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Fostering transformative climate action through the integration of transdisciplinary research and university teaching

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The accelerating climate crisis demands transformative action that connects individual learning with societal change. Universities are uniquely positioned to foster this link by developing students' transformative literacy. This Perspective presents a framework from the discipline of Geography that integrates transdisciplinary research with research-oriented teaching and learning. Iteratively shaped through case studies at Heidelberg University, it offers a transferable model that strengthens, within existing curricula, competencies needed to actively forge sustainable futures.

The role of universities in addressing societal transformation

Although numerous approaches to climate change mitigation[1,2] and adaptation[2,3] exist, a significant gap persists in what transdisciplinary research terms *transformation knowledge*[4]: the understanding, abilities, and skills necessary to transition from the current state to a more sustainable future. Climate action is one example of the many interconnected fields within the wider sustainability agenda where progress remains limited: according to the Sustainable Development Report 2025[5], only a minority of *Sustainable Development Goal* targets is currently on track worldwide.

Higher education institutions, in particular universities, occupy a pivotal position in bridging research, teaching, and societal engagement, making them central to addressing today's ecological and social challenges[6]. This Perspective presents a framework that connects academic research with university teaching and learning, aiming to foster students' competencies for responsible action in both professional and civic contexts, thereby supporting future decision-makers. The academic discipline of Geography provides an ideal foundation for this endeavour. As an inherently interdisciplinary field that connects natural, social, and technical sciences[7], it may be seen as a bridge discipline capable of addressing complex societal challenges. The framework emerged within this disciplinary context by harnessing Geography's integrative potential through transdisciplinary research projects and their incorporation into research-oriented teaching. These experiences revealed both opportunities and structural challenges in embedding transformative competencies within existing curricula. The resulting model was systematised to support transfer across academic fields.

The development of the framework was guided by a focus on strengthening two interrelated key interfaces: the alignment of teaching with professional practice, and the interplay between research and teaching. These considerations are reflected in the following overarching questions:

(1) How can university teaching in Geography, and beyond, be further developed to prepare students for their future roles in research and professional practice amid accelerating ecological and socio-economic challenges? (2) How can research and teaching formats be more effectively intertwined to strengthen students' competencies, enabling them to connect scientific knowledge with societal contexts and to participate in democratic deliberation on transformation-related issues?

From knowledge to action: the university as a site of transformation

Over recent decades, science has established a robust understanding of the human influence on the climate system[8] and of the rapidly shrinking greenhouse gas emission budgets[9] required to meet the temperature limits set by the 2015 Paris Agreement[10]. Similarly, significant progress has been made in understanding the societal processes that can either accelerate or hinder *social tipping dynamics*[11]. However, these transformations are often marked by the complexity and conflicting objectives associated with so-called *wicked problems*[12], involving interdependent socio-ecological processes, non-linear and multi-causal dynamics, uncertainties, and heterogeneous stakeholder viewpoints[13]. These features constitute the understanding of *complexity* adopted in this article. Transdisciplinary research has proven particularly effective in integrating insights from both

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science and practice to generate foundational and applied knowledge, as its co-productive processes bring diverse perspectives together and yield solution approaches characterised by higher feasibility and broader societal acceptance[4,14,15]. University education represents a promising avenue for amplifying the societal impact of these insights by enabling students to translate and disseminate them within real-world settings[16,17].

As future decision-makers, students rely on universities that combine scientific excellence with institutional capacities for innovation and transformation. Such universities act as learning organisations that balance internal academic traditions with external societal expectations, enabling students to engage with issues of sustainability and change. One approach to embedding this cross-cutting ambition is the notion of *culture(s) of sustainability*, understood as the alignment of norms, values, routines, and institutional practices with sustainability as a guiding orientation[18]. Although higher education institutions have engaged with sustainability for decades, their capacity to contribute meaningfully to sustainable development remains underexploited[19]. Institutional efforts have largely centred on education and research, whereas structured contributions to policy design and implementation have been comparatively limited. A *whole-institution approach* is therefore needed to embed sustainability across core operations and to strengthen the capacity of universities to shape responses to global challenges[19]. This concept harmonises with the imperative to render scientific knowledge actionable[14], and university teaching offers a powerful arena for such transfer[20]. The following section outlines the conceptual foundations of *transformative literacy* before introducing the integrative framework and its constitutive elements.

