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Hyperedu online learning program for hyperspectral remote sensing: Concept, implementation and lessons learned

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ABSTRACT

The increasing importance of Earth observation information for society and environment, particularly in the expanding domain of hyperspectral remote sensing, along with the significantly increasing data availability, emphasizes the demand for online education to address the growing need for expertise in this domain. We present a comprehensive review of existing online education programs on Earth observation that underline the limited availability of online resources for hyperspectral remote sensing.

To respond to this demand, we introduce HYPERedu, an online education program on hyperspectral remote sensing that has been developed as part of the EnMAP satellite mission since 2019. The program's core components, content, and participation statistics, along with insights from participant feedback, are presented. HYPERedu offers a wide range of resources, including slide collections, tutorials, video screencasts, and online courses, making them accessible to a broad audience for university teaching, training schools and individual learning. The program's effectiveness as well as challenges and insights encountered during program development are discussed. We emphasize the importance of collaborative learning, sustainability efforts for long-term material accessibility and quality assurance, and the need to bridge the digital divide with offline options, open-source tools, and multilingual content. Effective content presentation is vital, focusing on consistent branding, concise modules, interactive features, and narrative-style videos. Additionally, we explore the future of online Earth observation learning, considering enhanced participant interaction and the integration of new learning concepts. Finally, we underscore the significance of outreach and training for satellite mission utilization and advocate for open education to promote open science, data, software, and accessibility for inclusive education.

1. Introduction

Earth observation (EO) is the gathering of information about the planet Earth by terrestrial, airborne or spaceborne remote sensing technologies. One significant approach in EO is hyperspectral remote sensing, also known as imaging spectroscopy. This method facilitates the acquisition of geophysical and biochemical measurements across terrestrial and aquatic ecosystems required in various application fields such as agriculture and forestry, mineral exploration, soil mapping or water quality monitoring. Hyperspectral data availability is constantly increasing with the rising number of imaging spectrometers deployed on airborne and spaceborne platforms. In view of these developments, a strongly increasing interest in imaging spectroscopy data analysis in research and education is expected in the next few years.

The overall need for EO education and training activities is currently also reflected by a growing number of online learning platforms and Massive Open Online Courses (MOOCs) for various EO techniques, application fields and target audiences. The COVID-19 pandemic has certainly contributed to the fast expansion in online education. Dubois et al. (2022) investigated the impact of digital teaching and learning on EO courses at universities during the pandemic, suggesting the use of specific digital elements and interaction forms for different course types and proposing the integration of additional digital elements to enhance hybrid education in the future. Table S1 in the supplementary material provides an overview of selected major EO education platforms that are currently available and provide online courses, (recorded) webinars and learning materials with free access. While most platforms target students and young professionals, there are also specific programs and initiatives

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for EO education at schools (e.g., Hodam et al., 2020; Rienow et al., 2020). Filchev et al. (2020) give a comprehensive overview of online learning resources for EO education in secondary schools, including main EO education initiatives supported by international, EU and national organizations. Apart from the platforms offering EO online learning resources, network initiatives such as EOTEC DevNet (https://www.eotecdev.net) aim at improving coordination and engagement among national, regional, and global institutions providing training, education and capacity building in the field of EO.

However, hyperspectral remote sensing is currently underrepresented or only marginally covered on these platforms and online educational resources. In general, online resources on hyperspectral remote sensing are either provided by space agencies, national and international organizations, universities or companies working in the field of imaging spectroscopy. Our comprehensive web search has yielded an overview of currently available online learning resources for hyperspectral remote sensing, as presented in Table S2 in the supplementary material. Notably, many resources have been published only in the last few years, indicating that hyperspectral online education is a rather young and dynamically developing field. These resources predominantly comprise of recorded lectures, webinars and instructional videos , but to the best of our knowledge there is no modular course material on hyperspectral remote sensing other than the HYPERedu program that is presented in this publication.

In response to the limited and heterogeneous educational resources available for hyperspectral remote sensing, and recognizing the increasing demand for comprehensive training and educational tools in this specialized domain, we initiated the online education program HYPERedu in 2019 as part of the scientific preparation of the EnMAP mission (Guanter et al., 2015). EnMAP (short for Environmental Mapping and Analysis Program) is a German spaceborne imaging spectroscopy mission. The EnMAP satellite is equipped with a VNIR-SWIR pushbroom hyperspectral imager that spans a spectral range of 420–2450 nm across 224 contiguous bands. It features a ground sampling distance of 30 m and a swath width of 30 km. EnMAP operates in a sun-synchronous orbit with a nominal revisit time of 27 days, providing global coverage from 74° N to 74° S through on-demand data acquisitions. EnMAP was successfully launched into space in 2022 (Storch et al., 2023), further underlining the significance and timeliness of HYPERedu's establishment in advancing knowledge dissemination with regard to hyperspectral remote sensing.

HYPERedu targets primarily graduate students and professionals in research, business and public institutions seeking to learn (or teach) the principles, methods and applications of imaging spectroscopy. The learning materials encompass a series of MOOCs, slide collections, hands-on tutorials based on the EnMAP-Box software (Jakimow et al., 2023), educational videos and interactive graphics. All material is provided free of charge under a CC-BY License for use in training courses, university teaching or individual learning.

HYPERedu is funded within the German EO program by the DLR Space Agency and its development is coordinated by the German Research Centre for Geosciences (GFZ) Potsdam in cooperation with a range of international research partner institutions that are active in the field of imaging spectroscopy. Even though HYPERedu was initiated as part of the EnMAP mission science program, it is regarded as an initiative by and for the whole hyperspectral community. All learning resources and courses are published on the EO College platform, an open online learning platform for EO since developed since 2017. It caters to the specific needs of the EO community, providing a virtual learning environment that is accessible to learners worldwide, following an open education policy. EO College hosts courses and learning materials and also serves as a hub for networking and collaboration, allowing learners to connect with experts and peers in the field. EO College and HYPERedu also serve as the German contribution to the e-learning activities of the Working Group on Capacity Building and Data Democracy (WGCapD) of the Committee on Earth Observation Satellites (CEOS). The CEOS WgCapD supports coordination and partnerships among CEOS Space Agencies and other capacity building networks offering EO education

