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ARTICLE

Integrating Earth System Knowledge and Planetary Justice: Digital Modules for Systems Thinking

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Abstract
Education for sustainable development requires an understanding of complex Earth system processes with an ethical reflection on global justice. In this context, concepts such as planetary boundaries and the Doughnut model serve as reference frameworks. Their didactic connection to the concept of planetary justice has thus far only been partially addressed. This paper presents the theory-based, design-oriented development of a digitally supported learning module for geography in upper secondary education. The module is based on five conceptually integrated design principles: normative openness; planetary boundaries and Doughnut model as framework; systems thinking; integration of the three justice dimensions (interspecies, intergenerational, and intragenerational); and a problem-based, real-world learning environment. It was implemented using ArcGIS StoryMaps, which visualise narratives based on a case study to illustrate socio-ecological interrelations across local, regional and global scales. The paper contributes by facilitating a conceptually grounded integration of planetary justice into geography education.

Keywords: Doughnut model; education for sustainable development; planetary boundaries; planetary justice; system thinking

Introduction

Students must be encouraged to actively participate in the shaping of a sustainable future in the context of human prosperity and the ecological sustainability of the planet (Organisation for Economic Cooperation and Development, 2019). They must engage with factually and ethically complex problems. However, complex networks, time delays, and cross-scale interactions impede systems understanding and may lead to insufficient solutions (Roczen *et al.*, 2021). A prominent approach for structuring these complex ecological challenges is the concept of planetary boundaries, which captures the complexity from a scientific perspective and visualises threshold values, the transgression of which results in considerable risks for a safe operating space for humankind (Richardson *et al.*, 2023). Within this ecological framework, social minimum standards need to be ensured to expedite the realisation of human rights (Leach *et al.*, 2013). An ecologically secure and socially just development is further complicated since social and planetary boundaries are interdependent.

This highlights the didactic challenge of integrating system understanding and ethical reflection in education for sustainable development, which has been insufficiently elaborated thus far. Simultaneously, digital learning settings provide opportunities to visualise and connect these complex interrelations across local, regional and global scale levels. This paper explores how

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factually and ethically complex problems can be didactically addressed to foster socio-ecological systems thinking without imposing normative prescriptions.

Concepts such as planetary boundaries and the Doughnut model can serve as theoretical frameworks by connecting ecological boundaries and social minimum standards, thereby placing them in areas of tension. Against this background, this paper develops a digital learning module that integrates the aforementioned approaches. The learning module aims to develop students' systems understanding beyond individual planetary boundaries and utilise this understanding to initiate reflective consideration of questions regarding planetary justice. The focus lies on the contribution of a digital learning setting, based on StoryMaps, to making complex correlations visible across scale levels and critically reflecting on their scope of action in these complex contexts.

To this end, this paper first illustrates the theoretical base, explains the conceptual approach for developing the model, and then presents the concept and structure of the module. Finally, the didactic potential and limitations are critically discussed.

Theory

Planetary boundaries as a scientific framework for human activity

The concept of planetary boundaries has become highly relevant in science, politics, and civil society (Rockström *et al.*, 2024). The nine planetary boundaries (Climate change, Novel entities, Stratospheric ozone depletion, Atmospheric aerosol loading, Ocean acidification, Modification of biogeochemical flows, Freshwater change, Land system change) define limits for key biophysical Earth system processes and mark a safe operating space for humankind. All nine boundaries are integral components of the Earth system and are affected by human activities (Richardson *et al.*, 2023). Control variables have been developed for the quantitative operationalisation of the boundaries, which define the point at which the safe operating space is exceeded and a zone of uncertainty is entered. The planetary boundary "climate change", for instance, is defined by atmospheric CO_2 concentration as one of its two control variables. These boundaries should not be understood as exact tipping points but as a precautionary risk threshold, based on normative assessments of acceptable risks. Proposals for the operationalisation of all nine planetary boundaries now exist, but their robustness varies (Richardson *et al.*, 2023). Seven of the planetary boundaries are currently considered to have been transgressed on the global scale (Sakschewski *et al.*, 2025).

Even though the quantification of interactions among planetary boundaries poses a challenge and implies uncertainties, numerous advances have been made in this regard in recent years (Lade *et al.*, 2020). Understanding these interactions is central to assessing the consequences of human actions and identifying trade-offs and synergies between ecological and sustainability goals. With regard to the interactions among planetary boundaries, Lade *et al.* (2019) differentiate between (a) natural biophysical interactions and (b) human activities which either simultaneously influence several planetary boundaries via cascading effects or cause alterations in individual subsystems, which then affect other planetary boundaries. The interactions among planetary boundaries play a vital role in understanding the non-linear amplifying effects of anthropogenic interventions (Lade *et al.*, 2020).