Conceptual foundations for a *transformative literacy*

Addressing the climate crisis requires large-scale societal and political decisions[21]. Individual actions, while necessary, are insufficient unless people are equipped to participate meaningfully in collective transformation processes. Universities, therefore, play a crucial role in developing the competencies that enable such participation[22], both for students as individual citizens and in their future roles as multipliers, professionals, and decision-makers. The concept of *literacy* has evolved far beyond its original meaning of reading and writing. In contemporary educational theory, it refers to the ability to interpret, critically assess, and apply knowledge in different contexts[23]. Literacies are not static sets of skills but dynamic capabilities that connect understanding with action. Within this Perspective, *transformative literacy* denotes the integrated knowledge, skills, values, and dispositions that allow individuals to engage constructively in transformation processes and contribute to sustainable societal change. This notion sits alongside a broader landscape of competence frameworks, such as *21st century skills*[24] and *future skills*[25], which similarly seek to enable active participation in shaping sustainable futures. Following Scoones et al.[26], *transformation* describes profound changes in society, economy, and environment that lead to new ways of living and working. It can be understood as: (a) structural, involving shifts in fundamental social and economic systems; (b) systemic, relating to the governance of complex systems through politics, technology, and institutions; and (c) enabling, empowering people to act collectively, revise values, and explore new pathways. Thus, transformation is not merely a technical process of redesign, but a social negotiation aimed at shaping a sustainable and just future[26].

In this context, *transformative learning* describes the process through which individuals critically reflect on their assumptions, values, and worldviews, leading to changes in understanding and behaviour[27]. Such learning in formal and informal environments requires both cognitive insight and emotional engagement[28]. *Self-efficacy*[29] captures the belief in one's capacity to act effectively, while *self-determination theory*[30] emphasises the intrinsic motivation that arises when people experience autonomy, competency, and relatedness. Together, these concepts form the psychological and pedagogical basis of *transformative literacy*, a literacy that not only informs but has the potential to *empower*[31] individuals for transformative action.

The *transformative literacy integration framework*

Building on the theoretical foundations outlined above and drawing on my dual engagement in transdisciplinary research and research-oriented teaching projects, I developed an integrative framework for fostering *transformative literacy* through an iterative and reflexive process. Across successive project contexts, theoretical insights were brought into practice, critically examined, and refined. The framework did not originate as a purely deductive conceptual model, nor was it retrospectively induced from the cases presented below. The developmental trajectory began with transdisciplinary research initiatives at the science-society interface. These projects served as the basis for research-oriented teaching formats, whose implementation and evaluation revealed the need to more explicitly integrate cross-cutting transformative competencies within disciplinary learning processes. Through this sustained interplay of theory, research practice, and pedagogical reflection, I progressively designed and consolidated the framework in successive stages into the structured model illustrated in Fig. 1.

The framework connects research, teaching, and learning as complementary entry points for fostering *transformative literacy*. It visualises how competencies developed within these domains converge in *integrative learning elements* that build *self-efficacy*, enable participation, and thereby contribute to *empowerment* and transformative impact. In this model, the societal dimension is embedded directly within both research and teaching, creating a form of research-oriented education grounded in transdisciplinary enquiry, as elaborated in the following section. This integration links scientific investigation and academic learning more closely to societal relevance and transformative action.

The interaction of research, teaching and learning is facilitated through *integrative learning elements*: curricular spaces where disciplinary enquiry and societal engagement converge. Figure 1 visualises this convergence, highlighting how universities can operationalise their missions of research, teaching, and learning as mutually reinforcing elements of systemic change. Each entry point of the framework is described in greater detail below, before illustrative examples of practice are presented.

