distinction between data access and evidentiary expectations is particularly important in GE contexts because students are not being trained as remote-sensing specialists, but as broader users of spatial evidence who can evaluate and communicate spatial claims in civic, professional, and environmental settings (Jekel et al., 2025). Uncertainty is therefore not a peripheral technical issue but a central component of scientific reasoning and communication (Blauza et al., 2025). EO-integrated GE, therefore, requires curriculum designs that make evidentiary expectations visible by clarifying how spatial claims are supported, qualified, and limited. Without such expectations, courses may cultivate technical familiarity without fully developing spatial evidence literacy.

5.2 The Recontextualization Paradox: When Real-World Relevance Outpaces Evidence Standards

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Across the sampled courses, real-world environmental and sustainability themes served as entry points that connected geospatial data with lived experience. This contextual orientation is educationally valuable: climate and ecological impacts are unevenly distributed, and vulnerability is shaped by both environmental and social conditions (IPCC, 2022).

Yet this strength contains a paradox. Real-world problems make EO and geospatial data meaningful, but they do not automatically make spatial claims evidentially justified (Osborne & Pimentel, 2023). The prominence and urgency of environmental issues can overshadow attention to how spatial evidence is produced, interpreted, and justified. When students encounter satellite imagery of deforestation or urban heat islands, the environmental significance of the issue may become more visible than the evidentiary processes underlying the representation. This displacement is reinforced by the visual nature of EO representations. Maps and satellite imagery can appear persuasive because their visual concreteness creates an impression of certainty, even though their interpretation depends on underlying data, processing choices, and representational decisions (Bennett et al., 2022). Spatial uncertainty further complicates this interpretation, influencing how information is used in decision-making contexts (Huck et al., 2025). The result is a double substitution in which the relevance of the problem stands in for the rigor of the claim, while the visual concreteness of the imagery stands in for the validity of the evidence.

When these substitutions go unexamined, contextual relevance may fall short as a vehicle for evidentiary learning. Students may recognize the relevance of issues such as deforestation or urban heat islands while receiving limited support in examining the evidence quality, uncertainty, and limitations behind the spatial claims used to represent these issues. As argued above, geospatial data literacy requires understanding not only the analytical power of geospatial data but also its constructed nature. Contextual relevance achieves its educational promise only when learners are supported in examining how spatial evidence is constructed, evaluated, and limited (Heidari et al., 2026).

5.3 Evidentiary Alignment as the Threshold Between Spatial Outputs and Evidence-Based Reasoning

The four patterns reflect different levels of visibility of evidentiary standards across EO-integrated curricula, yet most courses in the sample do not make these standards explicit. This gap is not merely a difference in degree; it reflects how evidentiary expectations are embedded in curriculum design. Constructive alignment examines coherence between learning outcomes, teaching activities, and assessment tasks (Biggs, 1996), but coherence alone does not specify the evidentiary standards by which spatial claims should be evaluated (Newby & Cornelissen, 2025). Pattern 3 courses illustrate this limitation, as they require students to produce maps, Story Maps, or reports using real EO and geospatial data, while their assessment criteria more

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often specify deliverable formats than evidentiary expectations. A student may create a compelling climate-risk Story Map without explicit expectations regarding data sources, uncertainty, or the limits of spatial claims.
Evidentiary alignment extends this perspective by asking whether curriculum coherence is accompanied by explicit evidence standards. It concerns not only the organization of curriculum components but also whether the conditions that make EO and geospatial data credible as spatial evidence are visible to learners. This requires making expectations for selecting, interpreting, evaluating, and communicating EO and geospatial data explicit within curriculum design. The contrast between Pattern 3 and Pattern 4 illustrates what this looks like in practice. C01 requires Grade A students to "synthesize evidence masterfully" and "discuss limitations with exceptional critical insight", reflecting not merely a higher standard but a qualitatively different evidentiary expectation where reasoning is evaluated alongside the claims themselves.