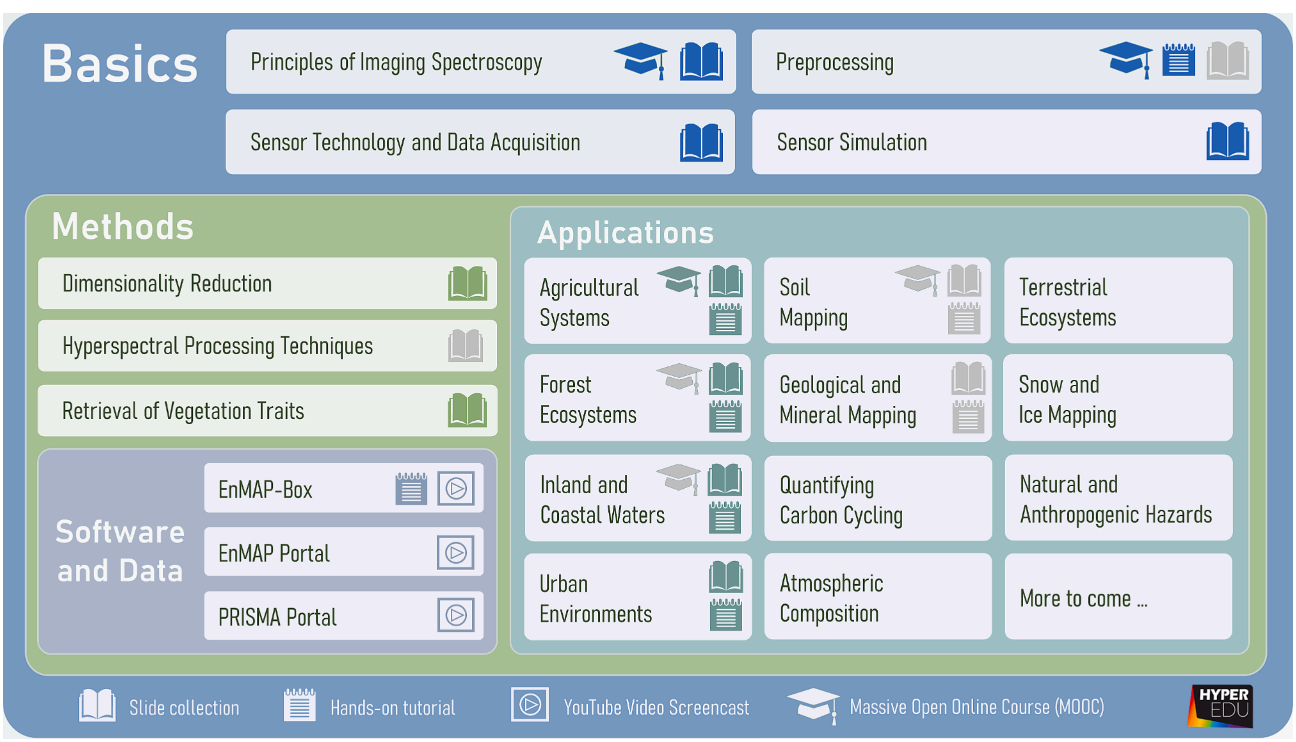

Fig. 1. Overview of contents, structure, type and status of publication of HYPERedu online learning materials. The colored icons mark already published material of different types (slide collection, hands-on tutorials, video screencasts, MOOCs) as of May 2024. The gray icons mark materials currently in preparation for publication.

and training. Teaching and training offers focus particularly on less developed countries to increase the capacity of effective use of EO data for the benefit of society and sustainable development.

After a short introduction to the current online education landscape in the field of EO and specifically hyperspectral EO in this chapter, the primary objective of this paper is to provide a comprehensive overview of the online education program HYPERedu for hyperspectral remote sensing. We will outline its core concept, content, and components, along with presenting statistical data regarding program participation and insights from participant evaluations and feedback. Additionally, we discuss the lessons learned and the challenges encountered during the implementation of the program. Moreover, we will offer an outlook on the future of online learning in the field of EO, considering aspects such as enhanced participant interaction, the integration of new learning concepts, and the adoption of open education strategies. Through this comprehensive work, we aim to contribute valuable insights to the field of EO education and online learning methodologies.

2. Concept, contents and components of the HYPERedu online education program

The development of the HYPERedu online learning initiative for hyperspectral remote sensing began in 2019. Our approach involved structuring resources into three key areas: basics, methods, and applications of imaging spectroscopy, as well as software and data, presented through diverse learning materials, including slide collections, tutorials, video screencasts, and complete MOOCs (Fig. 1).

2.1. Slide collections and tutorials

We began with the development of the slide collections and tutorials as these would form the basis for the subsequent MOOCs. Our goal was to provide professional, graphics-rich materials for educational purposes in training schools, university teaching and individual learning, all provided free of charge. In order to allow for the recombination of slides from different collections as well as to establish HYPERedu as a recognizable brand, we developed a corporate layout and style. This endeavor, which aimed to match all graphics with this style while ensuring they were freely available, proved to be a time-consuming activity. Careful assessment and documentation of image rights, the search for suitable open access images and the creation of many new images were essential. To engage and serve students and professionals in research, business, and public institutions, all materials are designed at a master's level. We set the standard that all slide collections should roughly fill a (German) standard 90-minute university lecture. To make the initiative work by and from the entire hyperspectral community, we decided to provide all materials in English with the option for translations to other languages at a later time.

The first slide collection *Principles of imaging spectroscopy* was published in September 2019. Since then, HYPERedu has evolved considerably. Within the subsequent years and with the support and contributions of many colleagues from various institutions worldwide, we published another two basic slide collections on *Sensor Technology and Data Acquisition* and *Sensor Simulation*, two slide collections in our methods section on *Dimensionality Reduction* and *Retrieval of Vegetation Traits* as well as several applications slide collections on *Agricultural Systems*, *Forest Ecosystems*, *Inland and Coastal Waters* and *Urban Environments*. In contrast to the materials from our basic and method sections, the materials in the applications section all come in combination with hands-on tutorials based on the EnMAP-Box software. Table S3 provides an overview of all currently available slide collections and tutorials available on EO College (https://eo-college.org/resource-spectrum/hyperspectral/).

We established workflows and templates that ensure all materials follow comparable structures. All resources are continuously extended and updated if needed.

2.2. Moocs and videos

According to learning theory, the average retention rate increases the more actively a person gets involved with the learning materials. While the traditional passive methods of lecturing, reading and audio-

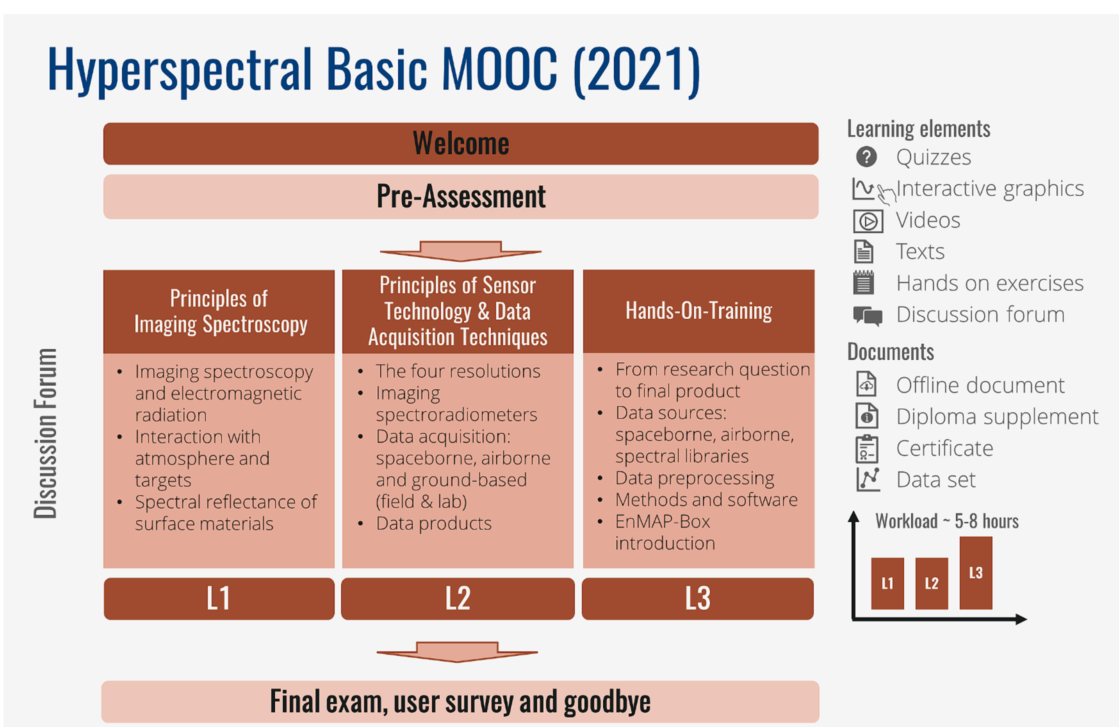

Fig. 2. Basic MOOC structure.

