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Research Article

From Theory to Practice: Design Principles for Teaching with Earth Observation Data Using the Key Concept "Spatial Patterns"

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Abstract: Earth Observation (EO) data provide significant opportunities for geography education, enabling students to better understand our changing world. To make this powerful knowledge accessible, the German key geographic concept of "spatial patterns" provides a promising foundation for helping students understand spatial relationships. However, little is known about how to apply this key geographic concept in task design and how students engage with EO data. In addition, the integration of EO data into geography education is often constrained by insufficient teacher expertise. Against this background, the present study employed a Design-Based Research approach to develop empirically grounded design principles that support teachers. To achieve this, the study developed and refined tasks that enabled lower secondary students to engage with EO data. Over three research cycles, both qualitative and quantitative data were collected to examine students' strategies, challenges, and outcomes. The findings highlight the importance of an analytical framework based on the key concept "spatial patterns" to help students engage with EO data. In addition, targeted prior knowledge and further scaffolding are necessary. Although students were able to analyze EO data and use spatial thinking skills, they continued to face challenges with open-ended tasks and recognizing the limitations of EO data. The study concludes with practical design principles and implementation guidelines to assist teachers in developing learning materials.

Keywords: Spatial Thinking Skills; Task Design; Satellite Imagery; Spatial Pattern; Design-Based Research; Geography Education

Highlights:

- Even lower secondary students were able to use complex EO data to answer geographic questions.
- The German key geographic concept "spatial patterns" enables students to analyse EO data in order to understand geographical phenomena and processes.
- We present empirically grounded design principles for integrating EO data into geography education, which support teachers.

1. Introduction

Earth Observation (EO), including aerial photography, satellite imagery, and maps derived from these sources, is a crucial resource for understanding our changing planet (Chuvieco, 2023). EO applications span a wide range, from analyzing environmental processes to examining human impacts (Gardent et al., 2014; Petersen et al., 2021). Many of these applications align closely with curriculum-relevant topics such as climate change or urban sprawl, offering valuable opportunities for educational practice (Asimakopoulou et al., 2023; Simerská, 2023).

Research indicates that teaching with geospatial technologies can foster students´ spatial thinking skills, geographic relational thinking, as well as problem-solving capabilities (Favier & van der Schee, 2014a; Metoyer & Bednarz, 2019; Jaeger, 2024; Bondarenko, 2025). More specifically, the use of satellite imagery is motivating for students (Dziob et al., 2020) and can enhance their systems thinking skills (Jahn, 2020). Studies also reveal that even lower secondary students can identify objects in false-color composites and prefer very high-resolution EO data (0.5 m per pixel) over maps (Svatonova & Kolejka, 2017). Furthermore, learners tend to focus on distinctive and prominent objects (Wabnitz, 2019), suggesting that false-color images and EO representations, such as vegetation indices, may be particularly suitable for educational purposes. Based on these promising findings and the growing availability of open-source EO data, several initiatives have sought to support teachers in integrating EO into classrooms by developing ready-to-use teaching materials, supplementary resources, and user-friendly applications (Schulmann et al., 2021; Dannwolf et al., 2020; Hodam et al., 2021; Ortwein et al., 2017; Jaeger, 2024).

Research has shown that the integration of EO in schools is constrained by teachers' limited knowledge (Hodam et al., 2020). Consequently, teachers require additional support to effectively integrate EO data into classroom practice, particularly when implementing inquiry-based learning approaches (Mašterová, 2023). Two measures are particularly critical in this regard: first, offering targeted professional development; second, providing design principles that guide the creation of suitable learning tasks (Serwene et al., 2024). Such principles can help teachers to design tasks tailored to their students' needs.

These tasks should actively engage learners with EO data by requiring them to independently select, extract, and process relevant information (Asimakopoulou et al., 2023; Lindner et al., 2022). This inquiry-based approach strengthens the learning process (Praetourius et al., 2018) and can foster geographical thinking skills (Bondarenko, 2025). If successful, it enables students to analyze, explain, and understand the world, fostering what can be described as powerful knowledge (Maude, 2016). However, little is known about how to design such learning tasks.

One approach to applying geographical thinking is the use of key geographic concepts, which serve as guiding principles for geographic thinking (Fögele, 2016; Bendl et al., 2025). In this context, Keller and Siegmund (2026) developed initial design principles to support teachers in using digital geo-media in the context of key geographic concepts, which can also be applied to the use of EO data. These design principles specify how key geographic concepts should be operationalized and introduced (Keller & Siegmund, 2026). To this end, they propose a three-step process comprising the operationalization of key geographic concepts, the development of a visualization, and its application (see Chapter 2). While these principles represent an important first step, they do not specify how they can be applied to the development of learning tasks in which students actively engage with EO data. Furthermore, the study does not yet clarify whether the use of key geographic concepts enables learners to effectively answer geographic questions.

Against this background, the overall aim of this study is to develop design principles that help teachers create tasks enabling students to independently select, collect, and process information using EO data. Following a Design-Based Research (DBR) approach, such learning tasks were iteratively designed, evaluated, and refined (Easterday et al., 2018). This process is used to inform the further development of design principles from Keller and Siegmund (2026), which serve as the starting point for the design process (Easterday et al., 2018). These design principles contribute to the dual output of DBR projects, comprising materials for practical application and theoretical development (Serwene et al., 2024). To inform the revision of these tasks and the theory development based on empirical insights, the following research questions were addressed:

1. How can key geographic concepts help students independently select, collect, and process EO data in order to answer geographic questions?
2. How should tasks be designed to enable independent work with EO data?
3. To what extent are lower secondary students able to analyze EO data, and what challenges do they encounter?

To achieve these objectives and answer the research questions, ten project days were conducted with lower secondary students to evaluate the learning tasks. Across three DBR cycles, quantitative and qualitative data were collected and used to revise the learning tasks.

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2. Project Day and Task Design

The learning tasks were evaluated during a 4.5-hour project day. Students were guided by the overarching guiding question, "*Where should the fictional Sahin family move?*", which structured the learning process, encouraged independent investigation and evidence-based reasoning (Asimakopoulou et al., 2023). In small groups, students compared two districts of a German city by formulating and addressing sub-questions related to recreational value and climate adaptation potential. Drawing on lesson plans by Keller et al. (2024a) and Keller and Siegmund (2026), they analyzed green spaces through a field trip and the analysis of EO data to support a reasoned decision. However, the procedure and required data were largely predetermined, due to the complexity of finding and processing EO data.

2.1. Analytical Framework for the Learning Tasks

To address the guiding questions, students must process relevant information from EO data and fieldwork. This requires an analytical framework that enables the systematic attribution of meaning to spatial structures or objects (Uhlenwinkel, 2013). One approach for that form of geographic thinking is key geographic concepts as an overarching structure for geographic reasoning (Fögele, 2016; Taylor, 2008; Bendl et al., 2025). According to the design principles of Keller and Siegmund (2026), a selected key geographic concept must be operationalized and combined with an appropriate visualization. For example, the German key geographic concept of "spatial patterns" can be operationalized by defining criteria, mostly related to specific structures or elements, for spatial relationships. By analyzing these criteria, spatial relationships can be systematically evaluated (Keller & Siegmund, 2026).