Making evidentiary expectations visible also reframes how uncertainty is treated in non-specialist geoscience education. Rather than an obstacle to be hidden, uncertainty can be engaged as a pedagogical resource that moves learners beyond observation toward reflection and argumentation (Chen et al., 2024). From a geoscience communication perspective, evidentiary alignment concerns not only how EO and geospatial data are communicated. It also concerns how the conditions that enable these data to become credible spatial evidence are made visible to non-specialist audiences. In this sense, evidentiary alignment supports the development of spatial evidence literacy by enabling learners to understand how spatial claims are constructed, evaluated, and communicated.

5.4 From Patterns to Design: Making Evidentiary Expectations Visible

Evidentiary alignment requires deliberate choices in how curricula position EO and geospatial knowledge, organize evidence-oriented tasks, and support students' engagement with spatial evidence. Positioning EO and geospatial data as sources of evidence rather than merely as content is the foundational move. In the sampled documents, less explicit evidentiary alignment tends to position EO as visual content, environmental context, or a technical instrument. In contrast, stronger alignment frames EO and geospatial data as resources for evaluating, justifying, and communicating spatial claims. This reframing does not require advanced remote-sensing training. Instead, it requires making visible the processes that shape responsible use of spatial data, including data production, interpretive assumptions, and the types of claims that the data can reasonably support. These considerations determine what a map can show, what it cannot show, and how confidently its claims should be presented (Bennett et al., 2024).

Once EO and geospatial data are positioned as sources of evidence, the assessment needs to shift from product criteria toward reasoning criteria (Xiang & Xi, 2025). In

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Pattern 3 courses, publicly available documents emphasize completion of a Story Map, lab exercise, or report; Pattern 4 assessment also makes visible whether students can synthesize evidence, discuss limitations, and justify claims. Curriculum design can make explicit what counts as credible spatial evidence and how practices such as interpreting EO and geospatial data, evaluating data quality, and communicating uncertainty are assessed.

Scaffolding must follow the same shift, moving from procedural support toward support for spatial reasoning. Pattern 1-3 courses often provide platform access, tutorials, or step-by-step workflows; such supports may facilitate task completion without necessarily making spatial reasoning visible. Scaffolds should help students connect evidence to explanation rather than merely follow procedures (Quintana et al., 2004; Reiser, 2004). Applied to EO-enabled general education, this means making the reasoning behind technical choices visible and communicable without replacing technical instruction.

These three shifts, involving positioning, assessment, and scaffolding, converge on a fourth dimension in which uncertainty becomes a routine part of curriculum design. Uncertainty can be incorporated into learning outcomes, tasks, rubrics, and feedback without requiring advanced technical specialization (Chen et al., 2024). Students can be encouraged to identify data limitations, justify spatial choices, compare alternative sources, and articulate what spatial visualizations can and cannot demonstrate. These design choices help move EO learning from technical familiarity toward spatial evidence literacy and more responsible geoscience communication.

Table 7 summarizes these design implications across six dimensions. The table should be read as an analytical heuristic derived from the cross-case patterns, rather than a prescriptive model for course development or a judgment of enacted classroom teaching.

Table7. From Less Explicit to More Explicit Evidentiary Alignment: Design Principles for EO-Enabled Geoscience Communication in General Education

Design dimension	Less explicit evidentiary accountability visible in public documents	More explicit evidentiary accountability as design target
Course positioning	EO and geospatial data are presented mainly as visual content, environmental context, or technical instruments for observing change.	EO and geospatial data are framed as spatial evidence requiring interpretation, justification, and qualification of claims.
Learning outcomes	Outcomes name geospatial concepts, tool skills, datasets, or product types.	Outcomes name evidence practices, such as interpreting EO and geospatial data, evaluating data quality, justifying spatial claims, comparing evidence sources, and communicating uncertainty.
Project tasks	Students produce maps, reports, labs, or Story Maps, but explanatory requirements for evidence use are limited or not publicly visible.	Students explain what EO and geospatial data show and do not show, and justify why particular data, scales, methods, and visualizations are appropriate for the claim being made.
Scaffolding	Public documents emphasize platform access, tutorials, step-by-step workflows, or task completion.	Scaffolds include evidence prompts, worked examples, comparison tasks, uncertainty prompts, and evidence-reasoning templates.
Assessment criteria	Assessment criteria focus mainly on completion, technical correctness, topic coverage, visual quality, or product format.	Assessment criteria include data selection, evidence quality, spatial interpretation, uncertainty, limitations, and communication of qualified claims.
Output purpose	Spatial products function mainly as course assignments or demonstrations of technical engagement.	Spatial products function as geoscience communication artifacts, such as Story Maps, reports, dashboards, or policy briefs, with explicit caveats about what spatial evidence can and cannot support.