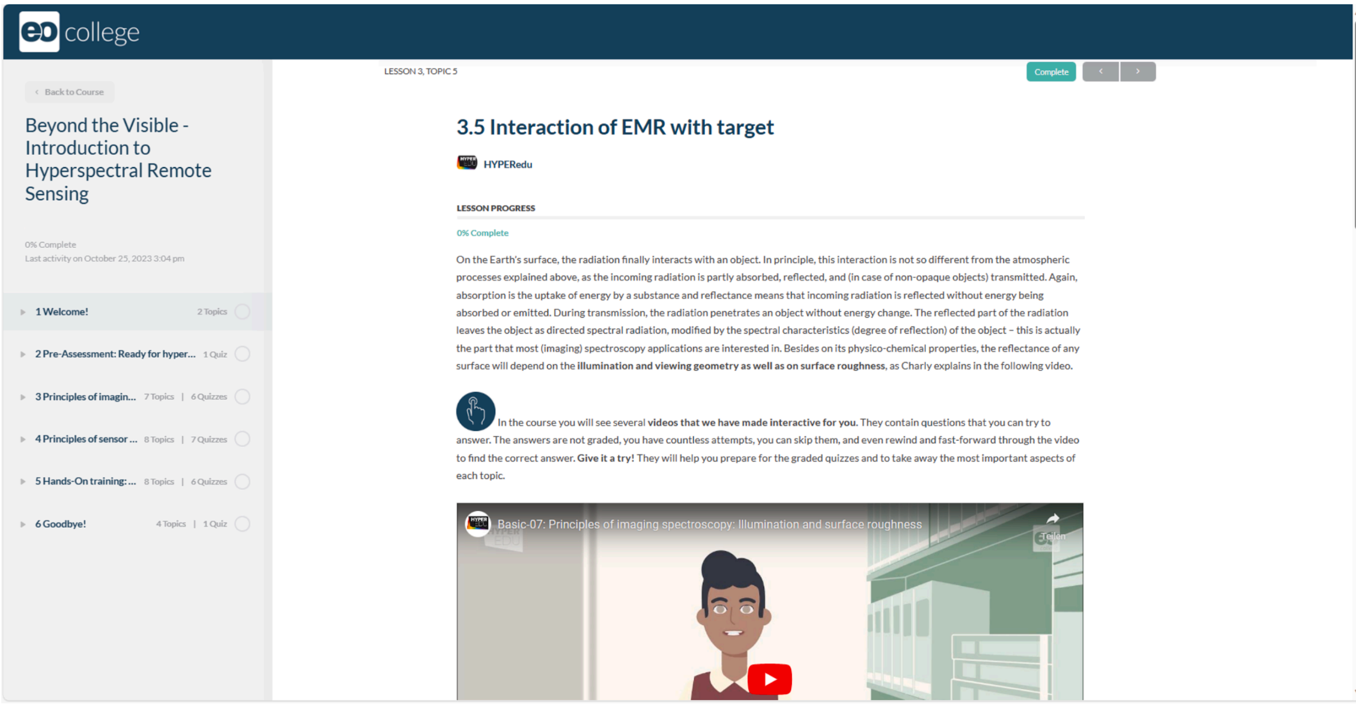

Fig. 3. Course interface of the Basic MOOC *Introduction to hyperspectral remote sensing* in the *Beyond the visible* course series published at the EO College platform.

visual learning result in lower retention rates, more active methods such as discussion groups, practical exercises and the immediate use of the learned can yield retention rates of up to 90 % (Dale, 1969). Thus, in order to get our students more actively involved, we started to work on a first MOOC in 2021. This MOOC titled *Beyond the Visible: Introduction to Hyperspectral Remote Sensing* was successfully opened in November 2021 and marked – to our knowledge the first-ever – MOOC on the fundamentals of imaging spectroscopy. The course is structured in three thematic lessons framed by a welcome lesson followed by a pre-assessment quiz and a goodbye lesson with final exam (Fig. 2). It is designed to take about five to eight hours to be completed at one's own pace at any time. It teaches the principles of imaging spectroscopy, sensor technologies and data acquisition techniques as well as data sources and software using state-of-the-art e-learning approaches. Building on the materials created in the first two years of HYPERedu, we expanded our range of learning elements. As a result, the course offers plenty of opportunities for activity and playful interaction such as interactive graphics, quizzes, a discussion forum and expert-led hands-on training exercises. In addition, it led to the creation of Charly (Fig. 3), a virtual character that guides the users through the basic course and all subsequent ones.

After successful completion and passing of the final exam, participants receive a certificate as well as a diploma supplement with a more detailed description of the course content.

The expansion of learning elements is reflected in Fig. 1 in the elements video and MOOC. While the MOOCs are available via the EO College platform, all videos that are part of the courses are also freely accessible on the HYPERedu YouTube video channel (@HYPERedu_GFZ) as a second platform. These videos are organized into separate playlists for each course. On EO College, the MOOCs are created within a LearnDash environment utilizing the WordPress platform and

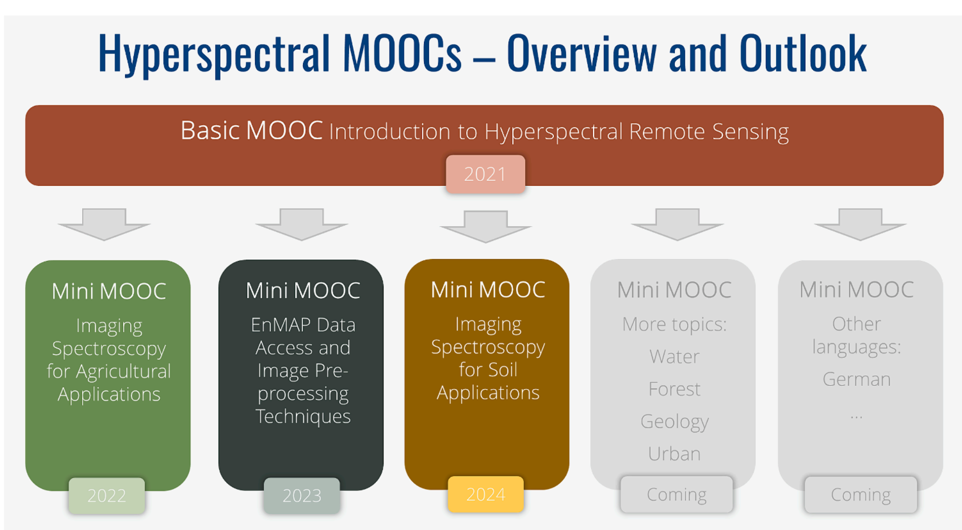

Fig. 4. HYPERedu MOOC series overview and outlook as of May 2024.

Table 1
Online courses published within the HYPERedu program as of May 2024.

Course title	Course contents	Type of course materials	First publication date	Number of participants that completed the course (as of 28.05.2024)	Course page / Reference
Beyond the Visible – Introduction to Hyperspectral Remote Sensing	Principles of imaging spectroscopy, sensor technologies and data acquisition techniques, data sources and software including screencast on EnMAP-Box	26 videos, 10 interactive graphics, 6 tutorials and 19 quizzes, final exam, offline course document.	November 2021	656	**Course landing page**: https://eo-college.org/courses/beyond-the-visible/ **Course material**: A. Brosinsky, S. Foerster, K. Koch, M. Brell, D. Scheffler, N. Pinnel (2023). Beyond the Visible – Introduction to Hyperspectral Remote Sensing. Massive open online course. Course material. HYPERedu, EnMAP education initiative, GFZ German Research Centre for Geosciences. https://doi.org/10.48440/enmap.2022.003.
Beyond the Visible – Imaging Spectroscopy for Agricultural Applications	Introduction to imaging spectroscopy for agricultural applications, hands-on exercise using the EnMAP-Box Agricultural Applications	17 videos, 2 interactive graphics, 6 tutorials and 12 quizzes, final exam, offline course document.	November 2022	127	**Course landing page**: https://eo-college.org/courses/beyond-the-visible-imaging-spectroscopy-for-agricultural-applications/ **Course material**: A. Brosinsky, C. Wilczok, S. Foerster (2022). Beyond the Visible – Imaging Spectroscopy for Agricultural Applications. Massive open online course. Course material. HYPERedu, EnMAP education initiative, GFZ German Research Centre for Geosciences. https://doi.org/10.48440/enmap.2022.002.
Beyond the Visible – EnMAP data access and image preprocessing techniques	Hyperspectral image preprocessing over land, EnMAP data access including screencast on the EnMAP Data Portal, hands-on training using EnMAP Processing Tool (EnPT) in the EnMAP-Box	10 videos, 2 interactive graphics, 5 tutorials and 13 quizzes, final exam, offline course document.	July 2023	69	**Course landing page**: https://eo-college.org/courses/beyond-the-visible-enmap-data-access-and-image-preprocessing-techniques/ **Course material**: A. Brosinsky, C. Wilczok, S. Foerster, K. Koch, T. Hank, K. Berger, M. Wocher (2022). Beyond the Visible – EnMAP data access and image preprocessing techniques. Massive Open Online Course. Course material. HYPERedu, EnMAP education initiative, GFZ German Research Centre for Geosciences. https://doi.org/10.48440/enmap.2023.001.
Beyond the Visible – Imaging Spectroscopy for Soil Applications	Introduction to imaging spectroscopy for soil applications, hands-on exercise using EnSoMAP in the EnMAP-Box		to be published in June 2024		**Course landing page:** https://eo-college.org/courses/beyond-the-visible-imaging-spectroscopy-for-soil-applications/

Table 2
Total number of users enrolled, started, and completed in the three published MOOCs as of 28.05.2024.