The understanding of the interactions among planetary boundaries poses a complex challenge, as interactions are characterised by non-linear responses in time and space. Consequently, certain changes have an immediate effect, whereas others lead to time-delayed reactions. This also applies to the effects of anthropogenic impacts, which may manifest in distant regions. Interactions across scales further impede understanding because effects that do not have local or regional consequences can aggregate and become effective on the global scale. Overall, many interactions among planetary boundaries are dependent on scale; thus, the strength, direction, and influence of

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change can have different ramifications depending on the scale (Friis, 2024). Understanding these interactions is essential for assessing human influence on planetary boundaries. Governance measures must consider these interactions to anticipate trade-offs. Simultaneously, considering interactions may also reveal synergies among boundaries (Lade *et al.*, 2020).

Planetary boundaries are also being applied with increasing frequency in sustainability politics (Downing *et al.*, 2019). This is reflected, among other aspects, in their use as a scientific reference in United Nations (UN) conferences; national, regional, and municipal assessment frameworks; and in companies' sustainability reports (Rockström *et al.*, 2024).

A normative and epistemic orientation towards the Global North is problematised, particularly by perspectives of the Global South. Since the concept was predominantly developed by scientists from the Global North, concerns have been raised that the implementation of the planetary boundaries could restrict future economic developments, particularly in regions of Africa, Asia, and Latin America. Accordingly, the concept is considered politically less resonant in certain parts of the Global South (Biermann & Kim, 2020). This suggests that a purely scientific framework is insufficient to address sustainability in the sense of global justice. At this point, the Doughnut model becomes relevant, which is further clarified in the following section.

The Doughnut model: between ecological limits and social justice

Even though the concept of planetary boundaries is primarily rooted in natural science, it is not free from political consequences and implications, particularly regarding questions of global justice (Biermann & Kim, 2020). Following these considerations, Raworth (2012) developed the so-called "Doughnut model" (Figure 1), which expands the concept of planetary boundaries using social boundaries. In the context of sustainable development, the aim of social boundaries is to ensure access to minimum social standards (e.g. Social Cohesion, Political Voice, Health) which are necessary for the fulfilment of basic human rights for all people.

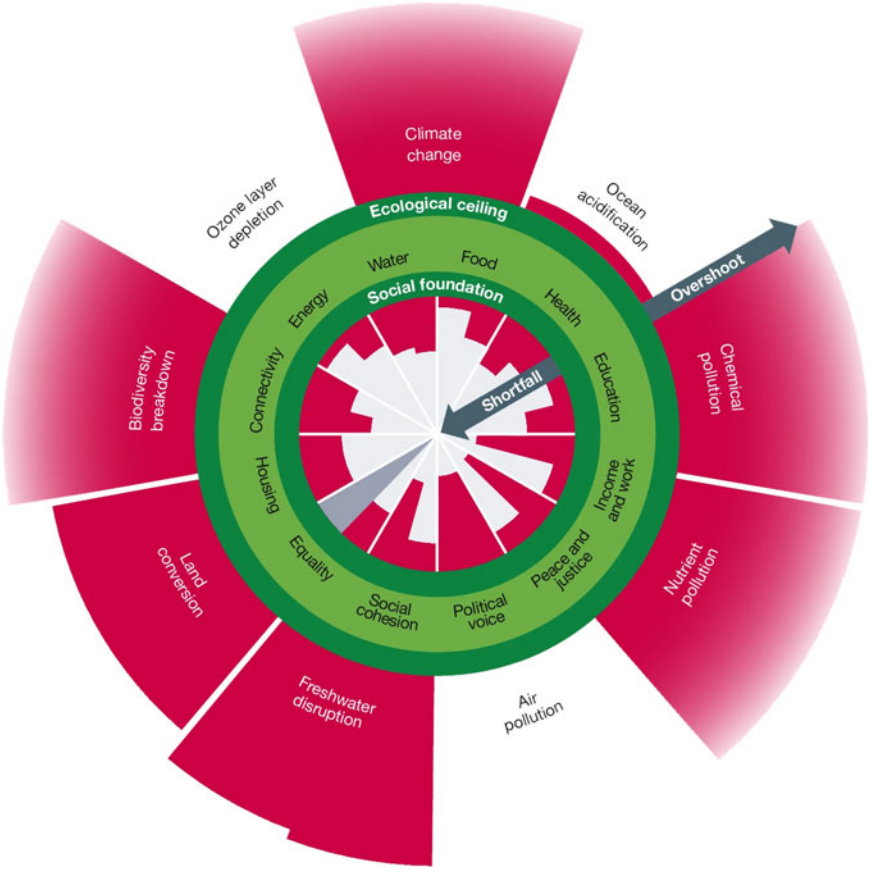
The two concentric circles in the figure form a doughnut, which defines a space within which actions can both secure planetary stability and ensure minimum conditions for a socially dignified life (Fanning & Raworth, 2025). The 12 social indicators are oriented towards human rights (Raworth, 2012) and display intersections with the UN's sustainable development goals (SDGs) (Fanning *et al.*, 2022). Both sets of boundaries are shaped by normative processes. Similarly, social boundaries result from societal negotiations regarding what constitutes the satisfaction of basic needs. Thus, the doughnut does not describe an objectively given space of opportunities but a normatively defined framework of orientation for sustainable development (Leach *et al.*, 2013; Raworth, 2012). It is precisely this openness that enhances the model's applicability to be analytically endorsed, but it simultaneously precludes simple technocratic policy prescriptions. Thus, the model is not primarily intended as a control instrument, but it structures conflicts and trade-offs while functioning as a heuristic framework for analytical approaches. Analyses reveal that a life within the doughnut space is currently not achievable. While billions of people fall short of the social boundaries (Fanning *et al.*, 2022), seven of the nine ecological boundaries are presently breached (Sakschewski *et al.*, 2025).