Research entry point: *transformative literacy* in research

Basic research forms the essential foundation and remains at the heart of academia. Its value stands on its own and is not called into question by this framework. Yet, when research extends towards the science-society interface, new forms of transdisciplinary enquiry can emerge. According to Pohl and Hirsch Hadorn[32], such research is characterised by its ability to capture the complexity of problems, embrace the diversity of scientific and societal perspectives, connect abstract scientific reasoning with context-specific knowledge, and generate insights oriented towards the public good and practical solutions. Within this approach, three complementary types of knowledge are distinguished: *systems knowledge*, *target knowledge*, and *transformation knowledge*[14,32]. The strength of transdisciplinary research lies in its integrative and solution-oriented nature. By bringing together diverse epistemic cultures, it creates spaces in which scientific enquiry and societal needs inform one another. This approach allows for the co-production of knowledge that is both academically rigorous and socially relevant[14]. It fosters reflexivity, mutual learning, and innovation across disciplinary and institutional boundaries[33]. Most importantly, transdisciplinary research not only expands the scope of scientific understanding but also has the potential to enhance the capacity of science to contribute meaningfully to societal transformation by strengthening individual agency and responsibility. In this sense, it resonates with recent conceptualisations of *catalytic research* that emphasise the role of science in facilitating participatory, evidence-informed transformation processes[34]. Engaging in such transdisciplinary enquiry fosters what can be described as *transformative literacy in research* (Fig. 1, lower left): the ability to navigate complexity, integrate multiple forms of knowledge, and align scientific work with societal needs without compromising academic integrity. This literacy extends beyond methodological competency; it encompasses reflexivity, ethical awareness, and the capacity to engage constructively with diverse stakeholders[35]. By cultivating these qualities, researchers develop not only a deeper understanding of