Course title	First publication date	Enrolled	Started (% of all enrolled)	Completed (% of all enrolled)
Beyond the Visible – Introduction to Hyperspectral Remote Sensing	November 2021	2552	1513 (59.3 %)	656 (25.7 %)
Beyond the Visible – Imaging Spectroscopy for Agricultural Applications	November 2022	543	312 (57.5 %)	127 (23.4 %)
Beyond the Visible – EnMAP data access and image preprocessing techniques	July 2023	252	132 (52.4 %)	69 (27.4 %)
Total		3347	1957 (58.5 %)	852 (25.5 %)

incorporating H5P elements to enhance interactivity and engagement. For all those who prefer more traditional learning over modern online courses or have limited internet access, there is the option to download the entire course in the form of a PDF document. However, to receive a certificate, participants must successfully pass the final online exam.

Lessons learned and user feedback were evaluated in detail and used for revising the course in 2022. In addition, feedback from the MOOCs final survey guided the development of subsequent shorter MOOCs focused on specific application fields (Fig. 4). Responding to user requests (24 % of all votes), a shorter MOOC *Beyond the Visible: Imaging Spectroscopy for Agricultural Applications* was published in 2022 in cooperation with colleagues from the LMU in Munich, Germany. Despite providing several tutorials already, the LMU colleagues designed a completely new hands-on exercise specifically for this course. The course follows the same general structure as the basic MOOC with three thematic lessons framed by a welcome lesson followed by a pre-assessment quiz, and a goodbye lesson with a final exam. With an estimated completion time of two to four hours it is considerably shorter though, thus we call it a Mini-MOOC.

Next, HYPERedu published a Mini-MOOC titled *Beyond the Visible: EnMAP data access and Image Preprocessing Techniques* in July 2023. Unlike the two previous MOOCs that were focused on hyperspectral data in general, this course focuses on EnMAP satellite data, specifically how to order and access them and take first processing steps. Structurally, the course follows the established scheme of three thematic lessons framed by an introduction, pre-assessment quiz and a goodbye lesson.

For 2024 and subsequent years, we are planning to publish Mini-MOOCs on soil applications, coastal and inland water applications, forestry, geology and urban applications. Additionally, we are working on a German version of the basic MOOC in response to user requests (Fig. 4). For a complete list of currently available HYPERedu MOOCs, please see Table 1.

3. Participants and evaluation results

In this chapter, we present the participant and view statistics based on course and YouTube video statistics, as well as the participants' feedback on the courses collected through a general and a final user survey, respectively.

3.1. Participant and view statistics

As described in the previous chapter, the HYPERedu program currently encompasses three MOOCs. Among these, the basic course *Beyond the Visible – Introduction to Imaging Spectroscopy*, as the longest available, has been successfully completed by more than 650 participants within less than two and a half years since its opening in 2021 (see Table 1 for details on participant numbers). The completion rates for all three MOOCs were approximately one-quarter of all enrollees (25.5 %) and almost half of all those who actually started the courses (43.5 %). (Table 2).

It is a common trend in online courses that more participants enroll than actually start the course. For all our courses, more than half of all enrollees (average 58.5 %) have actually started the course. It's worth noting that the rates of start and completion only show a momentary picture at the time of evaluation as some participants are still in the process of starting and completing the courses.

The MOOC participants are globally distributed with most participants in absolute numbers from Germany and India (Fig. 5). The global map of users viewing the videos provided in the HYPERedu YouTube

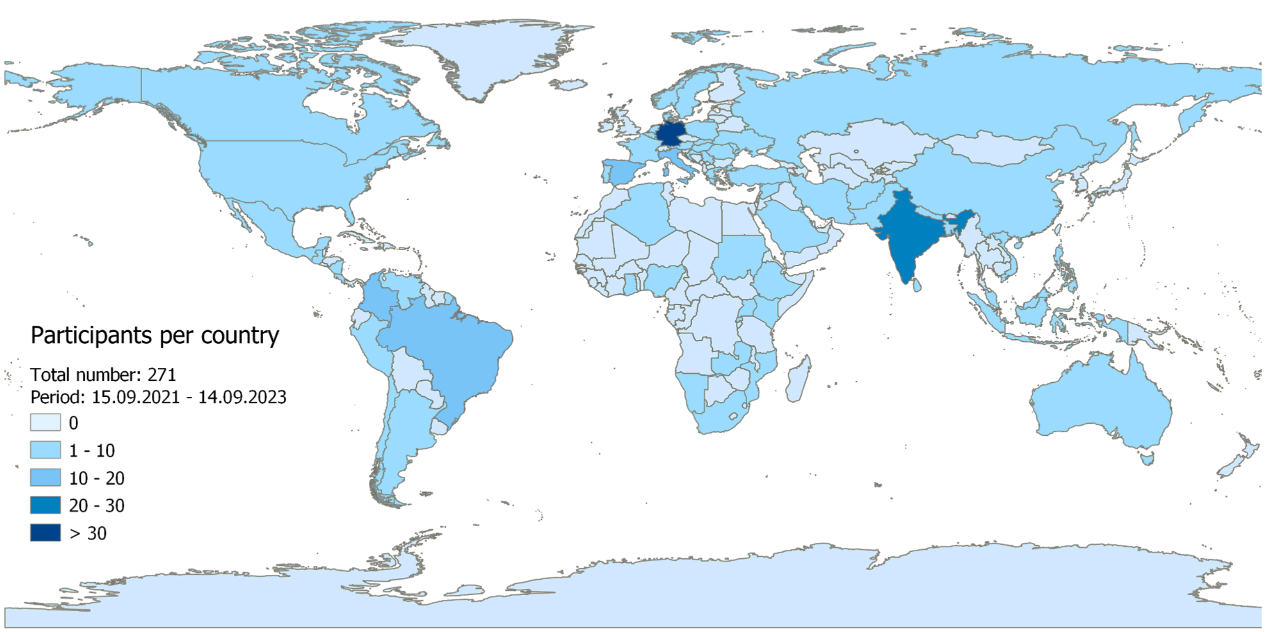

Fig. 5. Participant numbers of the Basic Hyperspectral MOOC, Agricultural Hyperspectral MOOC and the EnMAP data access and image preprocessing techniques MOOC per country that submitted the user survey (271) as of 14.09.2023.

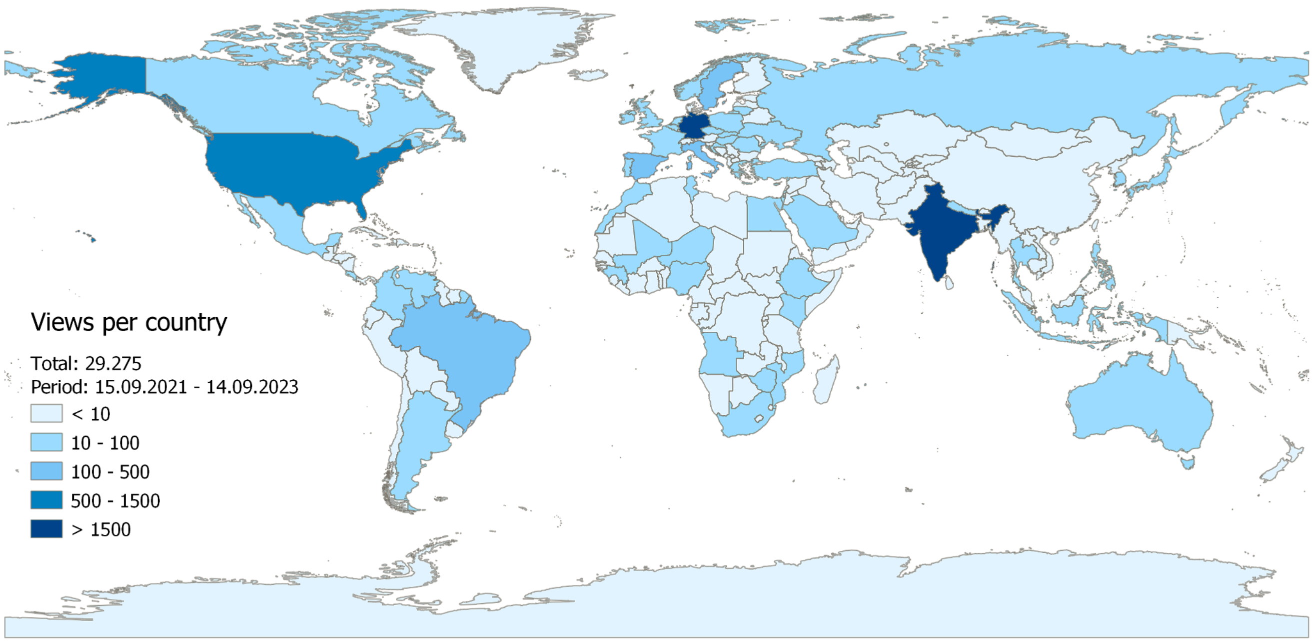

Fig. 6. Video views in the HYPERedu YouTube channel in percentage by country in the period 15.09.2021–14.09.2023.