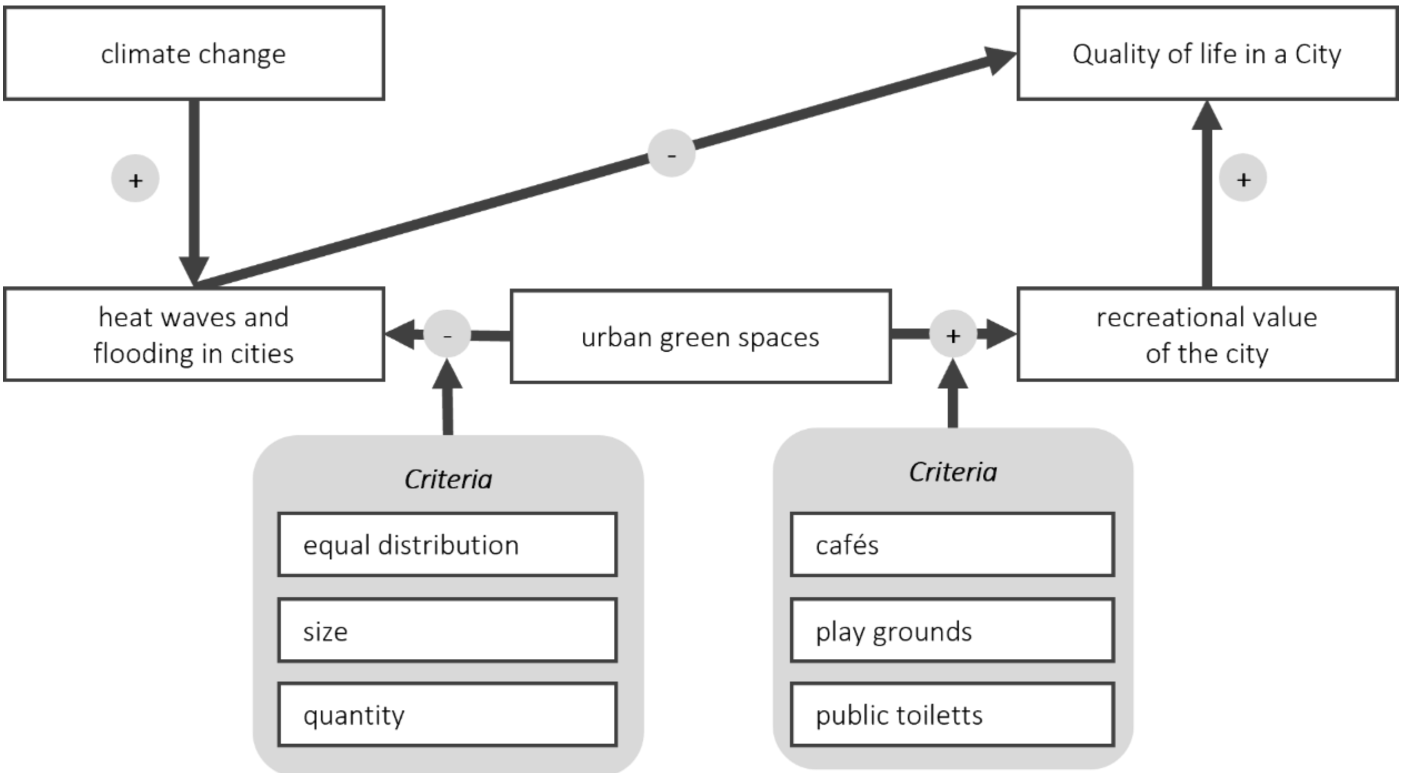

Figure 1. Expanded Concept Map visualizing spatial relations with the key geographic concept "spatial patterns". The upper part of the concept map visualizes interrelations between relevant elements. The boxes in the lower part display criteria for the evaluation of the climate adaptation and recreational value of areas. Image: Johannes Keller (CC-BY 4.0)

For example, the spatial structure of urban green spaces, defined by criteria such as distribution, size, and quantity, has a significant impact on climate adaptation (Emilsson & Ode Sang, 2017) and can therefore serve as a basis for comparing two areas (Figure 1, bottom left box). Likewise, criteria such as cafés, playgrounds, or public toilets help assess recreational value (Figure 1, bottom right box). Visualizations play a central role in supporting students' understanding of spatial interrelations (Dessen Jankell & Johansson, 2023; Keller & Siegmund, 2026) and in applying these concepts through geospatial technologies such as EO data (Pivarníková, 2025). Consequently, the expanded concept map shown in Figure 1 was designed for the project day, based on visualizations developed by Keller and Siegmund (2026).

This forms the conceptual basis for an analytical framework that structures learning tasks by drawing on key geographic concepts to foster geographical thinking (Bendl et al., 2025). First, students need to use criteria to identify relevant information (Favier & van der Schee, 2014b), select it, and assign meaning to it (Uhlenwinkel, 2013).

2.2. Structure of the Project Day and Task Design

Using the analytical framework with EO data is challenging because it requires several subskills. Students need to understand the contextual and conceptual background, develop a basic grasp of the EO data used, and acquire skills to extract information. To help students master these subskills, the Four-Component Instructional Design (4C/ID) model by van Merriënboer et al. (2002) and the design principles from Keller and Siegmund (2026) guided the project day design. The 4C/ID approach structures complex learning by introducing subskills step by step within authentic learning tasks. During the project day, students received supportive information (e.g. the expanded concept map as a visualization) and procedural guidance (e.g. instructions for using the vegetation index), which ensured effective application of the analytical framework in the learning tasks (Keller & Siegmund, 2026).

Overall, the project day consists of four parts: an introduction to the content, an introduction to EO, a field trip with subsequent debriefing, and learning tasks in which students select, collect, and process information using the analytical framework. In the first part, the expanded concept map (Figure 1) was used to teach relevant content and conceptual knowledge through learning tasks, with a focus on the role of criteria in assessing interrelationships. Following the design principles proposed by Keller and Siegmund (2026), the aim of this phase was to provide students with conceptual knowledge intended as supportive information. They were expected to apply this knowledge later when selecting, collecting, and processing information using EO data. For this reason, the knowledge was not presented in a decontextualized manner but introduced inductively using the example of the role of green spaces (Seidel et al., 2013; Serwene, 2023).

To analyze the spatial structure of urban green spaces, the vegetation index was selected. Since this representation of EO data highlights vegetated areas (Chuvieco, 2023), it was assumed that even lower secondary students would be able to work with it (Svatonova & Kolejka, 2017; Wabnitz, 2019). Since it can be assumed that the participating students had no prior knowledge of the vegetation index, sufficient time had to be allocated for its introduction (Keller & Siegmund, 2026). This was carried out in student-centered learning tasks, during which students learned how to use the vegetation index to describe the spatial structure of urban green spaces. In addition to gaining a basic understanding of how different surfaces are visualized in the vegetation index, students learned how to identify spatial structures. To this end, they practiced applying fundamental spatial thinking skills such as location and patterns to describe the spatial distribution of urban green spaces (Gersmehl & Gersmehl, 2006). The second phase provided students with the needed supportive information for the information collection with the vegetation index. Both the expanded concept map and the vegetation index were repeatedly used in part-task practice sessions during the project day to consolidate the associated subskills (van Merriënboer et al., 2020).

