Learning evolution through socioscientific issues

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CHAPTER 1 EDITORIAL

Learning evolution through socioscientific issues: A functional scientific literacy perspective

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Evolutionary theory is arguably one of the most important unifying conceptual and theoretical frameworks that subsumes the natural sciences (National Research Council, 2012). It is the model case of an interrelated set of amalgamating observations, inferences, predictions, and retrodictions that hold explanatory power to make sense of our living world. Yet, evolution understanding has been shown to be low in many countries, even for students attending biology related study programs at a university (Kuschmierz et al., 2021).

Scientific understanding of evolution is not bounded by geopolitical borders, but it may certainly be impacted by it, for public understanding of science is both facilitated and hindered by a plethora of sociocultural considerations. Sometimes these considerations may range from the innocuous, such as misunderstandings, to the deliberately deceptive, such as reshaping scientific evidence and transmuting it to serve religious or political ends (Jørgensen et al., 2019).

Other factors that impinge on public understanding of science in general, or evolutionary theory in particular, require that scientific and science education professional communities look inward on the efficacy of our own teaching practices. In doing so, we may uncover a pedagogical irony – that some of our conventional time-worn traditions of teaching get in the way of students' understanding (Zeidler et al., 2011).

It is important to note from the onset, that while we frame the learning of evolution through a contextualized lens of socioscientific issues (SSI; Zeidler, 2014; Zeidler & Sadler, 2023), we do not take the position that evolution as a unifying principle is, in and of itself, an SSI. SSI are ill-structured problems and dilemmas that are controversial in nature, with no clear-cut immediate solutions, require evidence-based considerations, and are overlaid with moral and ethical implications (Zeidler & Sadler, 2023). Evolutionary theory lacks these defining characteristics. That evolution has occurred and continues to transform the organic world through macro and micro processes is not, in and of itself, controversial in the scientific community. However, as it is controversial in some parts of the society, it can be classified as Societally Denied Science (Borgerding & Dagistan, 2018) and a Controversial Science Issue (CSI; Beniermann et al., 2021).

While particular understandings may be challenged and become modified when new evidence comes to light through discoveries and technological advances (e.g., phyletic gradualism versus punctuated equilibrium), it comes to no great surprise to those with informed views of the Nature of Science (NOS) because the very nature of epistemological scientific knowledge itself is characterized by knowledge that is durable, yet subject to change, socially and culturally embedded, necessarily subjective, tempered by human creativity, empirically-based, and guided by explanatory power (Abd-El-Khalick & Lederman, 2023; Lederman & Lederman, 2014).

Once we move outward from the academy to how we teach concepts related to evolution theory to students in school settings, subject matter may become more controversial because we find ourselves brushing up against different cultural assumptions, religious beliefs, and ethical norms. It is widely recognized that understanding evolution is crucial to finding solutions to the various challenges we face today (Carroll et al., 2014).

Moreover, this knowledge has impacts in several fields. In biodiversity conservation, for example, we can talk about the poor adaptation of species to climate change and pollution which causes a reduction in biodiversity through species extinction (Barnosky et al., 2011). In human health, problems resulting from changes in our diet, environment and lifestyles (i.e., obesity, diabetes, cancer, etc.) or, in the case of diseases, the evolution of new or drug-resistant pathogens (i.e., infectious diseases) (World Health Organization, 2014).

If we focus on food security, we can mention the increase in pesticide resistance that has been causing a decrease in agricultural production, compromising food supplies worldwide (Tabashnik et al., 2014). All of the aforementioned examples are related to evolutionary processes, and an increased application of evolutionary biology principles to challenges such as these can improve our ability to respond to many of the most pressing sustainability issues (Carroll et al., 2014).

Yet, while all SSI are controversial, not all controversial issues are SSI (Zeidler et al., 2019). However, we find in the *contextualization* of evolution within an SSI framework there lies a multitude of topics (e.g., competition among individuals, equitable distribution of resources, social-ecological systems, global warming, genetic modification) that are at once, relevant to students, controversial, ill-structured, require students to engage in dialogue or argument, necessitates degrees of ethical or moral reasoning, and help to build the formation of virtue and character over time.

Engaging students in such topics is referred to as the long route to both moral development and scientific identities that require a functional perspective of scientific literacy, developed not in isolated teachable instances, but in the deliberate and systematic construction of SSI-type of inquiry over time (Bencze, et. al., 2019; Zeidler et al., 2019).