Table 3
Overview of HYPERedu videos by type sorted by average playing time as of 21.09.2023. All videos are available in the HYPERedu YouTube channel at www.youtube.com/@HYPERedu_GFZ.

Video type	Number of videos	Overall number of views	Average number of views per video	Average playing time in %	Average video length in minutes
Animated lecture slides	9	6607	734	69,02	04:31
Lesson intro	9	1251	139	53,67	01:40
Instructional field / lab videos	6	4605	768	49,82	05:43
Goodbye	1	130	130	46,37	02:57
Expert interview	3	1455	485	44,09	07:58
Welcome	3	787	262	44,07	04:05
Course trailer	3	3998	1333	40,02	01:44
Screencast on software use	20	10,014	501	35,68	07:23
Making-of	1	162	162	32,06	02:47
Sum	55	29,009			

channel reveals a slightly different pattern (Fig. 6). Interestingly, it seems that some nationalities (e.g. several African countries) favor participating in our MOOCs over watching YouTube videos while users from other countries, like the United States, evidently prefer YouTube videos over MOOC participation. The regional differences of preferring MOOCs or YouTube videos may be due to a range of reasons such as differences in educational cultures, learning styles, willingness to commit to a MOOC or need for a credential upon finishing the MOOC.

The number of participants enrolling and actually starting the course, as well as the geographical distribution of participants is presumably also strongly dependent on the promotion channels of the courses. We have promoted the courses through various established distribution channels, including established email distribution lists within the community, social media and collaboration partner networks. In addition, we regularly raise awareness of HYPERedu through presentations to professional audiences but also to the general public. The enrolment figures clearly show peaks as a direct result of announcements via the distribution channels or after presentations, but also a steadily increasing number of enrolments over time.

The videos available through the HYPERedu YouTube channel are of different types and lengths (Table 3). They are viewed by users with varying frequency and for different durations. Course trailers achieved the highest number of average views per video with more than 1300 clicks, followed by instructional videos with > 750 views, animated lectures with > 700 views, screencasts on software use with > 500 views and expert interviews with > 450 views each. In contrast, the average playing time per video slightly varies: animated lecture videos were

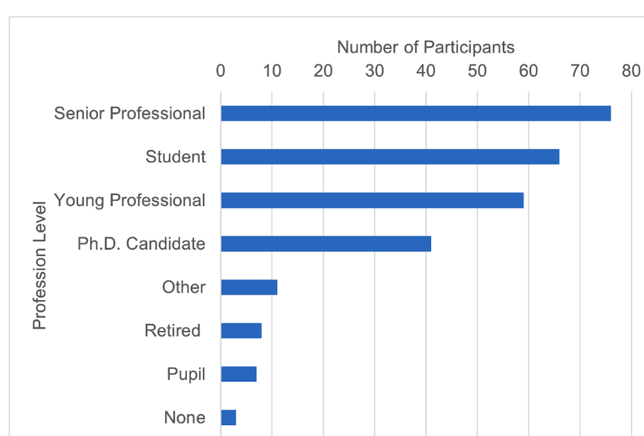

Fig. 7. Professional level of the MOOC participants based on a user survey that was completed by 271 participants as of 14.09.2023.

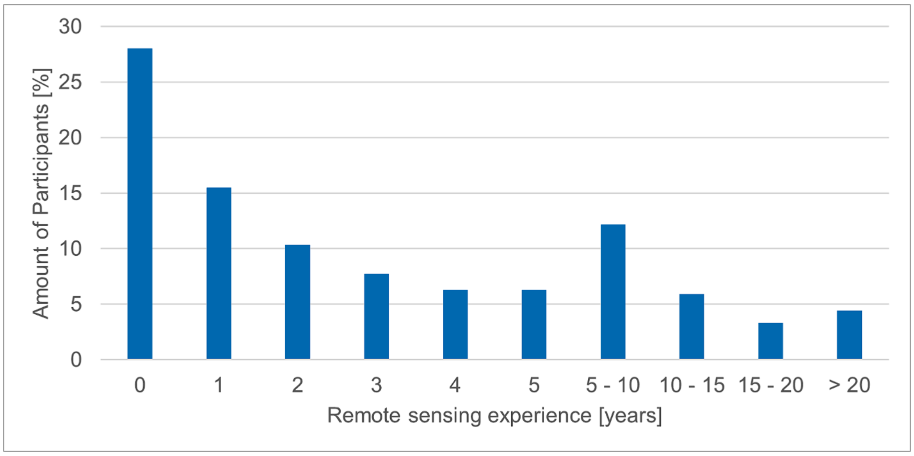

Fig. 8. Number of years of remote sensing experience of the MOOC participants based on a user survey that was completed by 271 participants as of 14.09.2023.

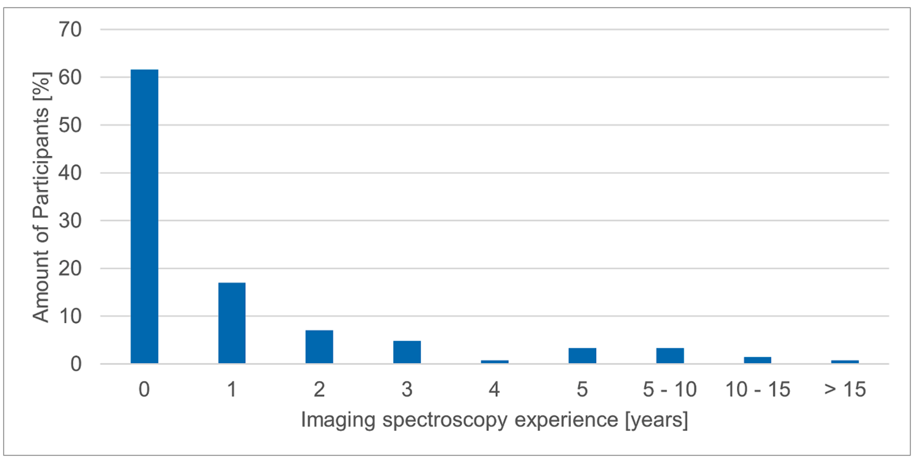

Fig. 9. Number of years of imaging spectroscopy experience of the MOOC participants based on a user survey that was completed by 271 participants as of 14.09.2023.

watched most completely, on average to almost 70 %, while all other videos types were typically stopped earlier.

3.2. Participants' background and prior experience based on a general user survey

Out of the course participants, a total of 271 responded to a general user survey which inquired about their professional background, prior knowledge of satellite remote sensing and imaging spectroscopy in particular.

As previously stated, all MOOCs are designed for students at master level and young professionals, whereby the phrasing of young professionals primarily refers to the professional experience preliminary to a participation in any of the MOOCs. The survey results indicated that out of 271 respondents, 203 were either senior or young professionals, students or PhD candidates (89 %, Fig. 7). Additionally, the results revealed that approximately 75 % of all participants possessed up to five years of experience in working with remotely sensed data, including roughly 29 % of participants (Group 0) with no prior experience in remote sensing before enrolling in a HYPERedu MOOC (Fig. 8). These findings underscore the focus of the HYPERedu initiative on participants at master level and beyond.

In terms of working experience in the field of imaging spectroscopy, the results reflected a similar distribution, with the majority of respondents (over 90 %) having less than five years of experience in working with hyperspectral data, including over 60 % who had no prior experience before taking a HYPERedu MOOC (group 0, Fig. 9).