Keller and Siegmund (2026) proposed introducing students to the use of the visualization but did not specify how this should be implemented. Taking students' age into account, students were taught to apply the analytical framework using an inductive approach (Seidel et al., 2013; Serwene, 2023). During a field trip, they collected information on the recreational value of urban green spaces in one district. In a teacher-centered debrief, this information was used to apply the analytical framework to compare the recreational value of two districts. For the comparison, additional data on the second district was gathered in the classroom using Google Maps and supplementary materials.

At the end of the project day, students used the analytical framework and the vegetation index to compare the climate adaptation potential of two districts. Following Keller and Siegmund (2026), the learning tasks were structured as a progression of three stages:

- **Task 1:** In this summarizing task (Favier & van der Schee, 2014b), students were tasked with completing a given expanded concept map (Figure 1). The aim of the task was to repeat relevant content knowledge and spatial interrelations, which were intended to serve as supportive information for Tasks 2 and 3. In the provided expanded concept map, the labels on the arrows and the boxes containing the criteria were missing. Additionally, students were expected to identify criteria for urban green spaces that contribute to climate adaptation and recreational value.

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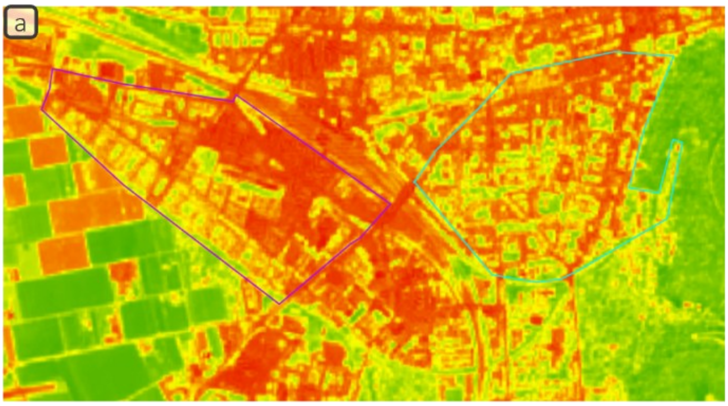
- **Task 2:** As shown in Figure 2, students collected information about urban green spaces in two districts of a German city using the vegetation index (Figure 2, a). Using the criteria displayed in Figure 1, the key geographic concept "spatial patterns" should support students in selecting relevant information using basic spatial thinking skills (Figure 2, c). To this end, a provided table (Figure 2, c) served as procedural information (van Merriënboer et al., 2002), in which the criteria should work as a relevance filter for information collection.
- **Task 3:** Students should synthesize their findings with the key geographic concept "spatial patterns" to determine which district better supports recreational use and climate adaptation.



b

Task 2 – cycle 1

Evaluate the green spaces in the two city districts. Use the printed satellite image with the vegetation filter for this task. Assign grades to each district in the table.

A grade of 1 means that the statement is completely true. A grade of 6 means that the statement is not true at all.

c	District 1 (purple)	District 2 (turquoise)
There are large green spaces here.		
There are many green spaces here.		
The green places are equally distributed here.		

Figure 2. Tasks 2 from Cycle 1. In this task, the learners use the vegetation index (a) to obtain information about green spaces in two districts (b). The criteria for which students should select information were provided in the task (c). Image: Johannes Keller, Vegetation index: based on Image © 2023, Planet Labs PBC.

Tasks 1 and 3 were only slightly modified throughout the three design cycles, whereas Task 2 was significantly revised based on insights from the evaluation. In Task 2, the main changes concerned whether the criteria were given in the task or had to be selected by the students themselves. Additionally, the content of the project day was iteratively adapted after each cycle, based on teacher feedback and informal observations. After the first cycle, the content scope was simplified by focusing solely on flooding instead of both heat waves and flooding. The introduction was shortened, and more time was dedicated to explaining the expanded concept map.

3. Methodology and Data Collection

With the overall aim of optimizing learning processes and supporting practitioners, DBR is a well-established evidence-based approach in geography education and subject didactics in general (Riegel & Rothhagel, 2025; Serwene et al., 2024). Consequently, a DBR approach was applied to achieve the overall goal of the study. After the initial theory-driven design of the project day and the three learning tasks, these were evaluated and redesigned across three iterative cycles (Easterday et al., 2018). To this end, the design decisions guiding the initial development of the learning materials were presented in the previous chapter, while subsequent refinements, presented in the results section, were closely informed by empirical insights (Obczovsky et al., 2024). Cycle 1 was conducted with four fifth-grade classes from a German grammar school in January 2024, Cycle 2 with two seventh-grade classes from a secondary school in May 2024, and Cycle 3 with four fifth-grade classes from a German grammar school in March 2025 (Figure 3).

During all three cycles, qualitative and quantitative data were collected. Quantitative data were collected using a printed post-instruction questionnaire, which all participating students completed after Part II (introduction to EO data, see Figure 3). The questionnaire consisted of three parts (Appendix Figure A1). The first part aimed at gauging the students' intrinsic motivation during their engagement with and comprehension of EO data. The questionnaire incorporated four selected items from the Short Scale of Intrinsic Motivation, developed within the framework of Self-Determination Theory (Keller et al., 2024b; Ryan & Deci, 2020; Wilde et al., 2009; Appendix Figure A1, Part 1). It was supplemented with a short quiz designed to assess students' ability to identify relevant objects (in this case urban green spaces) using the vegetation index (Appendix Figure A1, Part 2). In addition, an adapted C-test was employed in the form of a gap test. This diagnostic instrument required students to complete partially deleted words within a continuous text summarizing the delivered information during the project day (Appendix Figure A1, Part 3). By reconstructing relevant terminology in context, the test provided insights into students' lexical knowledge, comprehension, and the depth of content knowledge (Eckes & Grotjahn, 2006). These insights helped contextualize how students analyzed EO data. However, the validity and reliability of the quizzes were not further examined, which limits their interpretive power.