This volume is aimed at enacting a progressive vision of scientific literacy that provides teachers and science educators with tools to conceptualize and apply an SSI approach to instruction with the aim of promoting informed understandings of evolution. It is premised on the assumption that leveraging the insights of diverse stakeholders ranging from evolutionary scientists to science educators, from museum professionals to media experts, can contribute to educational solutions to develop students' scientific literacy, that are easier to implement and more effective in real educational contexts.

The fact that 34 authors and 29 reviewers from 15 distinct countries collaborated to produce this book, is a strong indication of the level of importance that professionals around the globe assign to this topic. It is important to note that moral and ethical issues, which are part and parcel to the SSI framework, can be informed by evolutionary topics as those topics do not stop at the border of any one country any more than global environmental problems are limited to the site of their proximal impact.

Furthermore, inasmuch as biological evolution is related to many global environmental problems that threaten the sustainability of our planet, understanding evolutionary processes may support the planning and evaluation of long-term solutions to these problems by enhancing the ability to understand and assess multiple possible, probable and desirable futures, and promoting the application of precautionary principles in the evaluation of the consequences of our actions. It is important to note that anticipatory competence related to sustainability is one of the competencies mentioned by UNESCO (2018) as essential to promoting sustainability.

There has never been a more pressing time to solicit the collective input of scientists and educators from multiple locations in different countries. We note, for example, that recent (rapid) advances in technology have presented new challenges to academics in general, and science instruction in particular. The most dramatic affront to classroom learning are students taking photographs of powerpoint slides that consist of words and images sans any degree of deep mental processing.

Missing are the kinds of imaginative and creative childhood experiences that encourage development of long-term memory and critical thinking skills (Duckworth, 2006). SSI can provide the kind of help needed to rekindle authentic learning experiences that facilitate the co-construction of knowledge based upon consensus building, participation and understanding that can withstand the challenge of scrutiny and counter instances (Zeidler, 2014).

Given that students are inundated with a torrent of information both reliable and misleading, the ability to utilize critical reasoning skills, employ multiple perspective taking, making decisions about the welfare of the biological and physical world in a just manner, represents scientific literacy in action.

The distal aim of an informed citizenry can be nothing less than the exercise of functional scientific literacy. This is, in all respects, a necessary condition for the spread of human flourishing. The competition to evolutionary understanding is not to be underestimated. Science educators face a virtual (and literal) wall of *'meta-ignorance'* where novices have an undue overestimation in their confidence to resolve matters outside of their domain of expertise.

This is a result of the Dunning-Kruger Effect (Dunning et al., 2003), and is best described as *"… a meta-ignorance (or ignorance of ignorance) [that] arises because lack of expertise and knowledge often hides in the realm of the 'unknown unknowns' or is disguised by erroneous beliefs and background knowledge that only appear to be sufficient to conclude a right answer"* (Dunning, 2011, p. 248). For example, it has not gone unnoticed that those who stake out political ideologies often do so with little to no grounding in the assessment or careful consideration of scientific evidence (Owens et al., 2017).

It is ironic, then, that while the rapid progression of technology development has provided opportunities to expand the boundaries of knowledge, it has also limited how deeply we connect to that knowledge. The diminished literacy scores can be explained through the increased use of cell phones, iPads and computers for acquiring knowledge, as textbooks are being replaced with visual presentations, without sufficient written explanations that encourage thoughtful consideration (Carter et al., 2017).

Synaptic connections that are necessary for imagination and problem solving require increased reading opportunities. Contrary to theoretical expectations (Herman, 2013; Zeidler, et al., 2016), the learning curve has been skewed away from critical thinking and problem-solving skills to improved multi-tasking and utilizing the Internet for uninterrupted personal communication. Does this suggest that the intrusion of *"i technology"*[1] has inhibited the ability of students to discern relevant, reliable and valid claims from competing falsehoods? If so, then students' brains will tend to

1. I technology was originally introduced by Steve Jobs in a keynote talk in 1998 as he introduced the internet capabilities of an iMAC computer. With the introduction of other Apple products, such as iPad, iBook, iPod, iPhone, iOS, etc., i technology has become not only ubiquitous with Apple branding, but also carries a generic connotation of individuals being connected with and to technology at a finger's length. Kember (2016) expands this notion in her book, *iMedia: The Gendering of Objects, Environments and Smart Materials.*

graft nearby non-facts to valid information to create a mutated and highly invasive species of fact-fiction hybrids. That students demonstrate confusion between knowledge and belief, where belief represents unproven but believable hearsay, has been shown in the research (Zeidler et al., 2002, 2018).