5.5 Limitations and future research

These findings should be interpreted in light of the nature of the available evidence. The analysis focuses on the formal intended curriculum represented in publicly available course documents rather than enacted classroom practice. Therefore, cases coded as "not evident" indicate that evidence-quality expectations were not visible in public documentation, rather than confirming their absence from classroom implementation. The twenty courses selected from APEC higher-education contexts provide analytically useful variation but do not represent all APEC or global EO-integrated GE curricula. The value of this study therefore lies in identifying a transferable curriculum-level design challenge concerning how evidentiary expectations are made visible, rather than estimating the prevalence of particular practices. Although the coding framework was strengthened through expert review, future research could further examine its applicability through additional coders, instructor perspectives, classroom observations, and access to internal curriculum materials.

These limitations point to several future research directions. The evidentiary alignment framework can be further examined across specialist programmes, interdisciplinary sustainability courses, and broader geoscience communication contexts. Comparative studies could investigate whether different institutional systems make evidence-quality expectations visible in different ways. Longitudinal research could explore how students move from technical familiarity toward more evidence-based spatial reasoning over time. Student-produced outputs, including maps, Story Maps, reports, dashboards, and reflective commentaries, would be especially valuable for examining how spatial evidence literacy is manifested in

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learners' actual practices.

6. Conclusion

This study develops the Evidentiary Alignment Framework for Curriculum-Based Geoscience Communication (EAF-CGC) to examine how EO-integrated general education curricula organize learning experiences for the development of spatial evidence literacy among non-specialist learners. Through qualitative document analysis of publicly available materials from 20 undergraduate courses in selected APEC higher-education contexts, the study identifies four patterns of evidentiary alignment. Although EO access and contextual integration are increasingly visible across these courses, evidentiary expectations are less consistently articulated. Publicly available curriculum documents provide more limited evidence of how students are supported in evaluating spatial evidence, recognizing uncertainty, and justifying spatial claims.

These findings suggest that the educational challenge of EO-integrated general education extends beyond access to technologies and tools. The key issue is how EO and geospatial knowledge are transformed into evidence-oriented learning experiences. The EAF-CGC framework contributes a curriculum-level perspective by foregrounding evidentiary alignment as a key process in EO-integrated GE. Through Knowledge Transformation, Task Transformation, and Evidence Transformation, the framework explains how EO and geospatial knowledge are communicated, transformed into spatial evidence, and engaged with by non-specialist learners.

From this perspective, the value of EO-integrated GE is not determined simply by whether students encounter satellite imagery, geospatial datasets, or produce spatial outputs. More fundamentally, it depends on whether curricula make visible the conditions through which spatial information becomes credible evidence. These conditions include data interpretation, uncertainty recognition, and justification of spatial claims. Non-specialist undergraduates are therefore not merely recipients of spatial information but future users and communicators of geoscientific evidence. This highlights the role of curriculum design in developing spatial evidence literacy and strengthening curriculum-based geoscience communication through explicit attention to how evidence is interpreted, evaluated, and communicated.

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Author contribution

The author designed the study, developed the analytical framework, collected and analysed the data, interpreted the findings, and prepared the manuscript.

Code availability

No custom code was developed for this study.

Data availability

The evidence database compiled in this study, including the extracted curriculum evidence and coding records, is provided in the Supplement. The original source materials analysed in this study are publicly available through the institutional websites and repositories cited in the manuscript.

Competing interests

The author declares that they have no conflict of interest.

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