Acting within this space is inherently complex, as social and biophysical boundaries are deeply interconnected and form a socio-ecologically complex system which needs to be holistically approached. Environmental degradation can lead to more poverty, and measures for the reduction of poverty can exacerbate environmental degradation (Raworth, 2017). The Doughnut model highlights tensions between social needs and ecological limits. Thus, actions for sustainable development need to simultaneously address poverty reduction and compliance with planetary boundaries.

Since contributions to the transgression of planetary boundaries vary greatly among states and social groups, a discussion regarding safe and just Earth system boundaries (ESBs) has developed over the last few years, complementing the Doughnut model by incorporating questions of

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Figure 1. The Doughnut model has been extended multiple times and was most recently updated in 2025. Adapted from Fanning and Raworth (2025), the ecological ceiling of ocean acidification is depicted as transgressed according to Sakschewski *et al.* (2025).



responsibility and distribution regarding material and social resources (Biermann & Kalfagianni, 2020; Gupta *et al.*, 2023; Rockström *et al.*, 2023). The concept of Earth system justice (ESJ) is defined as "an equitable sharing of nature's benefits, risks and related responsibilities among all people in the world, within safe and just Earth system boundaries to provide universal life support" (Gupta *et al.*, 2023). A central component of the concept for the assessment of justice is the consideration of the "3Is": interspecies justice and Earth system stability, intergenerational justice, and intragenerational justice (Gupta *et al.*, 2023; Rockström *et al.*, 2023). The 3Is are based on Weiss (2008) and extend it by adding the dimension of interspecies justice and stability of the Earth system. Interspecies justice and Earth system stability refer to justice among species and the objective of protecting humans, other species, and ecosystems while fundamentally questioning anthropocentric exceptionalism. It is assumed that maintaining Earth system stability is a prerequisite for achieving justice among species. However, intergenerational justice emphasises justice between generations by considering the long-term consequences of actions. Here, two types of intergenerational justice are differentiated: the effects of past actions on the present generation (between past and present) and the responsibility of the present generation to keep the damage for future generations as low as possible (between present and future). Lastly, intragenerational justice describes questions of distribution between present individuals and states and the consideration of different overlapping social identities, such as gender, age, or ethnicity. Hence, intragenerational

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justice refers to questions of distribution and non-harm among present individuals and groups (Rockström *et al*., 2023). Thus, inter- and intragenerational justice in the context of ESJ are closely connected to the central guiding principles of ESD (e.g. United Nations Educational, Scientific and Cultural Organization (UNESCO), 2020; Wiek, Withycombe & Redman 2011). In this context, the 3Is enable critical reflection on the challenges of inter-, intra- and interspecies justice, without prescribing specific courses of action.

Learning for planetary justice in the context of the Doughnut model

Public awareness and lifestyle change are crucial for sustainability transformation (UN, 2019). To achieve such a transformation, knowledge, skills, values, and attitudes need to be fostered among learners to enable them to actively participate in shaping society (UNESCO, 2020). Future citizens and decision-makers also need to be aware of the safe space for action defined by the planetary boundaries (Kleespies *et al*., 2023). With the Doughnut model, the educational focus shifts beyond a natural science perspective towards a holistic view of the Earth system shaped by political–economic logics and human as well as ecological injustices (Arevalo, Alcaraz, Edwards & Schandler 2023). In the context of the Doughnut model, education must provide learners with access to system understanding as well as to ethically complex questions related to planetary boundaries.