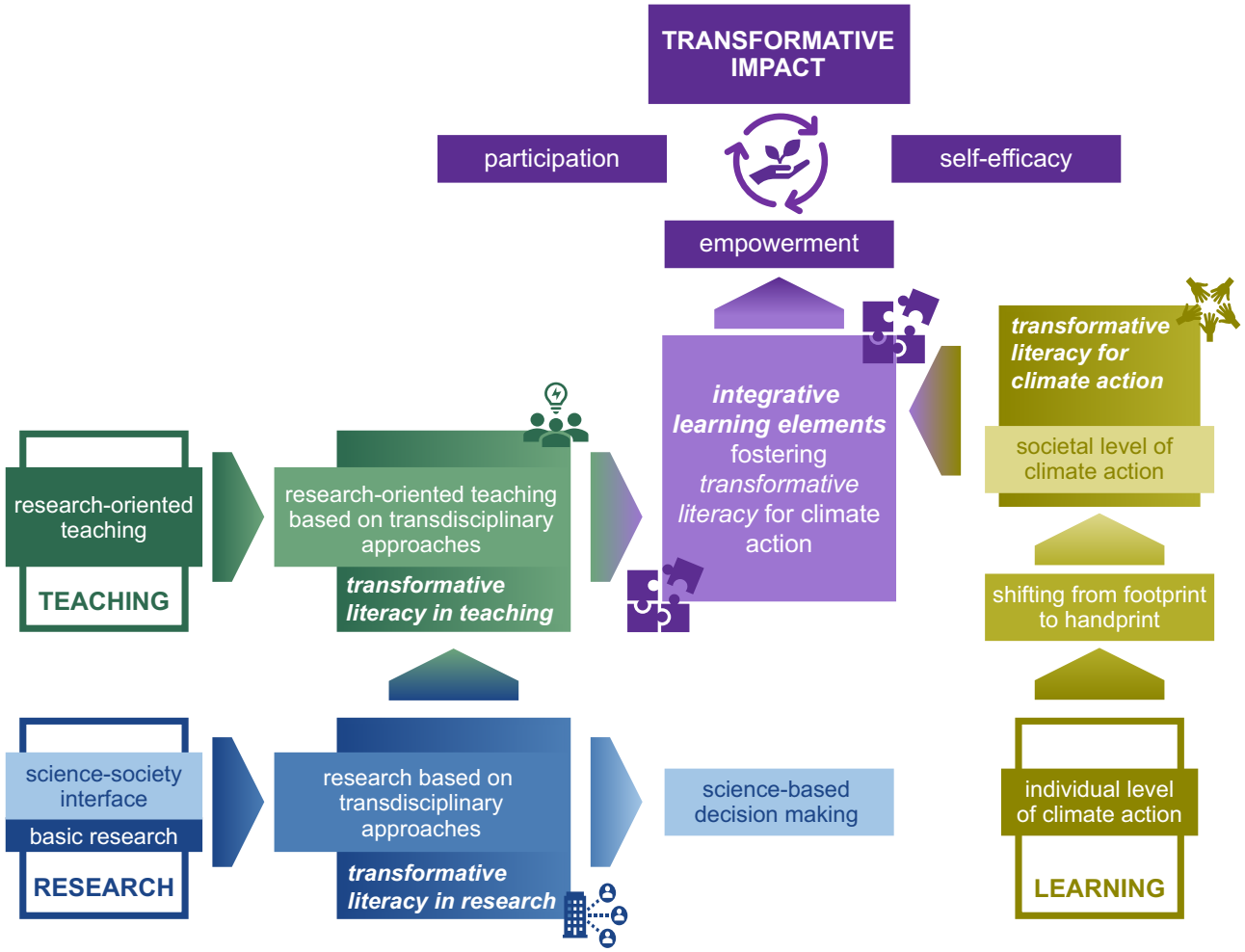

Fig. 1 | The *transformative literacy integration framework*. The schematic illustrates how research (lower left), teaching (centre left), and learning (lower right) serve as complementary entry points for fostering transformative literacy. Each domain contributes specific pathways that converge in integrative learning elements (centre), where knowledge, skills, and attitudes coalesce to strengthen self-efficacy and enable participation. These processes are intended to support empowerment and transformative impact at individual and societal levels.

socio-ecological systems but also the confidence and agency to contribute to their transformation.

Teaching entry point: *transformative literacy* in teaching

Research-oriented teaching is a well-established principle in higher education[36]. It familiarises students with the logic and methods of scientific enquiry and enables them to participate, at least in part, in authentic research processes. In this approach, teaching is informed by current research and fosters curiosity, analytical rigour, and a reflective understanding of how knowledge is produced. When combined with transdisciplinary research, this principle gains an additional dimension. Students are not only exposed to disciplinary methods and debates, but also to the interfaces where academic and societal perspectives meet. This creates opportunities to engage with complex, real-world challenges and to reflect on the ethical and social implications of scientific work. In this sense, *transformative literacy in teaching* (Fig. 1, centre left) emerges where research-oriented teaching is enriched by transdisciplinary perspectives, allowing educators to design learning environments that integrate scientific enquiry with societal relevance.

Learning entry point: *transformative literacy* for climate action

Within the context of climate and sustainability education, individual behaviour change is often portrayed as the main lever for sustainability. While personal responsibility and lifestyle choices play an important role, they are insufficient to address the structural and systemic nature of the climate crisis. Systematic reviews of climate change education show that many educational approaches remain focused on scientific concepts and private-sphere actions, while political literacy, climate justice, and public-sphere engagement are often underrepresented[37]. *Transformative literacy in learning* (Fig. 1, lower right), therefore, seeks to lift climate action from the *footprint* to the *handprint* level: The *footprint* concept[38] has become a widely used indicator for quantifying human impact on the environment. It captures measurable effects such as greenhouse gas emissions, resource use, and land or water consumption at the individual, organisational, or national scale. As a diagnostic tool, it helps visualise the ecological consequences of human activity and motivates behavioural change through reduction targets. Yet, by focusing on individual responsibility, it risks narrowing the perspective to personal consumption instead of addressing the systemic and corporate drivers of emissions, particularly those industries that strategically promote the *footprint* narrative to shift responsibility away from themselves[39]. This individualisation of responsibility can, in turn, foster moral fatigue and eco-anxiety[40,41]. The *handprint* concept[42,43], by contrast, shifts attention from reducing individual impacts to generating system-level contributions to sustainability. It focuses on actions that create leverage for transformation through innovation, cooperation, and institutional engagement. For example, while reducing one's food-related *footprint* might involve lowering individual meat consumption, a *handprint* action would be to establish diverse and affordable plant-based options in university canteens. In the mobility sector, it could involve launching initiatives within universities or municipalities that advocate for expanded cycling

infrastructure and improved public transport, rather than simply urging individuals to drive less.