3.3. Course feedback based on final survey

To gain a thorough understanding of the participants assessment of the course materials, as well as to continuously enhance the offered resources, a final user survey with a total of 27 questions is offered to each participant at the end of the respective course. The final user survey is identical for all MOOCs, hence the following evaluation summarizes the results across all currently published MOOCs. The survey questions encompass various topics, including course structure, course quality (support quality & portal quality), video tutorials and other learning elements, data as well as the potential interest in subsequent MOOCs on specific application fields of imaging spectroscopy.

As evident in Fig. 10, the majority of participants who completed the final user survey (n = 282) expressed satisfaction with the courses' structure. All questions related to the course structure received positive responses (more than 75 % rated 'Awesome' or 'Good'), indicating that next to an appropriate course level and course duration, the share between theoretical and practical course contents was considered well balanced. In addition, the absolute majority of participants appreciated the logic course structures and were able to extend their knowledge of imaging spectroscopy following the successful completion of the MOOCs.

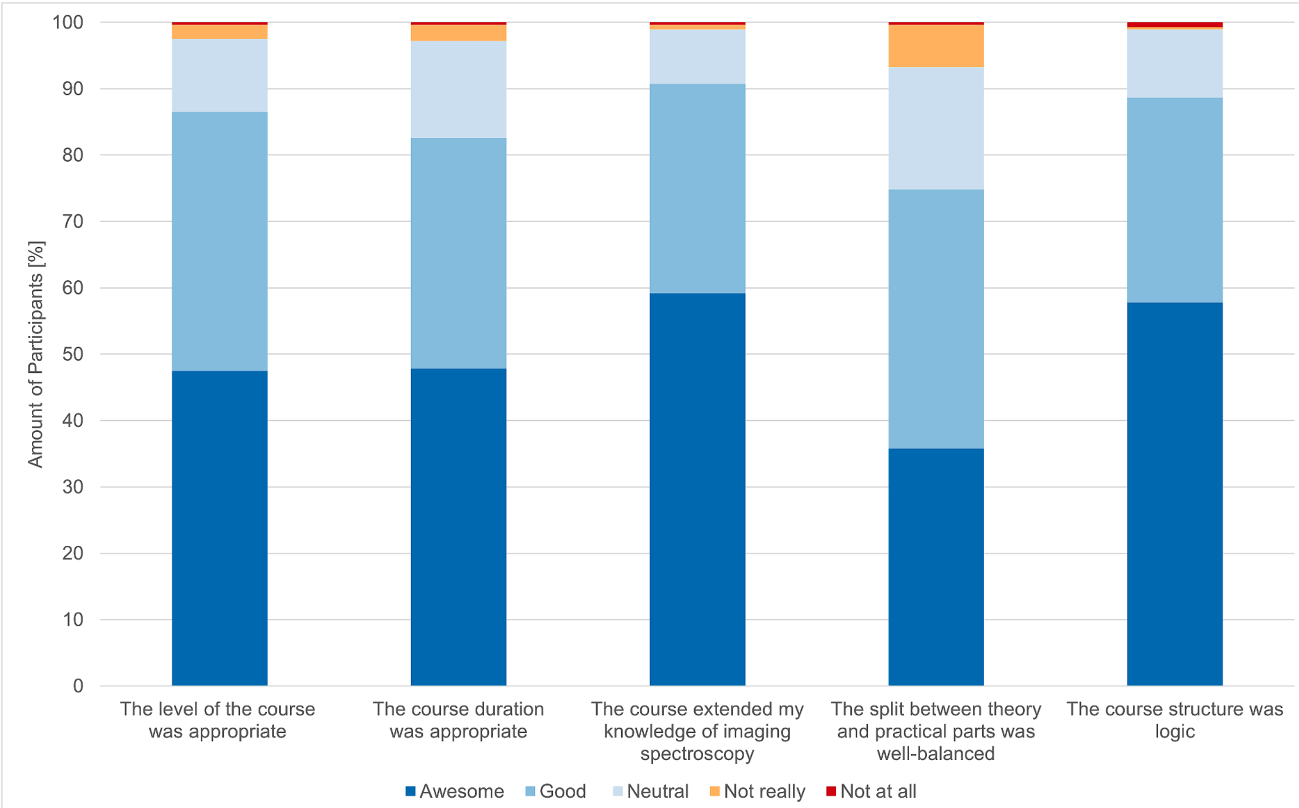

Fig. 10. Evaluation result on the course structure for all three published MOOCs based on 282 participants that completed the final survey as of 21.09.2023.

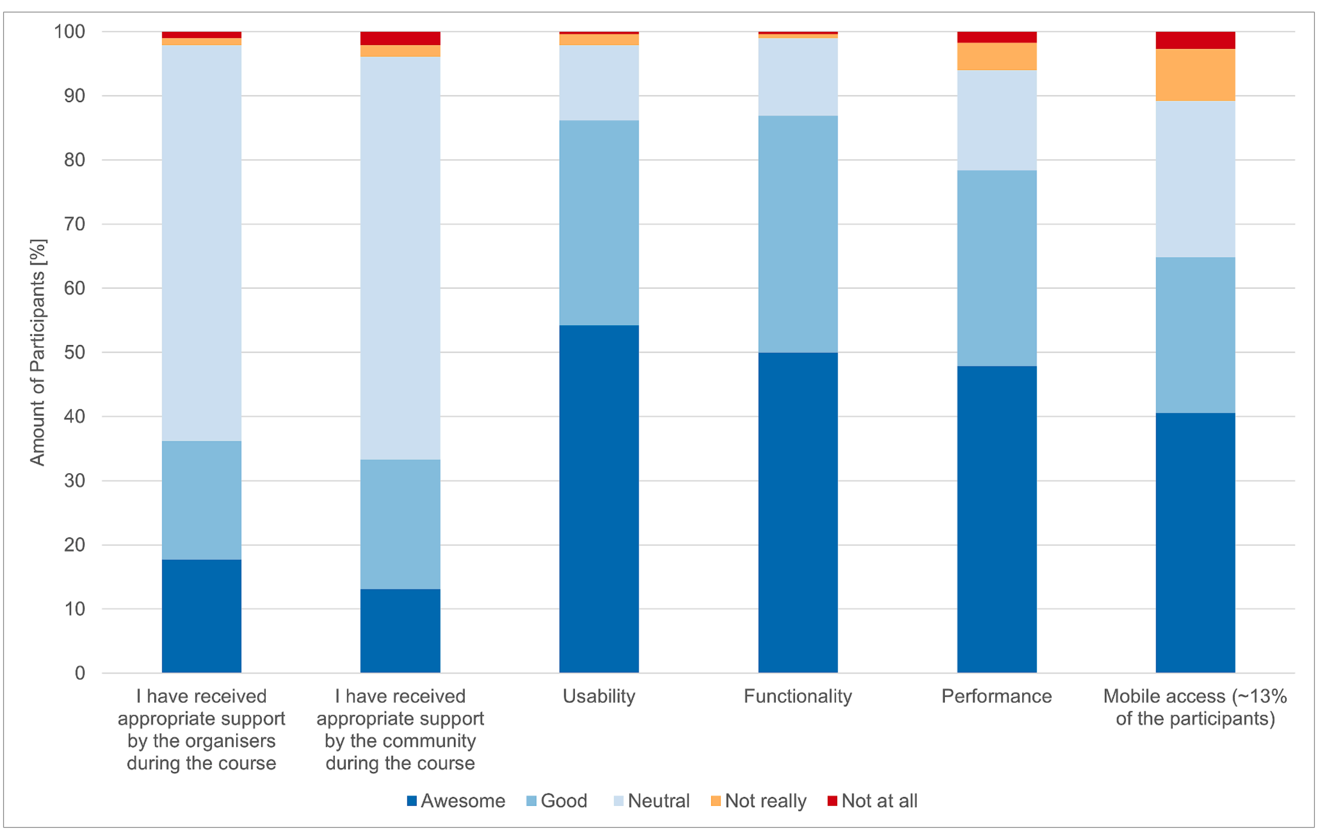

Fig. 11. Evaluation result on the quality and mobile access for all three published MOOCs based on 282 participants that completed the final survey as of 21.09.2023.