System thinking is perceived as a key competence for ESD to understand and evaluate interactions between ecological, economic and social processes, and to act accordingly (Roczen *et al*., 2021; Wiek *et al*., 2011). System thinking is defined as the ability to extract a "mental representation of a system [. . .] from the real world, which can then be used to analyse the complexity of situations and, thus, to achieve an understanding of spatial and temporal relations." (Roczen *et al*., 2021, 2). Competence models illustrate which competences learners need to acquire in order to handle complex challenges (Mehren *et al*., 2018), and that system thinking can be fostered if the learning environment is designed for the understanding of complexity and system concepts (Assaraf & Orion, 2005; Mehren *et al*., 2018). The highly visual and integrative character of the Doughnut model enables the vivid illustration of the scientific complexity within and between planetary boundaries as well as social complexity. Additionally, trade-offs between outer and inner boundaries along with the safe operating space can be made tangible for learners.

Apart from factually complex problems, the Doughnut model also emphasises ethical complexity. Closely related to the safe operating space, questions of distribution, responsibility, and the protection of future generations are raised (Gupta *et al*., 2023; Rockström *et al*., 2023). Therefore, education for planetary justice is characterised by a dual challenge: cognitive complexity and normative complexity. This normative dimension is also addressed in the context of ESD (Wiek *et al*., 2011). Learners should not be steered towards certain actions; rather, they should develop well-reflected judgements and critically reflect norms and values grounded in disciplinary knowledge and ethical reasoning (Lindau & Kuckuck, 2022). Justice-related questions can be structured through the 3Is and used to guide ethical reflection. Complex ethical and philosophical problems such as the "non-identity-problem" can be discussed (Parfit, 1984), thus questioning the responsibility assumed for people in the future who do not yet exist (Arevalo *et al*., 2023). Regarding questions of distribution, it becomes clear that education for planetary justice must not stop at teaching system interrelations but facilitate spaces for multi-perspectival approaches, competing worldviews, and ethical reflections.

Against this background, the question that arises is how educational approaches can didactically engage in concepts of planetary boundaries, the Doughnut model, and planetary justice to foster systems thinking as well as encourage the development of a reflective ethical judgement. The following section addresses this challenge and presents a didactic concept that integrates both aspects into a digital learning module.

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Conceptual design and development process

The aim of the present paper is the development of a digital learning module that addresses the understanding of complex Earth system processes as well as questions of planetary justice in the context of ESD within the framework of planetary boundaries. The focus is not on empirical evaluation. Instead, the paper focuses on the development of a theory-based module for geography lessons in upper secondary education, oriented towards didactic design principles. This emerged from a reflective design process involving various experts.

The learning module follows a theory-based, design-oriented approach, which integrates five didactic guiding principles:

(1) a normatively open approach, which does not prescribe predetermined "correct" courses of action, but encourages learners to reflect on values (Wiek *et al.*, 2011);
(2) the utilisation of planetary boundaries (Richardson *et al.*, 2023) and the Doughnut model (Fanning & Raworth, 2025) as a reference framework, structuring connections between ecological sustainability and social justice, and visualising trade-offs among the boundaries;
(3) orientation towards the empirically validated competence model of systems thinking by Mehren *et al.*, (2018), which is based on a socio-ecological systems perspective and differentiates between two dimensions – (1) system organisation and behaviour and (2) system-adequate intention to act;
(4) the integration of the 3Is for the systematic exploration of normative questions in the context of ESJ (Gupta *et al.*, 2023), used as criteria for reflection to discuss different responsibilities and conceptions of justice;
(5) a problem-based, real-world-oriented learning environment that connects different scale levels and relates local courses of action to global effects in socio-ecological contexts (Rokhman *et al.*, 2025).

In summary, the didactic leading principles are not to be understood as a mere additive sequence but as interconnected guiding principles, which determine the choice of content as well as the digital implementation of the module.

ArcGIS StoryMaps (ESRI, 2025) was utilised to implement the module, as it allows complex content to be presented in a visually appealing manner via interactive maps linked with texts, illustrations, and multimedia content (Cope *et al.*, 2018; Izquierdo, 2023). Dynamic interconnections can be visualised via interactive storytelling (Roth *et al.*, 2025), which supports the development of a system understanding based on the competence model proposed by Mehren *et al.* (2018). In addition, pragmatic considerations supported the choice of StoryMaps, as its user-friendly web-based interface, interactive elements, and collaborative features make it suitable for classroom use (Anunti *et al.*, 2023). Simultaneously, the narrative approach opens spaces for normatively open guiding questions that can incorporate value-related reflection impulses in the sense of the 3Is. Although the web-based format of StoryMaps enables broad accessibility (Cope *et al.*, 2018), the findings of practical school experience have to be considered, as they indicate infrastructural as well as time-related limitations (Strachan & Mitchell, 2014); this indicates the use of pre-designed StoryMaps. To support transparency and facilitate transferability, the complete StoryMap module is made available as Supplementary Material accompanying this article.