Exacerbating this is the fact that one's dominant culture many times serves as a double-edged sword, serving both as an ethnocentric lens to solidify group identity as well as a filter that sifts out dissonant values that may run counter to one's core beliefs (Kahan et al., 2011a, 2011b).

Hence, the topics and content that science teachers present in class compete with marketing of products through inaccurate science. An important implication is, therefore, that a primary role of the science teacher includes fostering the acquisition of knowledge and skills that would encourage questioning of claims and authority (Oliveira-Martins et al., 2017).

To that end, the chapters in this book present SSI-related approaches to counter some of these sociocultural issues, by diving deeper into areas of exploring conceptual understanding of evolution through tapping sociocultural approaches consistent with the SSI framework. In doing so, we align our approach to achieve functional scientific literacy with that of Roberts & Bybee's (2014) Vision II scientific literacy, stressing how science should be made relevant with personal and societal issues impacting the lives of students. Accordingly, topics covered by this volume also facilitate Vision II, as found in the following summaries below. Why is SSI an impactful pedagogical approach to foster scientific literacy Vision II and Vision III? What are the differences between SSI and other educational approaches that link science and society? And how can teachers plan educational instruction that address SSI? In Chapter 2 Emine Sarıkaya and Mustafa Sami Topçu describe their approach to socioscientific issues, how it appeared and how it is different from the science, technology and society approaches.

They also describe two models to design educational activities: the most recent version of the Socioscientific Teaching and Learning Model proposed by Friedrichsen, Sadler, Graham and Brown (2016) to design SSI based instruction and the 5E Model developed by Bybee that presents a framework to design science learning outcomes (Scott et al., 2014). The authors guide us through these two models and provide suggestions on how to make these two models compatible and useful to design SSI teaching approaches.

In fact, the complex and controversial problems we face today require education to empower citizens with scientific literacy and in particular with competencies in sustainability that allow them to contribute to more just and sustainable societies. In Chapter 3, Patrícia Pessoa, J. Bernardino Lopes, Alexandre Pinto and Xana Sá-Pinto address this field of education for sustainable development and its connection to evolution education and the SSI pedagogical approach. By means of a systematic literature review they identified studies comprising these different approaches to identify which competencies of sustainability are developed in these studies. They demonstrate that only a few studies addressed evolution education and education for sustainable development by means of an SSI approach. This highlights the importance of performing more studies and developing more activities on how to promote education for sustainability by exploring SSI under an evolutionary perspective.

Furthermore, although evolution is related with many of today's sustainability problems, for example human health, biodiversity conservation, or food security, most of the topics addressed in the papers analyzed are related to the biotechnology field. Lastly, this study also highlights the importance of fostering participatory work to promote the development of competencies in sustainability through collaborative, meaningful and contextualized learning in the resolution of real problems.

In Chapter 4 Martha Georgiou, Maria João Fonseca, Corinne Fortin, Sébastien Turpin and Camille Roux-Goupille explore the application of SSI in non-formal education contexts, especially in museums. Activities from the Natural History Museum of Porto, the National Museum of Natural History of Paris and the Zoological Museum of Athens are presented as examples.

These activities focus on biodiversity, one of the aspects of evolution that is becoming increasingly noticeable and an essential component of life. They also reference the integration of SSI activities in other non-formal education environments and offer a critical reflection on the contribution of such environments to SSI education. But how is evolution related to SSI? In Chapter 5 Alex Jeffries describes how evolution is relevant to subjects that impact our daily lives and how these subjects can be used as hooks to foster students' engagement in the classroom.

From the evolutionary perspective of humanity's place in nature to the importance of evolution in predicting biodiversity changes during climate change, through to evolutionary insights about cancer and COVID-19, Jeffries guides us through the processes and how understanding of evolution can be used to make informed choices in our daily lives.

Although evolution is widely recognized as one of the most valuable scientific theories, hundreds of studies have documented a variety of sociocultural, linguistic, cognitive, and epistemic factors that influence the understanding and acceptance of evolution, making it one of the most challenging disciplines to communicate and teach effectively.
In Chapter 6, Ross H. Nehm and Kostas Kampourakis provide a brief overview of some of the most significant topics relevant to effective teaching and communication about evolution (worldviews, the nature of science, the language of evolution, cognitive biases and misconceptions, reasoning about evolutionary phenomena, cases and curriculum, teaching practices, and assessment and learning), inviting the readers to use this chapter as an entry point into the rich literature on evolution education. These authors suggest focused attention on all of these topics for effective evolution education and outreach.