In this sense, *transformative literacy in learning* reframes education for climate action: from an emphasis on individual carbon emissions reduction to the development of collective capacities for societal transformation. Students learn to connect scientific understanding with systemic reasoning, to analyse how structures and values shape responses to the climate crisis, and to identify points of leverage for change. They begin to see themselves not merely as consumers or private actors, but as participants in professional, civic, and democratic arenas where transformative agency can unfold. Learning in the sense of *Education for Sustainable Development (ESD)* engages cognitive, emotional, and social dimensions[44,45]. Cognitively, students integrate scientific and ethical reasoning; emotionally, they cultivate agency and hope rather than guilt or paralysis; socially, they learn collaboration and participation as drivers of transformation. Together, these dimensions build *self-efficacy* and participation as the essential foundations of *empowerment*.

Embedding *transformative literacy* across higher education

The question arises of how *transformative literacy* can be effectively embedded in research, teaching, and learning. The approach proposed here centres on integrating *transformative literacy* into existing disciplinary curricula as a lever for advancing the transformation of higher education as a whole. Rather than establishing isolated sustainability programmes, the aim is to embed elements of climate action learning within regular courses across disciplines. This positioning does not dismiss the value of dedicated sustainability programmes, which can provide a coherent curricular structure, interdisciplinary collaboration, and focused project work that fosters systemic thinking and social responsibility. They have the potential to serve as incubators for innovative approaches to climate action and to prepare graduates for emerging professional fields at the interface of science and society. However, when sustainability education is primarily confined to isolated courses, its transformative potential may remain institutionally bounded, and such courses risk creating academic niches that reach only a limited number of students. They also tend to marginalise the disciplinary entry points to research and teaching that are central to the framework developed here. To address this limitation, the goal is to incorporate elements of *climate action learning* into regular courses through collaborative teaching formats and co-created learning materials. This offers a faster, more accessible, bottom-up route to capacity building than the creation of entirely new degree programmes. The embedding strategy relies on sustained support for academic staff, including professional development in higher-education didactics that equip educators with the pedagogical and methodological tools necessary to design transformation-oriented learning environments[46]. By enhancing staff capacities, such support ensures that integration efforts become institutionally embedded rather than remaining the responsibility of individual educators.

This strategy of embedding allows transformation-oriented learning to reach students across disciplines and levels of study, making it a shared responsibility of the academic community rather than the focus of a specialised few. It thereby contributes to institutional and disciplinary transformation in line with a *whole-institution approach*. The development of *transformative literacy* in higher education represents only one part of a broader educational landscape. Equally crucial is the systematic integration of sustainability-related competencies into vocational and continuing education[47], including teacher training, where enhanced competencies translate into strong multiplier effects through the educators who influence large numbers of learners.

Integrative learning elements as spaces of transformation

Embedding *transformative literacy* across research, teaching, and learning requires dedicated spaces where these domains intersect. Such *integrative learning elements* (Fig. 1, centre) serve as experimental zones within the curriculum in which research-oriented teaching and transdisciplinary collaboration converge. They may take the form of joint seminars, project-based modules, or interdisciplinary workshops co-taught by academic staff and practice partners. Within these settings, students engage with authentic societal challenges that demand both scientific analysis and creative problem-solving. They learn to navigate uncertainty, negotiate multiple perspectives, and translate insights from different disciplines into actionable strategies. Teachers, in turn, act as facilitators of enquiry rather than transmitters of knowledge[48], enabling reflexivity and mutual learning. The process of designing and implementing the learning elements also involves discussion within the respective units to consider the disciplinary prerequisites and possibilities.

These *integrative learning elements* can foster *self-efficacy* by providing students with tangible experiences of agency, seeing that their knowledge and actions can make a difference. They strengthen participation through collaborative processes and shared responsibility. Taken together, these experiences form the foundation of *empowerment*, understood as the capability to contribute meaningfully to societal transformation. In this way, *transformative literacy* becomes not merely an educational objective but a lived practice within the university.