The module was developed through an iterative process, combining theoretical foundation, practical testing, and expert-informed refinement. In addition to a pilot run with students, inputs from experts in geography education as well as practical experiences from geography teachers were incorporated into the development process. A conceptual design phase was followed by a pilot run with a class, which primarily functioned to test the understandability, didactic fit, and practical feasibility of the model. The feedback collected in this process was used

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to fundamentally revise the module. The disciplinary level was adjusted and the underlying software was modified. The revised version developed with StoryMaps was eventually discussed with geography teachers ($n = 3$) in guided interviews. All teachers participated voluntarily and were informed about the purpose and intended use of the interview. To this end, the teachers received information regarding the aim of the module as well as the underlying theoretical concepts (planetary boundaries and Doughnut model) beforehand and independently familiarised themselves with the module before participating in the interview. The interviews were conducted in accordance with research ethical standards. The participants provided written consent, and the study was approved by the responsible ethics review committee. The interviews were not systematically analysed but served as formative expert consultation within the design-based development process. Quotations are anonymised in the discussion, translated into English, and marked by sequential codes (I1–I3).

Design and conceptual development of the module

A flexible module structure was selected, thereby enabling teachers to adapt the scope and depth depending on the learner group as well as the structural and organisational conditions. Apart from a central base module, two optional extension modules are offered, which engage more deeply in (a) the concept of planetary boundaries and (b) ethical questions in the context of the Doughnut model. The two extension modules are not presented here in detail since the focus of the results section is on the base module. The base module is self-contained, but allows for a content extension if needed. Work on the StoryMap is mostly done in small groups, but it is interrupted by consolidation phases or whole-class discussions. In the following, the base module is presented in terms of its structure and learning activities, showing how the design principles described in the methodology section are concretely implemented in the learning tasks. The base module "When delight meets its boundaries"[1] begins with a problem-oriented lead-in using a fictitious Instagram post regarding strawberry consumption. The format is intended to provide a low-barrier entry point to the topic. On the one hand, the question posed by the Instagram post "What do supermarket strawberries have to do with flamingos in Spain?" quickly makes it clear to learners that a complex question is addressed that cannot merely be answered in a linear fashion and further provides a structuring and framing function for the entire module (*design principle 5*). The question posed in the lead-in is deliberately linked to a spatial example from the outset, which is further examined below.

Strawberry cultivation in Huelva has been selected as a spatial example for various reasons. It addresses a topic in which several planetary boundaries are closely connected and further enables the linkage of regional, international and global scales through patterns of consumption, cultivation practices, and ecological cause–effect relationships.

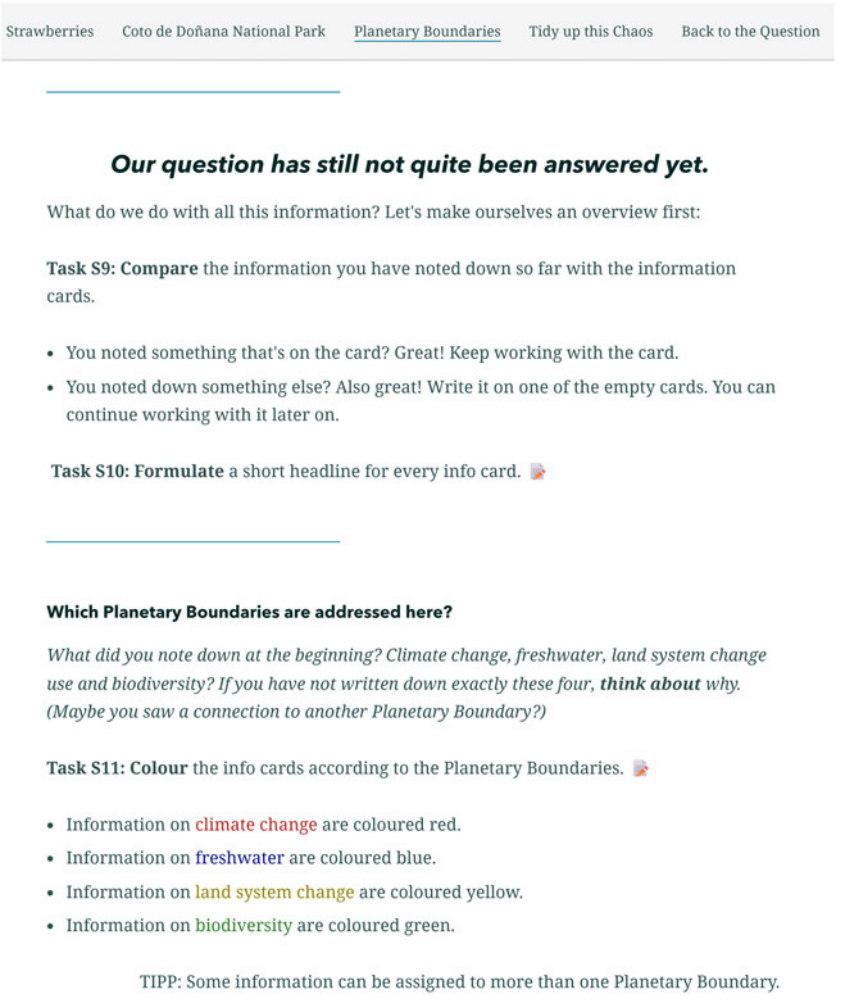
After basic information regarding the spatial example has been provided, students are introduced step by step to the concept of planetary boundaries (*design principle 2*). This sequence enables the learners to link abstract concepts with spatially locatable information. The central element of the module is a set of printed information cards provided by the teacher, which students complete independently based on the provided materials. In a cumulative task within the module, the students have to arrange the cards into a concept map, which enables them to answer the leading question. The information cards are also used as a basis for conceptual elaboration. For example, the information contained in the cards has to be assigned to scale levels and planetary boundaries (Figure 2).