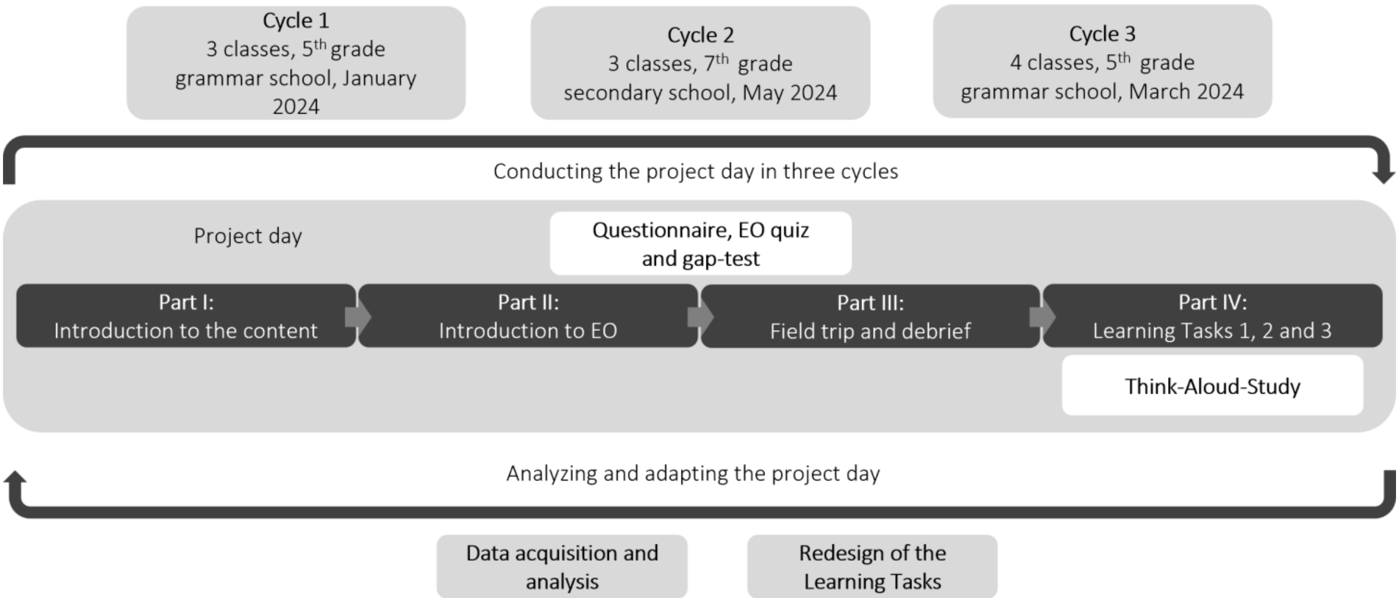


Figure 3. Methodological Framework of the Study. The educational material was redesigned during three research cycles and tested during ten project days. During these cycles the material was evaluated by collecting data through questionnaires, quizzes and gap tests as well as a think-aloud study. Image: Johannes Keller (CC-BY 4.0)

Following the methodological approach of Keller and Siegmund (2026), think-aloud protocols (TAPs) were recorded from small student groups (2–3 students) while they worked on the learning tasks in Part IV. By verbalizing their cognitive processes and engaging in group discussion, insights can be gained into how students engage with EO data (Wolcott & Lobczowski, 2021; Pottier et al., 2010). To this end, a guideline for conducting the TAPs was developed based on a previous study by Keller and Siegmund (2026). The guideline also includes prompts and guiding questions to support students during the cognitively demanding process of thinking aloud (Cowan, 2019). To rate the complexity of Task 2, students were additionally asked to rank it from 1 (very easy) to 5 (very difficult) and to give a short justification for their ranking. Due to time constraints, this rating was skipped in Cycle 3. To create a trusting conversational atmosphere in which participants could freely express their thoughts, all think-aloud protocols were collected by trained research assistants without the presence of teachers or the instructor of the project days (Helfferich, 2022). Eleven TAPs were conducted in Cycle 1, five in Cycle 2, and ten in Cycle 3.

To conduct the qualitative content analysis, an inductive coding scheme was developed based on the collected TAPs, and all 26 protocols were coded by the first author (Kuckartz & Rädiker, 2022). Based on these categories, the TAPs were structured to gain insights into how students engage with EO data and how they use the key geographic concept of "spatial patterns." Given the importance of prior knowledge, which was intended to be provided during the project days, for successfully engaging with EO data, the TAPs from Task 1 were analyzed to explore students' conceptual understanding and content knowledge. In Cycle 2, students worked with a web map on a tablet (Figure 2). To better understand their procedures, the screen was recorded to supplement the TAPs.

Only students who participated voluntarily and with signed parental consent were included in the study. As a result, the sample is a convenience sample, which limits the generalizability of the findings. Non-participation had no disadvantages for learners. The collection, processing, and storage of the data were based on the rules of the Ethics Committee of Heidelberg University of Education. Due to restrictions in the participation conditions, the collected data cannot be published, even in anonymized form.

4. Results

To successfully complete Tasks 2 and 3, students needed prior knowledge of EO data, urban climate adaptation, and the key concept of "spatial patterns," which they were expected to acquire during the project day. Across all three cycles, participants demonstrated high intrinsic motivation when working with EO data and the vegetation index (Table 1). Only in Cycle 2 was students' perceived competence in using the vegetation index below average. Most students solved the quizzes about the vegetation index correctly (Table 1).

Table 1. Brief overview of the prior knowledge of the vegetation index and the content gathered by the participants during the project day.

Results	**Cycle 1**	**Cycle 2**	**Cycle 3**
n participating students (mean age)	28 (10.4)	7 (12.3)	18 (10.5)
Groups participated in the TAPs	11	5	10
Mean values for the four dimensions of Intrinsic Motivation during work with EO data* with standard derivation	4.5 (0.8) | 3 (1.3) | 3.6 (0.9) | 1.5 (1.0)	4 (1.0) | 4.2 (0.8) | 2.9 (0.9) | 1.1 (0.4)	4.4 (0.6) | 3.5 (0.8) | 4.1 ((0.7) | 1.1 (0.3)
Representation quiz correctly solved	78.6 %	85.7 %	88.9 %
Matching quiz correctly solved	78.6 %	85.7 %	94.4 %
Gap Test	72.8 %	70.7 %	76.3 %
Name "criteria" in the gap test.	69.9 %	36.6 %	61.1 %
Task 1 Concept Map	No mistakes occurred	One group failed	No mistakes occurred
Task 1 Criteria	- Unable to label the box with criteria - Memorized criteria for climate adaptation correctly - Found criteria for recreational value	- Unable to label the box with criteria - Found wrong criteria for climate adaptation - Found criteria for recreational value	- The label of the box with criteria was given in the task - Memorized criteria for climate adaptation correctly

* *Mean values for: interest | perceived autonomy | perceived competence | pressure, which represent the four dimensions of the short scale for intrinsic motivation (Wilde et al., 2009). Scale ranged from 1 = "strongly disagree" to 5 = "strongly agree".*

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On average, they completed more than two-thirds of the gap test accurately (Table 1). However, students, particularly in Cycle 2, struggled with newly introduced terminology such as "criteria" and technical terms like "percolation". In Task 1, most groups labeled the arrows correctly. However, in Cycles 1 and 2, they struggled to label the boxes with criteria for climate adaptation and recreational value. In Cycle 1, all groups accurately recalled the criteria for climate adaptation and provided justifications for their choices regarding recreational value ("*Because the green spaces* [...] *should not all be in one place, otherwise the water will only drain away in one spot.*" C1, G9, L26[1]). In Cycle 2, only one group memorized all the climate adaptation criteria correctly; others confused adaptation with mitigation or left boxes empty ("85: '*Climate?*'; 84: '*That may be because we are living in a time of climate change,*'" C2, G2, L49). Although students in Cycle 2 could explain the general role of criteria, they struggled to identify suitable ones for recreational value. In Cycle 3, all groups recalled the criteria correctly but without further explanation (Table 1).