Illustrative cases: applying the *transformative literacy integration framework*

To clarify how the *transformative literacy integration framework* operates in practice and how I progressively shaped it through a recursive interplay between project development and conceptual refinement, the following section presents illustrative cases aligned with the three entry points and the *integrative learning elements*. These cases demonstrate how research and teaching projects informed the framework and, in turn, were further designed in light of its evolving structure. The examples draw on projects conducted in Germany at the Institute of Geography, Heidelberg University, and at the Heidelberg School of Education, a joint institution of Heidelberg University and Heidelberg University of Education. The cases serve a dual function: they represent research and learning settings in which the framework was both developed and put into practice, and they exemplify its structured application across research, teaching, and learning.

Transformative literacy in research: mitigation and adaptation

Climate action measures are often associated with conflicting goals. A prominent example within the university context concerns academic air travel. On the one hand, mobility is essential for establishing and maintaining international collaborations that drive scientific excellence. On the other hand, the associated greenhouse gas emissions contradict institutional and societal efforts to reduce carbon footprints. Inspired by the pioneering flight reduction initiative at ETH Zurich, Switzerland[49,50], the *FlyingLess* project (www.flyingless.de/en) was initiated under the leadership of the *Institute for Energy and Environmental Research (ifeu)*, a non-university research institute based in Heidelberg, Germany. In collaboration with universities and other research institutions across Germany, we conducted surveys and workshops to establish an evidence base and co-produce practical instruments, such as a monitoring tool for flight emissions and a travel-decision tool, in the spirit of *transformative literacy in research*[51].

In the adaptation-oriented research project *Heat Adaptation for Vulnerable Groups (HEAL)*, geoinformatics research was combined with practical application through a transdisciplinary collaboration with municipal departments and user groups. The project developed a web-based navigation service (https://heal.openrouteservice.org) that identifies routes less affected by heat, providing location- and time-specific guidance during heatwaves[52]. The close involvement of user groups significantly enhanced the applicability and user orientation of the routing tool.

Transformative literacy in teaching: research-oriented teaching based on real-world problems

In the context of *FlyingLess* and *HEAL*, we developed a series of teaching and learning formats that involved students directly in research activities through regular geography courses and thesis projects. Students conducted surveys, analysed data, designed workshops, and engaged in diverse transfer

activities co-created with user groups and school classes. These projects benefited significantly from students' perspectives, and assessments conducted in the associated courses indicate that learning outcomes related to the direct integration of real-world problems into *research-oriented learning* were achieved.

At the Heidelberg School of Education, the *Certificate in Sustainability* (www.hse-heidelberg.de/nachhaltigkeit) equips future teachers with the competencies to connect *Education for Sustainable Development (ESD)*[53], as mandated in the school curricula of the federal state of Baden-Württemberg, with their respective academic disciplines. It exemplifies how transformation-oriented teaching can be embedded across disciplinary boundaries while maintaining curricular coherence and practical relevance. The blended-learning module *Climate Physics meets Education for Sustainable Development* integrates state-of-the-art climate science with approaches to teaching and learning for sustainability. Students collaborate in project-based activities, develop digital learning resources, and build both subject-specific and cross-cutting competencies[54]. The complementary self-study course *Critical Literacy for Climate Action* (www.hse-heidelberg.de/selbstlernkurs-cl4ca) strengthens this framework by focusing explicitly on media literacy. The student products and thesis projects indicate that learners developed competencies for addressing *wicked problems* in solution-oriented ways.

Transformative literacy in climate action: from individual to structural change

Across all project examples, the focus shifts from individual behaviour change to societal and structural transformation. They draw on the idea of the *handprint*, which emphasises positive, enabling contributions to sustainability, and on the concept of a *culture of sustainability*. The *FlyingLess* project illustrates particularly clearly how decisive the transformation of organisational conditions, such as travel policies, can be for advancing climate action.