The last chapter of the theoretical part of the book - Chapter 7 - bridges theory and practice. In this chapter Merav Siani and Anat Yarden present three training activities that could be applied in secondary schools as well as in teacher training programs. The activities address three human health issues: lactose tolerance, celiac disease and starch consumption affecting diabetes.

The principles that guided the design of these three activities are described. In addition, some results are presented after the implementation of one of the activities to a group of pre-service teachers. According to the results, a significant proportion of teachers used more key concepts of evolution after experiencing the activity and a significant proportion of them increased their acceptance of evolution.

In Chapter 8 Susan Hanish, Dustin Eirdosh and Tammy Morgan deal with a classic dilemma of how to cooperatively and sustainably deal with common-pool resources (a problem also known in economics as the '*tragedy of the commons*'). The problems of navigating self-interest in a finite resource within human society are very real-world issues that range in scale from the individual through to global challenges such as sustainability, mitigating climate change and dealing with pandemics.

Similar resource *'tragedies'* exist in the natural world and have evolutionary mechanisms and implications for the species involved. Hanish and colleagues provide an overview of common-pool resource dilemma theory in both evolutionary and human natural resource contexts. This theoretical background is then developed into a flexible set of five secondary school teaching lesson plans (with practical advice to teachers) which help students grasp the SSI implications of sustainable resource use.

The five lesson scenarios and sets of questions allow students to reflect on and discuss both the theory and problems associated with common-pool dilemmas, allowing them to develop understanding of SSI in general, evolution, scientific practices, the nature of science and its interface with society, and develop transversal skills such as analysis, critical evaluation, epistemic understanding, and open mindedness. In Chapter 9, Ümran Betül Cebesoy considers how evolution itself, as a societally controversial issue for parts of the society, can be addressed by means of the SSI framework and proposes an activity for higher education.

As evolution is often addressed in negotiating SSI, and argumentation is a frequent tool in SSI approaches, this activity applies an approach in which argumentation plays a key role. With the goal to increase participants' understanding of natural selection she applies an antibiotic resistance context. The activity comprises three parts, the first explores participants' prior ideas about evolution and their prior conceptions about antibiotic resistance. The second part comprises some specific reading activities and input concerning antibiotic resistance and the role of natural selection. In the last section, a classroom discussion challenges student's ideas and fosters their argumentation competences.

The whole activity targets several learning objectives concerning SSI (develop understanding of SSI, decision-making skills, realize the existence of different viewpoints, and informed decisions about natural selection contexts), evolution (realize natural selection as one of the mechanisms of evolution, identify variation, heritability/inheritance, and reproductive advantage/differential reproduction as three main concepts of natural selection, to discuss the role of these factors in understanding natural selection, and to recognize the role of mutations as significant sources of genetic variations), scientific practices (construct explanations, engage in argumentation and seek evidence, and obtain, evaluate and communicate information), Nature of Science (realize that science is based on empirical evidence), and transversal skills (analyze issues from multiple perspectives).

In Chapter 10, Rebecca Lewis, Ellen Bell and Eleanor Kent present us with the dilemmas that farmers face when deciding how much to invest in agricultural practices that are pollinators' friendly. Through an engaging game, students learn about these, by playing the role of farmers, making decisions and receiving the return of the crops sold in the end. Some of the processes of the games are related to evolutionary processes such as co-evolution or natural selection driven by disease resistance and the authors provide ideas and suggestions on how to explore these processes in the classroom.

In Chapter 11, Rita Ponce, Susana Carneiro, André Rodrigues and Mustafa Sami Topçu, deal with the correlation between the geographical distribution of human skin color and solar radiation intensity as one of the most remarkable examples of how natural selection has shaped the evolution of our species and the divergence between human populations. In addition, the impact of solar radiation on human health is discussed, while highlighting the importance of communicating its potential negative effects and how to avoid them.

To this end, the authors present an educational activity (K9-K12) that calls for the creation of a dissemination campaign focusing on the effects of solar radiation. The goal of the activity is to help students learn about natural selection, how it causes population divergence, and how these are related to evolutionary processes. Furthermore, students will explore the concepts of subspecies and races (and how the latter has no real biological existence). Ethical and medical issues are also the axes of a debate organized by students to communicate health issues related to evolution and develop scientific practices.