Elements of systems thinking – such as chains of arrows, feedback loops, and cycles – are not assumed but introduced through guiding prompts and examples (Figure 3).

[1]The base module was originally developed in German and translated to English for this publication.

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Figure 2. Tasks for an in-depth examination of the information cards (own illustration).

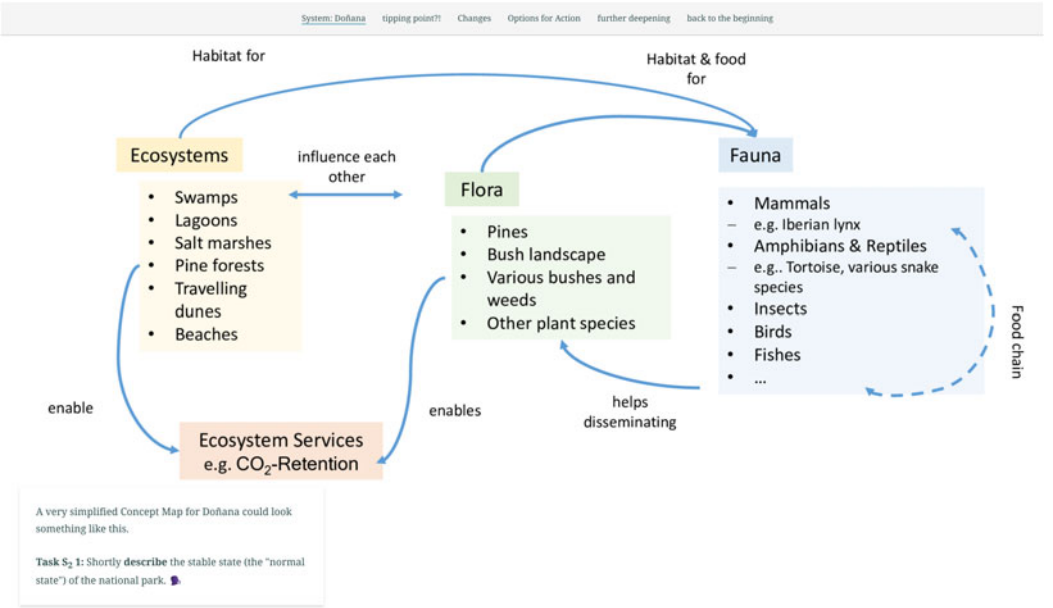


In this manner, the students' systems thinking should be fostered, thereby resulting in a well-structured concept map. Thus, the base module first focuses on an interconnected understanding of complex socio-ecological interrelations. This goes beyond the consideration of individual environmental problems and makes the interconnected nature of multiple planetary boundaries tangible.

Following the completion and discussion of the concept maps, which can be assigned to the dimension "*system organisation and behaviour*" of the competence model (Mehren *et al.*, 2018) (*design principle 3*), the module transitions to the second dimension called "*system-adequate intention to act*." This transition is shaped by the original Instagram post. In this context, the module functions as a reflective point of reference. Within the system understanding developed thus far, the focus shifts to questions of action. For this, the different levels of action within the system are presented to learners, which can be located at the individual, collective–social, political–institutional, and economic–structural level. Possible actions and the corresponding level of action are marked at the corresponding point in the concept map, thereby creating a basis for discussion regarding the differing effectiveness and potential for influence of the options of action, depending on the level. The aim here is not the prescription of specific actions for the students, but rather a critical

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Figure 3. Exemplary concept map of the Doñana region implemented in the StoryMap (own illustration).



examination of the courses of action with their effects in complex socio-ecological systems (*design principle 1*). To reflect on these from a normative perspective, the view is extended in the next step.