4.1. Cycle 1 – Task 2: Strategies to analyze EO data

In Task 2, students in Cycle 1 successfully collected and processed information about the given criteria using a vegetation index map. The groups applied various strategies, such as describing locations or making comparisons, to evaluate the distribution, size, and quantity of green spaces across the two districts (Table 2). In most cases, students relied on descriptive assessments of specific areas. When disagreements arose, they refined their ratings through more detailed descriptions, quantification, and comparisons within or between districts (Table 2). One group explicitly incorporated knowledge gained during the field trip. Overall, students had no difficulty identifying green spaces or navigating the vegetation index map.

Students participating in Cycle 1 rated Task 2 as relatively easy, with an average score of 1.8 out of 5. In general, they perceived the task as accessible and encountered minimal comprehension difficulties. Groups 1 and 2 reported that assigning grades was straightforward, whereas Groups 4 and 5 experienced challenges in reaching consensus within their teams. Groups 7 and 8 found it difficult to assign grades and provide adequate justifications due to the absence of a clear reference value.

Table 2. Strategies applied by the students to collect information about the spatial probabilities of urban green spaces with the vegetation-index map compared between the three cycles.

Strategy	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Representative Quote**
Description of Areas	All groups	G1, G2, G4, G5	All groups	*„Ok, [district 1]. There are large green areas here. Well, actually yes. There is a really big one."* (C1, G3, L99)
Quantification	G4, G7	G2	G10	*„Four large areas. So, a 1 minus or a 1 to 2 now?"* (C3, G10, L332)
Comparison within a district	G1, G2, G5, G6, G7, G8, G9, G11	G4	G1, G2, G3, G8, G10	*„Well, in [district 1], yes. Up there, there are a few as well. A few, so I would... But below, there are really, really many. And then in the middle…*[student suddenly stopped here and paused]. *Kind of a one minus."* (C1, G1, L147)
Comparison between districts	G1, G4, G5, G6, G8, G9, G10	G1, G2	G1, G6	*„Yeah, I would have said the same thing. So, in the other district, it's definitely much better. There is significantly less red and a lot more green. So for me, it gets a 1 to 2."* (C2, G1, L270)
Use insights from the field trip	G1	G1, G2, G5	G1, G6	*„Well, I think it's really great in [district 2] with all the playgrounds and everything." (C2, G5, L236)*

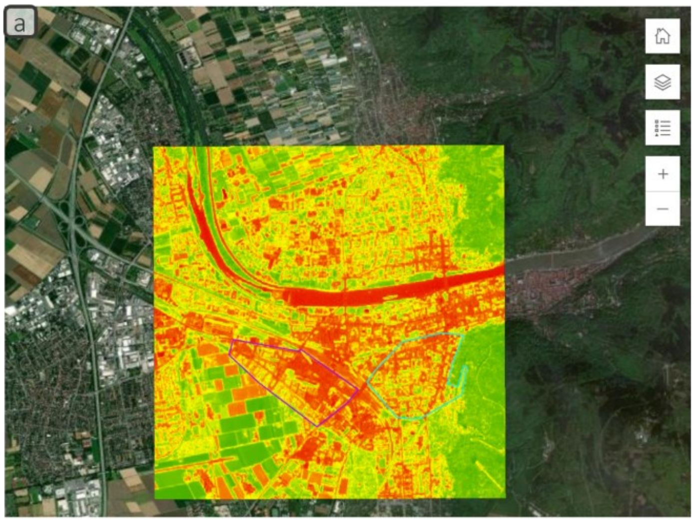
[1] Short for: Cycle 1, Group 9, Line 26

4.2. Cycle 2 – Task 2: Struggling with open-end tasks

In Cycle 1, the criteria were predefined, which proved to be effective. Consequently, the task was transformed into an open-ended format in Cycle 2, requiring students to select the criteria themselves in order to foster inquiry-based learning and problem-solving skills (Bayarcal & Tan, 2023). In Task 2, Cycle 2 students selected criteria to evaluate flood protection and recreational value in two city districts (Figure 4, c). In Task 2b, they were then asked to determine whether information on these criteria could be better collected with a digital vegetation index map or with Google Maps. Both web maps used high-resolution aerial imagery as their base map and both approaches were presented during the project days as methods of geographic inquiry. In the last part of Task 2, the students were to assess and grade the two districts based on the selected criteria.

The students struggled with Task 2a. Overall, they identified 15 criteria for flood protection; however, only four of these had been mentioned during the project day (e.g., “size” or “quantity”). Criteria such as “green spaces” or “trees” were related to the general topic, while others like “altitude” or “distance to the river” were broadly correct but lacked a clear connection to green spaces. Only two groups reused the criteria they had identified in Task 1.

a



b

Task 2 – cycle 2

Complete the table from left to right.

a) Select criteria to evaluate the protection against flooding and the recreational value of the two districts.

b) Select a method of geographic inquiry to collect information about the districts – Choose between the vegetation index map and a virtual field trip with Google Maps.

c) Assign grades to each district in the table. A grade of 1 means that the district fulfils the criteria completely. A grade of 6 means that the district does not fulfil the criteria at all

c

	Task 2a	Task 2b	Task 2c	
	Criteria	Collect information with	District 1 (purple)	District 2 (turquoise)
Protection against flooding	*Large green spaces*	*Vegetation index map*	*4*	*2*
Recreational value				

Figure 4. Task 2 from Cycle 2: In this task, learners use the vegetation index map displayed in a web map (a) or Google Maps to obtain information about green spaces in two districts (b). The criteria and the method of geographic inquiry for collecting information to be used for this purpose should be selected by the learners themselves (b, c). Possible solutions were inserted in italics. Image: Johannes Keller, Vegetation index: based on Image © 2023, Planet Labs PBC; Basemap: ArcGIS Living Atlas[2].

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Selecting between the vegetation index map and Google Maps in Task 2b was challenging for students ("[Choose a] *method for geographic inquiry that allows you to easily check whether a district meets the specified criteria. Recognizable in... Ah, now I can write down districts. Or what? Do you have any idea?* [...] *The task* [...] *is confusing us a little at the moment.*", C2, G5, L161). Only two groups completed the task, but their justifications for choosing a method were superficial and lacked clear links to the selected criteria. Other groups either skipped the task or could not recall what a method of geographic inquiry was.

All groups used the high-resolution aerial imagery provided as a base map in the web maps to assess how well the selected criteria were met. Only one group actively incorporated the vegetation index. All groups applied criteria to evaluate the climate adaptation of the districts; however, only two groups referred to criteria named in Task 2a, while the others used those mentioned during the project day. To evaluate the districts, four groups applied strategies similar to those observed in Cycle 1 (Table 2) and had little difficulty identifying green spaces.

No group developed a clear strategy for identifying information related to the criteria for recreational value. Instead, the students navigated the map randomly, zoomed in on various locations, and overlooked the markers provided for guidance ("*Where do you think there might be a playground? Maybe near the hospital?*", C2, G5, L364). Instead, most groups relied on prior knowledge or argued that the provided data source was unsuitable for the task ("*And you don't really see the leisure activities that much because it's a bit blurry, a bit out of focus.*", C2, G3, L94).