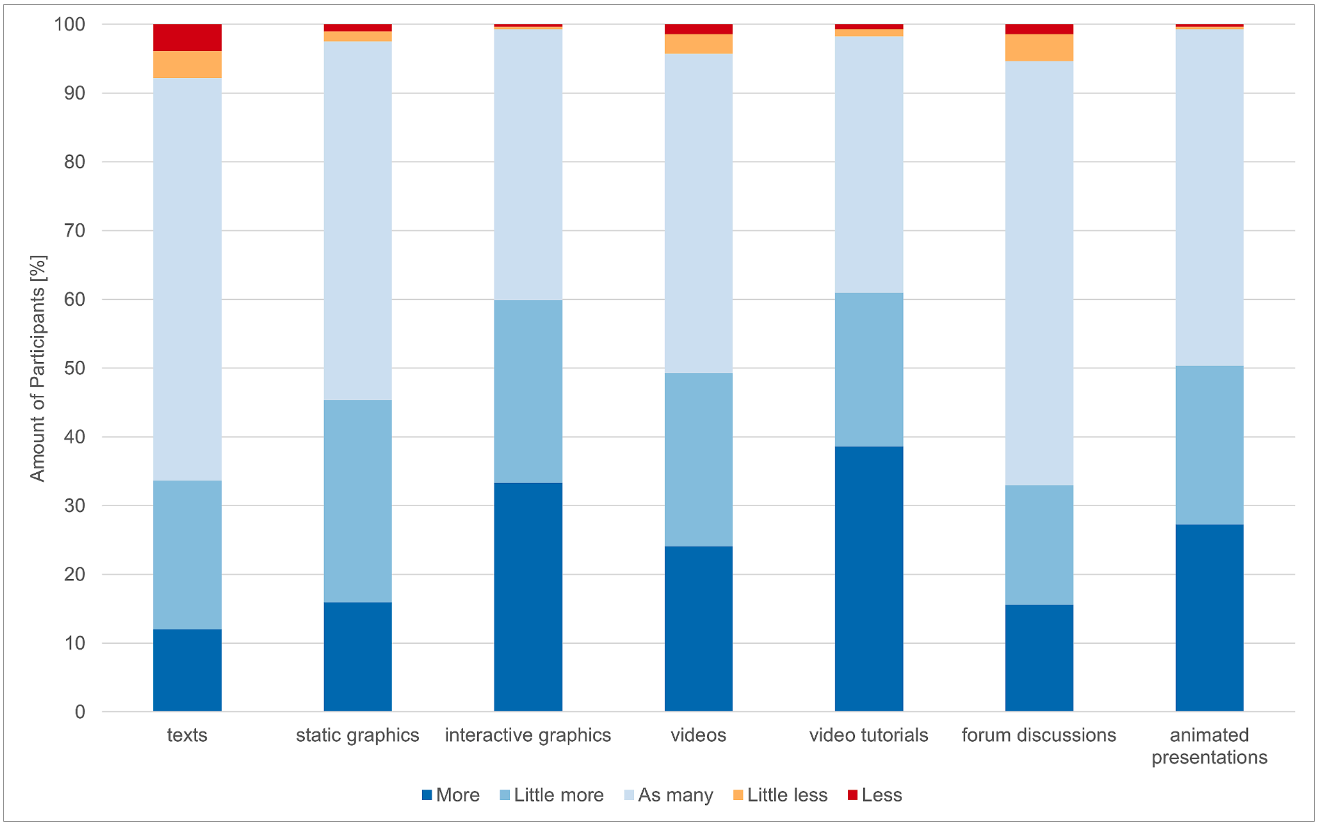

Fig. 12. Evaluation result on the type of learning materials used in all three published MOOCs based on 282 participants that completed the final survey as of 21.09.2023.

On the subject of the courses' overall quality, including support quality and portal quality, survey responses displayed more diversity (Fig. 11). The portal quality (as hosted by EO College) received very positive feedback concerning usability, functionality and performance (more than 77 % rated 'Awesome' or 'Good'). However, the majority of participants remained neutral on the support (~60 %), likely due to the fact that no support was requested. Mobile access registered the highest proportion of seemingly negative responses. Nevertheless, only 13 % of the participants accessed the web portal on a mobile device, making this response relatively insignificant.

Based on the user feedback, HYPERedu is able to continuously adjust and optimize the course contents and provided materials, as well as prioritize future learning material. Survey questions targeting learning elements showed that the majority of participants would like to see even more video tutorials, interactive graphics and animated presentations, while learning elements such as texts and forum discussions could be integrated to a lesser extent (Fig. 12). Nevertheless, the absolute majority (>90 %) of respondents expressed satisfaction with the learning elements of the MOOCs, with minimal (less than 10 %) requests for improvement.

Additionally, the survey indicated a strong demand for subsequent MOOCs dedicated to specific application fields of imaging spectroscopy, with 94 % of the respondents expressing interest in such follow-up MOOCs. Moreover, training needs on a multitude of technical environmental topics was displayed. The five most prominent topics for future resources were identified as agriculture, soil, water, geology and urban applications in descending order (Fig. 13).

4. Challenges, lessons learned and potential solutions

The conceptualization and implementation of online education programs come with their own sets of challenges. This chapter discusses the main challenges and lessons learned during the development of HYPERedu, and potential solutions to overcome these obstacles in the development of online learning in the context of EO education in general.

4.1. Completion rates and participant interaction

MOOCs have revolutionized global education by providing courses across various disciplines to an international audience. Despite their widespread influence, MOOCs often receive criticism for their low completion rates, i.e. the percentage of participants who actually complete a given online course (Poelmans and Wautelet, 2016; Onah et al., 2014; Xing et al., 2016; Jordan, 2014). On average, reported course completion rates are below 10 % of the participants who have actively started the courses (Hone and El Said, 2016). Compared to these figures, the completion rate of 25.5 % of all who enrolled and even 43.5 % of all who started the HYPERedu MOOCs (cf. Table 2) can be considered to be substantially higher than average, but still has potential for further improvement. Numerous factors contribute to MOOC completion rates, including both intrinsic and extrinsic motivational elements. A supportive online learning environment is vital for encouraging active engagement and enhancing completion rates (Cilliers et al., 2023). Social learning is another crucial factor in mitigating student dropout, implying that MOOC platforms could benefit from additional social and interactive elements (Crane and Comley, 2021). Gamification approaches have also positively influenced completion rates, suggesting that course designs can become more interactive and engaging (Nesterowicz et al., 2022). Moreover, interventions from instructors, like personalized email reminders, exhibit both immediate and long-term effects on quiz and final exam completion, highlighting the significance of active instructor involvement in MOOCs (Kurtz et al., 2022). In the HYPERedu MOOCs we have used several of these strategies such as