Here, the 3Is (Gupta *et al.*, 2023; Rockström *et al.*, 2023) are introduced as criteria for reflection (*design principle* 4). The 3Is are conceptualised as guiding questions that serve as analytical lenses for the learners in the analysis of ethical tensions in the context of planetary boundaries. For this purpose, the students are presented with learner-appropriate, normatively open questions that should lead to a reflection of the courses of action from the perspective of the different dimensions of justice. For example, the effects of human action on other species and ecosystems, long-term effects for future generations, and present asymmetries of power and distribution between social groups and regions are put into focus. Students' reflections are subsequently discussed in plenary, and an evaluation or prioritisation is deliberately omitted, since normatively open questions are addressed therein.

The individual responsibility and different courses of action within the system and the field of tension are addressed in a concluding phase. Students' own scope of agency is discussed and the structural limits of individual action are assessed. Thus, the module does not aim at a specific behavioural change, but targets a reflective judgement regarding complex socio-ecological questions.

Discussion

The conceptual development reveals how the module connects systems thinking, the reflection on potential actions, and normative perspectives in the context of planetary boundaries. The following discussion highlights both the pedagogical potential and the structural limitations of the approach.

The concept of planetary boundaries aims to conceptualise a scientific understanding of a safe operating space for humanity, in which the Earth system is regarded as a whole (Richardson *et al.*, 2023). An understanding of such complex systems is challenging for learners (Jacobson & Wilensky, 2006) and emphasises the need for a pedagogical simplification in a school context (Mehren *et al.*, 2018). Simultaneously, a fully holistic representation of planetary boundaries is

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scientifically only achievable to a limited extent, as cross-boundary interactions are thus far only quantifiable to a restricted degree (Richardson *et al.*, 2023). An exemplary focus on selected aspects within and among planetary boundaries, as conducted in the module, can be both pedagogically and scientifically justified. At the same time, this focus demarcates the limitations of the approach, since neither all planetary boundaries nor all elements of the respective problem situation can be considered. The necessary reduction of content further provides the opportunity to make complex global issues tangible through a concrete case. The problem-oriented approach, grounded in students' everyday lives, can be regarded as a didactic strategy to motivate learners (Wijnia *et al.*, 2024) to engage in complex topics. The problem-based design of this module follows this approach by concretising a global sustainability topic via a place-based case study close to students' everyday lives. The lead-in by a problem-oriented question and a narrative design of the StoryMap were described by the interviewed teachers as highly relatable ("*The case study with the strawberries from Spain, that fits very well, because it is just very close to the reality of the students*". I2) and highly motivating. It was reported that the initial problem question created interest and motivated further engagement (I1). Through narrative formats such as StoryMaps, personal experiences can thus be connected to broader societal and political contexts (Ryan & Aasetre, 2021) so that the abstract discourse on planetary boundaries is made tangible for students. Here, everyday-life relevance was explicitly mentioned as a didactic strength by the teachers because it made students realise that it "*[affects] my life much more than I thought*" (I1). Thus, problem orientation and everyday-life relevance function not only as a motivational lead-in but make complex, socio-ecological connections accessible and establish an individual connection to abstract concepts.

Based on the problem-oriented lead-in, the module aims at fostering systems thinking as a central competence of ESD (Wiek *et al.*, 2011). The ability to understand complex interactions among Earth system components is regarded as fundamental for reliable predictions of potential Earth system trajectories (Richardson *et al.*, 2023). The incremental development of the concept map in the module supports this process by enabling learners to build a mental representation of selected system interactions. The gradual, example-based introduction follows the assumption that systems thinking unfolds via consecutive stages of development (Assaraf & Orion, 2005). In this context, one teacher emphasised the introduction to the method: "*[That] the methodology behind the concept map is visualised so clearly and presented in a comprehensible way*." (I3). At the same time, the high level of step-by-step guidance was critically discussed with regard to its appropriateness for upper secondary students (I3). The feedback emphasises the potential and the limitations of the approach. While the structured approach facilitates the visualisation of key relationships among selected planetary boundaries, the resulting systems understanding inevitably remains selective, both in terms of the content addressed and the learners' individual meaning-making processes. Accordingly, one teacher emphasised that the students "*may not comprehend the entire model, but would definitely pick up central elements*" (I2). In this respect, the module resonates with Roth *et al.* (2025), who highlight the potential of interactive digital storytelling to foster the understanding of non-linear developments, reveal system interconnections, and deepen learners' comprehension of complex systems. Based on this complex system understanding, the action dimension is introduced in the module (Mehren *et al.*, 2018). However, an understanding of the system does not constitute a sufficient condition for responsible action, as sustainability choices are always shaped by uncertainties, trade-offs, and normative considerations. Thus, it is not possible to provide learners clear recommendations for action due to subject-specific and ethical complexity, particularly in the context of sustainability topics (Lindau & Kuckuck, 2022). Accordingly, in this module, action is not understood as the deduction of "correct" solutions but as a reflective process, explicitly involving uncertainty, trade-offs, and differing interests.