Students in Cycle 2 rated Task 2 as relatively easy, with an average score of 2 out of 5, regardless of their success in solving the task. Nevertheless, they reported difficulties with Tasks 2a and 2b and found the detailed task design somewhat exhausting.

4.3. Cycle 3 – Task 2: Solving the Task well

The results from Cycle 2 showed that students struggled with the open tasks. Consequently, Task 2 was simplified in Cycle 3 to provide clearer guidance. In Task 2a, students in Cycle 3 were only required to select criteria for climate adaptation, while the vegetation index map was predefined as the method of geographic inquiry. In Task 2b, they were then instructed to use the vegetation index map to evaluate and grade the districts based on the selected criteria (Figure 5).

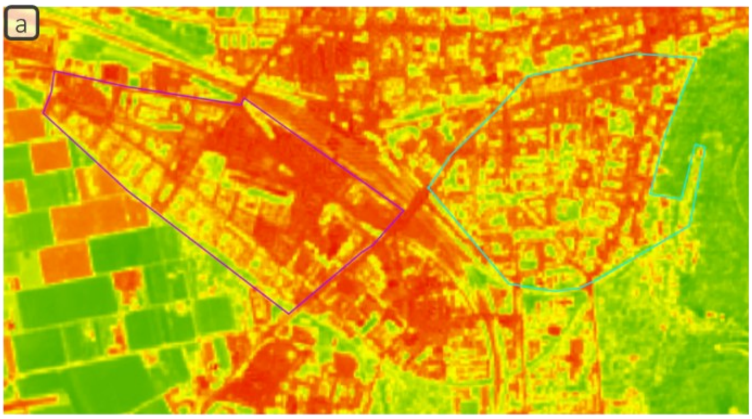
All but one group correctly recalled the criteria mentioned during the project day; only one group confused the topic with recreational value. The remaining groups employed strategies similar to those used in Cycles 1 and 2 to complete Task 2b (Table 2). No difficulties were reported in applying the vegetation index.

The limitations of the vegetation index were addressed through a dedicated task during the field trip. However, during the classroom debriefing, it became evident that most students had not completed this task in the field. Consequently, the teacher provided a summary of the index's limitations during the in-class follow-up. No group referred to these limitations in Task 2b.

4.4. Cycle 1 to 3: Insights into Task 3

Most groups successfully completed Task 3. The majority incorporated at least one criterion from Task 2 into their argumentation. In many cases, the structure of the argument followed a pattern such as: "*I would say* [this district], *because the western part of the city has so many small green spaces. And also some large ones.*" (C1, I9, L147). While some groups in Cycles 1 and 3 expanded their reasoning by establishing causal chains, no such elaboration was observed in Cycle 2. Across all cycles, students supplemented their arguments with prior knowledge.

In Cycles 1 and 3, students often made absolute statements about criteria ("*because* [district 1] *has so many small green spaces*", C1, I9, L174), whereas in Cycle 2, such claims were often relativized and explicitly framed as personal opinions ("*I think there are more playgrounds in…*", C2, I5, L470), especially concerning recreational value. In Cycle 1, two groups expressed uncertainty about whether selected criteria were sufficient, due to misunderstandings: "*It says here that we're supposed to talk about heatwaves too. But evenly distributed green spaces only protect against flooding. They don't protect against heatwaves.* […] *Trees protect against heatwaves.*", C1, I8, L222).



b

Task 2 – cycle 3

In which district can green spaces better prevent flooding? Complete the table using Task 1 from left to right.

a) Select criteria for green spaces to evaluate protection against flooding

b) Assign grades to each district in the table. A grade of 1 means that the district fulfils the criteria completely. A grade of 6 means that the district does not fulfil the criteria at all.

c

	District 1 (purple)	District 2 (turquoise)
There are large green spaces here.	2	3

Figure 5. In this task, students used the vegetation index map to collect information about green spaces in two districts (a). For this purpose, they were asked to select criteria for gathering information to be used in the analysis (b, c). Possible solutions were inserted in italics. Image: Johannes Keller, Vegetation index: based on Image © 2023.

5. Discussion

This study aimed to develop design principles to help teachers create tasks enabling students to independently select, collect, and process information using EO data. Following a DBR approach, tasks were designed, evaluated, and revised across three cycles (Easterday et al., 2018). When designing tasks that require students to use EO data to answer geographic questions, it is essential to provide a conceptual foundation to guide their thinking (Favier & van der Schee, 2014b; Keller & Siegmund, 2026). The study demonstrated that, by using the key geographic concept of spatial patterns, even lower secondary students were able to analyze EO data in order to answer geographic questions. The insights gained from these processes can be applied to support teachers and students in the effective use of EO data. The combination of conceptual knowledge and the ability to analyze EO data provides students with powerful knowledge to analyze, explain, and understand the world (Maude, 2016). Consequently, the main design principle "The key geographic concept 'spatial patterns' offers a conceptual foundation for integrating EO data into school education" proposed by Keller and Siegmund (2026, p. 17), prooved to be effective and was therefore further specified (Table 3). However, the study also identified specific conditions for successful implementation of this principle and areas requiring further refinement. These insights were used to address the research questions and to develop implementation guidelines for the main design principle, following the approach of Feulner et al. (2021). In doing so, existing implementation guidelines from Keller and Siegmund (2026) were adapted and refined (Feulner et al., 2021).

5.1. Development of the Implementation Guidelines

Key to implementing the main design principle was the development of the analytical framework, which also answers the first research question. This enabled teachers and students to use the key concept "spatial patterns" as a tool for developing lesson plans or, respectively, for analyzing EO data. The framework explains how criteria can translate spatial relationships into measurable components, which guide the selection, collection, and processing of information (Keller & Siegmund, 2026). As a result, it supports the selection of appropriate EO data and defines steps for answering guiding questions. The latter was used to develop a task progression, which students were generally able to use to apply the analytical framework in order to answer the guiding questions of the project day. Consequently, the developed analytical approach is designed to operationalize key geographic concepts and thereby support students in thinking geographically (Bendl et al., 2025). Although the analytical framework developed is limited to specific research approaches, it can be adapted to other research questions. Therefore, both the development and use of such a framework in task design were identified as the first two implementation guidelines for applying the main design principle (see Table 3). As contextual, conceptual, and methodological prior knowledge and the corresponding subskills are crucial for students to apply the analytical framework (van Merriënboer et al., 2002), it was selected as the third implementation guideline (Table 3). Although the implementation guidelines proved generally effective, the findings highlighted specific conditions for their successful application and outlined essential specifications:

In Tasks 2 and 3, students in all cycles applied the analytical framework by using criteria to evaluate spatial relationships. This enabled students to apply the key concept "spatial patterns", supported by the expanded concept map as a visualization (Dessen Jankell & Johansson, 2023). While Keller and Siegmund (2026) emphasized the importance of introducing the visualization and its application, the results of the present study showed that introducing the analytical framework inductively in a teacher-centered manner was effective. The latter aspect helped the students to familiarize themselves with the approach and develop the procedural knowledge needed to apply the analytical framework in the learning tasks (Seidel et al., 2013; Serwene, 2023). It also became evident that the expanded concept map, as a representational tool, effectively provided students with the necessary conceptual background and supportive information (Dessen Jankell & Johansson, 2023; Hmelo-Silver et al., 2017; van Merriënboer et al., 2002). Consequently, building a key conceptual understanding of "spatial patterns", as suggested by Keller and Siegmund (2026), appears unnecessary. Those aspects give rise to specific requirements for the analytical framework as specified in IG1 in Table 3.