Integrative learning elements: embedding transformative literacy in the curriculum

The most comprehensive integration of disciplinary study components with *transformative literacy* is currently being developed through the *Transformative Environmental Research (TrafU)* initiative (https://www.geog.uni-heidelberg.de/en/trafu). *TrafU* expands existing specialisations within the master's programme in Geography at Heidelberg University by introducing a new focus on transformative research in combination with the STEM components of Geography. Central to this initiative is a *Learning Companion* that we developed to guide students through self-directed study of the conceptual foundations and practical applications of *transformative literacy*. The *Learning Companion* explicitly integrates the three entry points of the framework: research, teaching and learning (Fig. 1). We designed it with higher education didactics support from *heiSKILLS* (https://www.heiskills.uni-heidelberg.de/en). Through a narrative structure and interactive assignments, students apply transdisciplinary methods to questions from Physical Geography and Geoinformatics. They participate in in-person sessions and peer-group meetings for deeper reflection. Teaching and learning activities draw on cases such as the *FlyingLess* and *HEAL* projects. A portfolio encourages students to connect *transformative literacy* with the broader content of their master's studies. Reflection is guided by the *handprint* concept, emphasising pathways from individual learning to structural change. In this way, *TrafU* combines rigorous disciplinary and methodological training with research-based engagement in transformation processes. The *Learning Companion* is being developed as an *Open Educational Resource* to support educators within and beyond Geography and to serve as a model for embedding *transformative literacy* in academic teaching.

Towards transformative impact

When research, teaching, and learning are connected through *integrative learning elements*, universities may build on existing efforts to evolve from institutions that analyse transformation to institutions that actively contribute to it. The resulting impact does not stem from outreach or communication alone, but from cultivating capacities for systemic thinking, collaboration, and responsible action within the academic community. This approach complements existing practices of science communication by enabling students to act on scientific understanding in ways that foster societal change.

As such practices expand, questions of assessment gain importance. *Constructive alignment*[48], as a central approach in higher education didactics, links learning outcomes with appropriate activities and assessment formats and allows course assessments to determine whether the intended outcomes have been achieved. Evidence from Climate Change Education suggests that well-designed courses can have lasting effects on participants' pro-environmental decision-making, underscoring the relevance of assessing not only immediate learning gains but also longer-term impacts[55]. Building on this, further work is needed to develop instruments capable of monitoring the development of *transformative literacy*. Useful starting points lie in indicators developed in sustainability education. Redman, Wiek and Barth[56], for example, provide an overview of current tools for assessing competencies such as systems, futures, values and strategic thinking, as well as interpersonal competency. These include concept mapping, scenario or case tests, reflective writing, focus groups or interviews and performance observation. The authors emphasise that many assessment practices remain insufficiently developed[56].

Through successive research and teaching projects at Heidelberg University, I iteratively refined and consolidated the framework, and this process has informed teaching design initiatives extending from individual courses to institutional discussions. The concept allows for adaptation to local and discipline-specific conditions and aligns with *whole-institution approaches* that embed sustainability across higher education. At the same time, it delineates a research agenda, particularly regarding robust methods for monitoring implemented measures and evaluating their contribution to *transformative literacy*. Building on these considerations, universities can strengthen their role as spaces of critical enquiry and democratic engagement, where scientific excellence and social responsibility are brought into closer alignment. For universities seeking to embed *transformative literacy* more systematically, the framework can serve as a structuring tool for collaborative curriculum development. Teaching teams may apply it to analyse existing modules in terms of their research, teaching, and societal interfaces, and to identify where *integrative learning elements* could be introduced or strengthened. The framework may, for example, be used in programme reviews to map existing courses against the three entry points, to identify blind spots, and to design *integrative learning elements* collaboratively across disciplinary boundaries.

Through such processes, *transformative literacy* may become both a guiding principle and a lived practice that evolves across disciplinary and institutional contexts. By creating opportunities for students, educators and researchers to engage with societal challenges in informed and collaborative ways, the framework presented here has the potential to support higher education in contributing to ongoing transformation processes and in preparing graduates to participate constructively in shaping sustainable futures.

Data availability

No datasets were generated or analysed during the current study.

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