With this understanding, the module connects to the OECD's (2019) concept of transformative competence, in which a critical reflection of the effects of one's own action and responsibility are considered a central competence domain. This is supported by the

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teachers' statements, who emphasise the importance of understanding the effects of one's own actions on different scale levels (I2). The structure of the module, organised along the 3Is, supports this critical reflection by making different perspectives visible without prescribing normative positions. In this manner, ethical reflection is established as an integral component of engaging in the planetary boundaries framework, aligning with the conceptions of sustainability education that emphasise the collective negotiation of values (Wiek *et al.*, 2011). The module integrates systems thinking and digitally supported learning environments while reflective action orientation highlights the potential to foster learners' informed judgement regarding complex questions of sustainability (Roth *et al.*, 2025).

The design of the StoryMap emphasises the potential of digital narrative formats for ESD beyond content-related design principles. Through their visually appealing representation of complex sustainability topics across scales, StoryMaps have the potential to foster cross-cutting competences such as creativity, collaboration, and critical thinking (Tusam *et al.*, 2024). In particular, the visualisation of different scale levels is a didactic strength, as global interdependencies and local action are vividly interconnected (I1; I3).

Furthermore, feedback from the teachers confirms familiar limitations of StoryMaps, among them greater time demands and technical requirements (Strachan & Mitchell, 2014; Tusam *et al.*, 2024). Additionally, a perceived lack of clarity in the presentation due to the amount and complexity of content was also mentioned in the interviews (I1).

Concrete implications for classroom practice can be deduced from the identified potential and limitations. The feedback indicates that pre-designed digital modules can contribute to reducing teachers' workloads (I1). Simultaneously, the feedback reveals that the successful implementation of digital narratives requires a clear didactic structure. Therefore, for classroom practice, it appears useful to structure StoryMaps in a more modular manner, incorporate orientation aids (e.g. advance organiser), and integrate plenary reflection phases.

The present analysis is based on a small number of expert interviews and does not claim representativeness. While the module was piloted, its full pedagogical potential under regular classroom conditions remains to be empirically examined. Moreover, learners' perspectives and actual classroom interactions were not systematically analysed herein. Therefore, future research should investigate how students engage with normative tensions and translate systems thinking into action-related reasoning. Mehren *et al.* (2018) point out that system-adequate intentions to act do not necessarily result in actual behaviour. Here, reference can be made to the value-action gap in sustainability research, which indicates an inconsistency between values, subject-specific knowledge and people's actions (Portus *et al.*, 2024). Furthermore, a specific StoryMap that has been developed over a long period of time was evaluated in the interviews, only considering an anticipated, but not actual, classroom practice.

In conclusion, the contribution of the study lies in the conceptual development and reflection of a digitally supported didactic approach for the teaching of planetary boundaries in a school context.

Conclusion

The central aim of the learning module was to foster systems thinking in relation to complex sustainability challenges, thereby enabling reflective judgement as well as an ethical engagement with sustainability conflicts in the sense of ESD. The conceptual development of the module emphasises that the concept of planetary boundaries and the Doughnut model can contribute to visualising complex socio-ecological interrelations and making sustainability trade-offs tangible for learners as structuring frames of reference. As a complementary reflective framework, the inclusion of the 3Is proved useful; with the help of the 3Is, relationships of power, normative tensions, and scope of action can be critically questioned, without making normative prescriptions

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to the learners. A key didactic challenge lay in condensing the content and the ethical complexity of the topic in developing a systems understanding. Simultaneously, central trade-offs and normative ambivalences ought not to be oversimplified.

The implementation of ArcGIS StoryMap reveals its potential to visualise system interrelations and integrate different perspectives. In particular, the narrative structure of the learning setting based on a spatial example aims to connect different scale levels, thereby making complex interrelations pedagogically accessible. However, StoryMaps also has familiar limitations regarding time investment or technological equipment.

This paper makes a conceptual contribution of a theoretically founded and didactically reflected development of a digital learning module for the operationalisation of planetary justice in school contexts. An empirical assessment of the module's implementation in school as well as the learners' perspectives is a valuable direction for further research.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/aee.2026.10172.

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