Table 3. Summary of the further developed design principles from Keller and Siegmund (2026, p. 17f) as a list of implementation guidelines with practical recommendations, which specify the main design principle.

Main Design Principle
The key geographic concept "spatial patterns" provides a conceptual foundation for integrating EO data into schools. To this end, …
Implementation Guidelines (IG) with further requirements and specifications
IG 1: Teachers should develop an analytical framework to structure the use of EO data. • The analytical framework should illustrate how information that can be collected using EO data can be applied to answer a specific research question. In the example, criteria for spatial interrelations serve as measurable components to assess these relationships. • To help students understand the conceptual background of the analytical framework, an appropriate visualization should be developed or selected (see Keller and Siegmund, 2026, p. 18). • As the analytical framework is intended to be introduced inductively, it should facilitate the investigation of diverse geographic questions. For instance, the presented framework can be used to evaluate both the climate adaptation of two areas and their recreational value. • Teachers should be aware that the analytical framework serves as a tool for applying the key geographic concept "spatial patterns" only within a limited range of research approaches.
IG 2: The developed analytical framework should structure the selection, collection and processing of information using EO data. • Students should first identify which information is relevant, then collect it, and finally process it (Keller & Siegmund, 2026). Since these steps build strongly on one another, open task formats are only suitable when feedback is provided after each step and the focus remains on a single method of geographic inquiry, e.g., given EO data. • The analytical framework helps students define which information is relevant. To this end, it has proven effective to revise conceptual and contextual background using the developed visualization as presented in a summarizing Task 1 (Favier & van der Schee, 2014b). Allowing students to select criteria themselves is only effective with certain EO data and has proven challenging. Successful implementation requires prior knowledge, a focus on given EO data, and teacher feedback. • Students need procedural and supportive information to translate EO data into meaningful insights. Suitable learning products can be used for this purpose (e.g., tables), and spatial thinking skills should be introduced. Additional scaffolds, such as more examples or sample arguments, can provide further guidance. Collaborative learning environments enable students to engage in meaningful discussions and effectively apply spatial thinking skills. • Further consolidation of the information using the expanded concept map, as suggested by Keller and Siegmund (2026), appears unnecessary. • Limitations of the EO data and the analytical framework should be addressed through a dedicated task to foster EO-related data literacy.
IG 3: Students need to acquire contextual, conceptual, and methodological prior knowledge and the corresponding subskills to apply the analytical framework.

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- Contextual and conceptual background should be introduced using the visualization (see Keller and Siegmund, 2026, p. 18).
- The analytical framework should be introduced inductively to help students build procedural knowledge. It proved effective when the analytical framework was applied in a teacher-centered manner.
- EO data should be introduced through hands-on activities and meaningful examples. In this context, students should learn how to apply spatial thinking skills to translate EO data into meaningful information.

The implementation guideline IG2 was primarily applied in the development of learning tasks. As suggested by Keller & Siegmund (2026), it has proven effective for students to first identify which information is relevant, then collect, and finally process it. To collect information, students need to decide which information is relevant and identify it within the EO data. In Cycle 3, the summarizing Task 1 seemed to be effective in supporting students in finding correct criteria, as most students solved it correctly. However, students in Cycle 2 experienced challenges in selecting appropriate criteria for further analysis in Task 2a. This discrepancy can be attributed to two main factors:

First, students in Cycle 2 had lower prior knowledge than those in Cycle 3, and only one group was able to recall criteria related to climate adaptation from Task 1. Others, for example, confused climate adaptation with climate mitigation in Task 1 (Graulich et al., 2021). Consequently, they were unable to use the summarizing task as intended, which is why further support may be necessary (Brod, 2021).

Second, Task 2 in Cycle 2 was more open-ended, which introduced additional sources of error. For example, students selected unsuitable criteria that could not be evaluated using the given methods of geographic inquiry (vegetation index or Google Maps) or did not use the provided maps as intended. Since the individual steps within the analytical framework build strongly on one another, open task formats are only suitable to a limited extent for implementation (Sullivan et al., 2015). To effectively implement open-ended tasks, prior knowledge must be systematically built, tasks should focus on a single method of geographic inquiry, and teachers should provide feedback at each step.

The results indicated that, under certain conditions, students successfully used the vegetation index to collect relevant information. In Cycles 1 and 3, it became evident that defined criteria (Favier & van der Schee, 2014), along with procedural and supportive information, were particularly helpful (van Merriënboer et al., 2002). The latter, such as the tables in Figures 2, 4, or 5 and the use of spatial thinking skills, enabled students to translate EO data into meaningful information (Gersmehl & Gersmehl, 2006; van Merriënboer et al., 2002). Additional scaffolding could be provided by offering more examples, including best- and worst-practice cases or sample arguments. Spatial thinking skills were primarily observed during group discussions, where students negotiated and agreed on a final assessment. This suggests that collaborative settings play a key role in fostering and applying spatial reasoning in EO-based learning, a finding supported by other research (Chi & Wylie, 2014; Pilato et al., 2023).

Furthermore, a targeted introduction to EO data, using meaningful examples, hands-on activities, and explicit application of spatial thinking skills, proved effective. The difficulties in Cycle 2, for example, may be attributed to the brief introduction on using Google Maps for information collection, which appeared unproblematic for older students (Keller & Siegmund, 2026). For younger students, it seems beneficial to narrow the topic and provide a clearly defined method of geographic inquiry and EO data.

Overall, results indicate that students were able to use the vegetation index to identify green spaces at a basic level. This may be attributed to its ability to highlight vegetation (Svatonova & Kolejka, 2017; Wabnitz, 2019). However, all groups ignored vegetation index limitations, indicating insufficient EO-related data literacy (Gebre, 2022). Although such forms of geographic inquiry are well suited to fostering data literacy (Gebre, 2022), this potential can only be realized if tools and tasks are deliberately designed to support the development of students' data literacy skills (Dorsey et al., 2025). However, it remains unclear whether addressing these limitations during a field trip is effective (Keller et al., 2024b). Overall, there is a lack of established concepts for teaching EO-related data literacy, as existing approaches focus primarily on the responsible use of geo-data and maps (Gryl et al., 2012), and a general implementation in German national curricula is still missing (Peter & Sprenger, 2022). Additionally, such forms of inquiry-based teaching require teachers' expertise (Mašterová, 2023), which is why more explicit design principles and further training are needed. In summary, these explanations show that various measures must be taken to enable learners to independently analyze EO data, which provides answers to the second and third research questions.