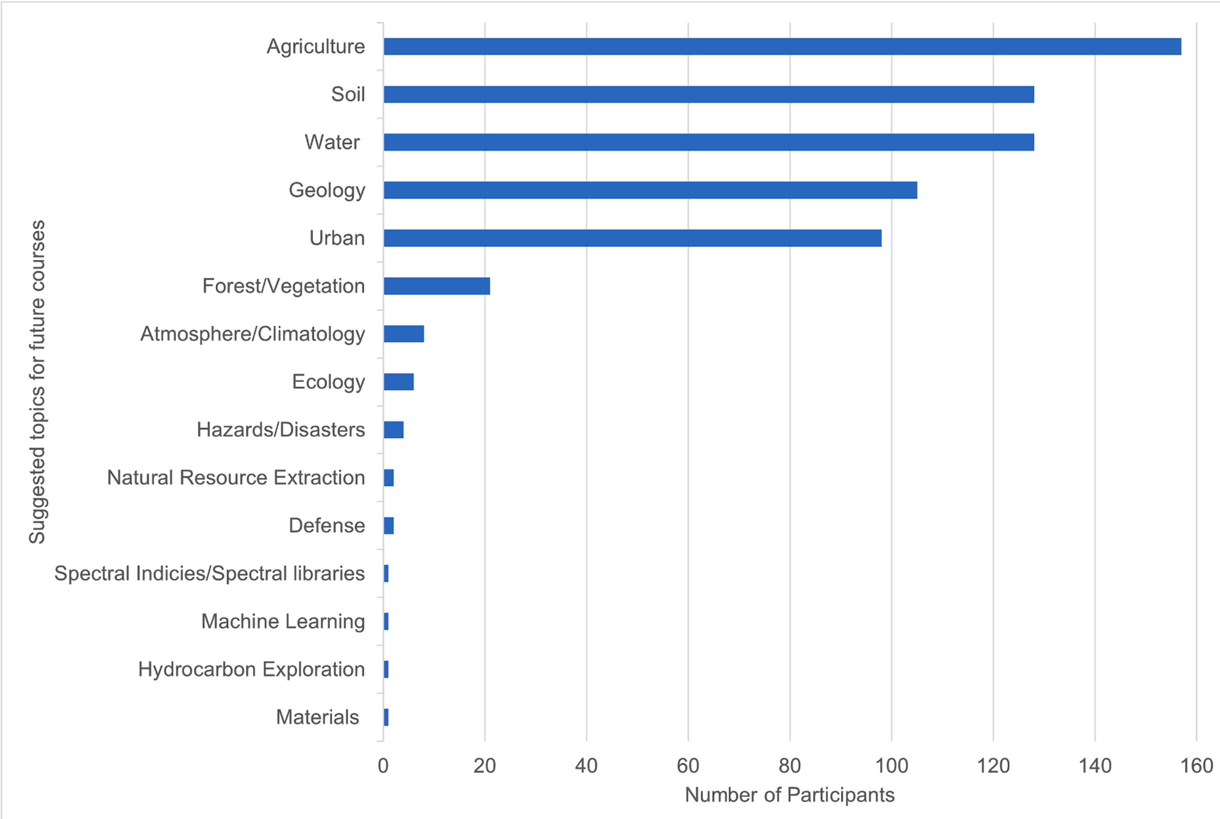

Fig. 13. Evaluation result on the topics for future courses (multiple answers were allowed) based on 282 participants that completed the final survey as of 21.09.2023. Please note that the category of forestry/vegetation includes the health of forests and wetlands, while the category atmosphere/climatology also includes greenhouse gases and air quality.

setting up a forum for participant interaction, sending reminder emails, making the courses both interactive and engaging with short video sequences, quizzes of different types, small games and a colloquial writing style. With regard to the promotion strategy, a lesson learned in our courses was to announce the course no earlier than the opening day to retain participants. The discussion forum was underutilized, although we encouraged its use several times throughout the courses. One possibility to replace the discussion forum would be the use of automated feedback and bots. This is one of many potential future applications of Artificial Intelligence (AI) in science education and e-learning programs. In a comprehensive review, Jia et al. (2023) reveal ways how AI technologies can enhance various aspects of science education, including collaborative learning, computer-aided instruction, and automated feedback.

Course deployment methods also significantly influence learner engagement. There is a current debate over the merits of self-paced versus session-based courses (Shah, 2015). Each mode has its advantages and drawbacks. Self-paced courses offer flexibility but can be challenging to maintain, while session-based courses allow for structured updates but impose deadlines, potentially pressuring learners. For HYPERedu we adopted the self-paced approach allowing participants to start and progress at their own pace, while we are making minor updates throughout the ongoing courses.

Research indicates that collaborative learning is vital for keeping learners engaged and increasing completion rates (Morales et al., 2015). Thus, to enhance the quality of online learning and reduce MOOC dropout rates, fostering student interaction and collaboration is crucial. Thereby, research suggests that MOOCs can foster collaborative communities and learning in ways not conceived as feasible until recently (Haipinge and Kadhila, 2021). Overcoming the challenge of geographically dispersed participants is possible through virtual communities of practice utilizing structured approaches with weekly sessions and breakout groups. Another alternative is blended learning that combines face-to-face instruction with online elements and thus offers flexibility and personalization. It enables students to access course materials in physical classrooms and on digital platforms.

4.2. *Sustainability and quality*

Sustaining online courses is inherently complex, involving two primary dimensions: long-term learner success and effective course deployment. Course design goes beyond the selection of suitable online tools and includes long-term material accessibility.

A critical component of online education is quality assurance. To ensure professional quality, we collaborate with expert colleagues in the development of the learning materials such as slide collections and the MOOCs, and reference peer-reviewed literature and data sources. A major challenge was the time-consuming and cost-intensive process of checking copyright with publishers or creating own figures to avoid licensed figures. We prioritized open access images whenever possible, along with proper references to open access publications, datasets, and software.

Maintaining the quality and relevance of MOOCs extends beyond initial course creation. It requires not just updating the course material but also ensuring that references between materials are accurate and up-to-date. Long-term quality depends on continuous support for the online learning program with suitable mechanisms such as regular (in our case annual) revision of the materials and the possibility for course participants to provide feedback and suggestions for improvement.

Generally, established quality assurance agencies exist for higher education in most countries (Daniel, 2012). The evaluation criteria for online courses should be as rigorous as those for traditional educational programs. Such mechanisms should be integrated into existing quality assurance frameworks or developed explicitly for online courses.

4.3. Bridging the digital divide

The digital divide, rooted in factors like geography, income, education, and gender, persists despite widespread access to information and communication technology. Economic inequalities are reflected in uneven technical infrastructure and broadband internet access, further deepening disparities (Haack and Ryerson, 2016). Bridging the gap requires equitable strategies, including offline course versions for those with limited internet access, open-source tools and multilingual content. In HYPERedu, we offer course documents in PDF format for offline use, rely on open access resources whenever possible, and are working on providing subtitles for all videos in multiple languages besides English. Generally, establishing educational centers in developing nations, user-friendly platform design and improving digital literacy are crucial for enhancing inclusivity and accessibility.

4.4. Content presentation

HYPERedu established a consistent brand identity by applying a corporate layout and style guide to all materials, including slides, graphics, and videos , with the intention of maintaining uniformity and adaptability. Another effective approach to improve presentation is the use of short content modules. Research shows that shorter course durations can lead to higher completion rates (Padilla Rodriguez et al., 2020). Similarly, shorter video length enhances engagement, focus, and perceived content retention (Slemmons et al., 2018). In HYPERedu, we limit video length to a maximum of 8 min (cf. Table 3). Interactive educational elements like quizzes and explorable graphics are beneficial. Studies have shown that meaningful gamification, especially when combined with a modular MOOC design, can significantly improve learner engagement (Buchem et al., 2020).

Furthermore, research indicates that narrative-style videos embedded within a coherent story, can significantly improve learner engagement and satisfaction (Guo et al., 2014). These videos can be designed to be more interactive, incorporating elements like quizzes and feedback loops to further engage the audience. In HYPERedu videos , we follow this approach by introducing the character Charly (cf. Fig. 3) to guide users through the courses, using a narrative and colloquial style, and embedding short quiz questions.

5. Summary and outlook

Online education plays a pivotal role in democratizing Earth observation by making valuable knowledge and resources accessible to a global audience, fostering a deeper understanding of our planet.

In the future, online learning will continue to evolve through new approaches such as virtual communities and blended learning. Ensuring the sustainability and quality of online education involves ongoing maintenance, expert collaboration, and quality assurance mechanisms to keep materials accurate and up-to-date. Bridging the digital divide is vital by providing offline course options, open-source tools, and multilingual content. Effective content presentation, with consistent branding and modular, interactive, and narrative-style materials, enhances user engagement. Collaboration among learners is key to promoting interaction and increasing completion rates.

The future of AI in online learning holds promise for personalized education, analyzing individual learning patterns, providing tailored content, and offering real-time feedback to make online learning more accessible and engaging.

Outreach and training are essential in the successful utilization of satellite missions like EnMAP. These programs enhance the understanding of satellite data but also encourage its practical application, fostering a community of knowledgeable and skilled users. Similarly, the development of projects like HYPERedu serves as a community-strengthening activity in itself, where education and knowledge dissemination are integral to building a robust network of participants. Furthermore, the concept of open education is a crucial element, emphasizing the value of open science, open data, open software, and open access in publications, making education accessible and inclusive to all who seek knowledge and enhancing the effective utilization of satellite data.

CRediT authorship contribution statement

Saskia Foerster: Writing – review & editing, Funding acquisition, Conceptualization. **Arlena Brosinsky:** Writing – review & editing, Conceptualization. **Katrin Koch:** Writing – review & editing, Visualization. **Robert Eckardt:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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