In the concluding phase in Task 3, students are expected to apply the key geographic concept "spatial patterns" and synthesize the collected data to respond to the research question. The study showed that most students applied the given analytical framework by comparing the areas using the criteria. Further consolidation of the information using the expanded concept map to process information, as suggested by Keller and Siegmund (2026), appears unnecessary (Table 3, specification of IG2).

Although the analytical framework helps structure the selection, collection, and processing of information by reducing complexity, they may also oversimplify interrelationships and restrict open-ended or authentic problem-solving tasks. To overcome these shortcomings, it is essential to facilitate a broader discussion of the results during the project day, as this also supports the development of students' data literacy (Gebre, 2022).

5.2. Limitations

The convenience sample consisted of German students from two different school types and age groups. Participants in Cycles 1 and 3 were fifth-grade students from the same grammar school, which is considered comparatively high-achieving relative to national benchmarks (Reiss et al., 2019). In contrast, Cycle 2 included seventh-grade students from a secondary school. Participation rates were much higher in Cycles 1 and 3, which made these two cycles more comparable to each other than to Cycle 2.

The group discussions conducted during the think-aloud studies provided valuable insights into learners' strategies and challenges. Nevertheless, even with targeted probing, some cognitive processes may not have been verbalized (Leighton, 2024). Additionally, in group work settings, dominant participants may have constrained the contributions of others (Morgan, 1997). Given the strong alignment of the findings across the cycles and with existing literature, intercoder reliability was not calculated.

Overall, the sample size was relatively small, which limits the representativeness of the quantitative data. To assess the multidimensional construct of intrinsic motivation (Ryan & Deci, 2020), a short scale consisting of four items was employed. While this approach reduced cognitive load and administration time, it limits the validity of the questionnaire (Keller et al., 2024b). No measures were taken to ensure the validity or reliability of the developed quizzes and the gap test. However, the collected data were strongly consistent with the results from the think-aloud studies. Still, the quizzes administered after instruction on the vegetation index were considered relatively easy (Table 1), which could result in a ceiling effect (Garin, 2014) and limit their usefulness for assessing students' deeper understanding of the vegetation index. Despite these limitations, the quantitative data provided valuable complementary insights into the qualitative findings, which formed the basis for addressing the research questions.

The study design and chosen methods clearly limit the generalizability of the findings. The overall results indicate that the students were able to use key geographic concepts, thereby supporting the application of geographical thinking skills. However, it remains unclear whether these skills or other relevant competencies increased over the long term. To evaluate this, further quantitative research is required. Despite these limitations, the data provide valuable insights into how students from different school types engage with EO data using the key concept of "spatial patterns".

Furthermore, this study provides only a local theory (Serwene et al., 2024) for integrating the vegetation index into learning processes, based on the German key concept "spatial patterns". It seems reasonable that these design principles could apply to EO data in general as well as to geographic inquiry methods such as maps and digital geo-media (Keller & Siegmund, 2026). Since specifications of the implementation guidelines, such as feedback or the use of visualizations, are broadly supported by other research, it can be assumed that the design principles could be adapted to other key geographic concepts, including "space and place" or "interdependence" (Taylor, 2008). Further research is required to validate this assumption.

6. Conclusion

Using EO data to understand our changing planet provides students with powerful knowledge. However, its implementation in geography education is limited by insufficient teacher expertise. This study demonstrates that the German key geographic concept of "spatial patterns" can help students apply geographic thinking to analyze EO data and provides empirically grounded design principles for their implementation. Together with additional training, these design principles should enable teachers to create educational materials that are tailored to their students' needs. Our findings show that even lower secondary students can successfully select, collect, and process information using EO data when supported by a well-defined analytical framework, targeted prior knowledge, and method-specific scaffolding. However, challenges persist, especially in open-ended task formats and the promotion of EO-related data literacy, particularly regarding the limitations of EO data. In summary, this study delivers practical tools and clear recommendations that empower teachers to make EO data an integral and effective part of geography education. Future research should aim to expand existing design principles for inquiry-based learning with EO data and investigate how these principles can inform task design through the use of artificial intelligence.

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SI_TGEO
Teaching Geography
for a World in Transition

Contribution to the Special Issue Topics: The ability to analyze EO data enables students to explain and understand our changing world, thereby providing access to powerful geographical knowledge. As ongoing digitalization expands the availability and use of geospatial technologies, EO data offer increasing opportunities for geography education and inquiry-based learning. Building on these developments, this paper presents empirically grounded design principles that support teachers in effectively integrating EO data into school practice.

Appendix

Survey & Quiz

Part 1

This is about your opinion on Worksheet 2. Tick the appropriate box: 1 = "strongly disagree" to 5 = "strongly agree". If you do not want to give an answer, simply leave all boxes unchecked.

Item	1	2	3	4	5
I enjoyed working with the satellite images.					
I was able to decide for myself how to work with the satellite images.					
I was very good at working with the satellite images.					
I felt under pressure when working with the satellite images.					

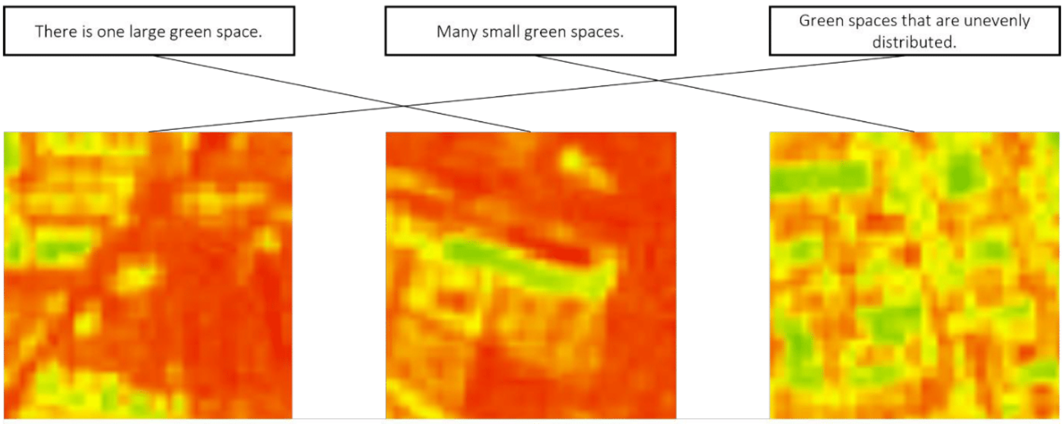
Part 2

Task 1 (Representation Quiz):

What color do green spaces have in the vegetation filter? **Green**

Task 2 (Matiching Quiz):

Match the pictures with the appropriate statement.



Vegetation index: based on Image © 2023, Planet Labs PBC

Part 3

Task 3 (Gap Test):

Due to climate change, the risk of flooding in cities is increasing. **Green spaces** help to **protect** cities from flooding, because rainwater can **infiltrate** on green spaces. For green spaces to protect particularly well against the **impacts** of climate change, they must meet certain **criteria**. The larger a green space is, for example, the more **rainwater**.

If you like, you can hand in this survey and quiz to support my research. Thank you!

Figure A1. Survey and Quiz which formed the basis for the quantitative data. The test was completed individually using pen and paper. Solutions are inserted in bold and underlined.

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