In Chapter 12 - *"Are we allowed to tinker with (human) DNA? Addressing socioscientific issues through philosophical dialogue: the case of genetic engineering"* - Jelle De Schrijver, Stefaan Blancke, Eef Cornelissen, Jan Sermeus and Lynda Dunlop, argue that education about socioscientific issues such as genetic engineering can be challenging. Underlying tensions can surface when discussing genetic engineering.

These tensions can be related to (1) the molecular biology of genetics and genetic engineering, (2) the evolutionary aspects of genetic engineering, (3) the nature of science, and (4) the ethical understanding of the SSI. The tensions may lead to confrontation, either between students or between students and teacher. To address such tensions, the authors suggest a pedagogical approach: *'Philosophical inquiry'* that entails dialogue where a teacher (facilitator) helps a group of students to uncover hidden presuppositions and elicit an argumentative conversation. Stimuli such as cases, pictures or quotes provide a context to help students engage in dialogues about philosophical questions. At the end of the chapter, the authors provide tips to keep in mind when addressing SSI through philosophical inquiry.

The breadth of the chapters introduced above suggests that the curriculum of SSI is an evolving organism of instruction, as novel issues parallel constantly changing media headlines and challenge core students' beliefs. Not coincidentally, the current debate regarding fake news has been a constant challenge of deciphering authentic science concept knowledge.

It is, therefore, educationally prudent to provide students with the skills necessary to engage in informed, moral decision-making that impacts issues like sustainable development, dealing with controversy, understanding the critical need of biodiversity, and the like (e.g., Oliveira-Martins et al., 2017; Stevenson et al., 2012; UNESCO, 2018, 2021).

Because of these opportunities, students begin to move away from more narrow epistemological beliefs and begin to widen their worldview within new perspectives and issues exhibiting what some might refer to as horizontal decalage (Gauvain & Cole, 2009) as they articulate broader and more inclusive views or moral decisions based on scientific evidence. As students begin to engage in evidence-based reasoning, they also display improved abilities in sharing their own perspectives and understanding the perspectives of others (Newton & Zeidler, 2020). Pedagogically, the evolving social milieu of students is also constantly shifting. As social issues evolve, how students become sensitized or engage in those issues also may change. It is a given that there will always be a changing moral landscape of students. It is imperative to be attuned and sensitive to the Zeitgeist of sociocultural norms[2].

In the teaching of SSI, it is important to understand that any given experience is interpreted personally, referenced and understood within the cultural norms of a unique temporal human condition (Bencze, et al., in press). It follows then, that as generations or cohorts of students change over the years, the intellectual Zeitgeist in which SSI may be shaped to *'fit'* within a particular educational context must also be sensitive to those changes.

Therefore, planned and extemporaneous questions must be designed and constructed in a manner that maximizes student engagement for a given time and place. Doing so supports references to Vision II scientific literacy stressing an understanding of how science is relevant in personal and societal issues (Roberts & Bybee, 2014). For the purpose of preparing students to become scientifically literate citizens, it is educationally prudent to provide them with the skills necessary to engage in informed, moral decision -making that will impact their lives. These experiences provide opportunities for students to engage in discourse that develop their ethical reasoning skills allowing them to become more sensitive to moral and ethical issues. Moreover, the nature and scope of science concept knowledge requires justified belief. The challenge for educators is creating a core curriculum and lesson plans that are engaging and interesting to students. Fundamental scientific vocabulary and content instruction compete with a daily barrage of information that is delivered to adults and children through electronic mass media. Using social issues as context for science instruction has become essential during the past decade, as increased use of the Internet and social media require students to make moral and personal decisions of a scientific nature.

As commonly accepted scientific concepts (e.g., climate change, evolution, stem cell research) are contentious topics in parts of the society (Beniermann et al., 2021), SSI instruction provides a safe environment for learning the scientific as well as ethical and interdisciplinary vocabulary and content. Introducing lesson plans through the lens of personally relevant social issues provide an authentic and robust framework for acquiring a better understanding of relevant concepts and ethical issues.

In learning evolution through SSI, we need to create a curriculum for the developing brain that includes the experiences necessary for improved literacy, global and individual problem solving, moral decision-making and intuitive self-awareness. That the sociocultural milieu leaves its mark on the developing brain should not be understated (Harris, 2010).

We are born with high neuroplasticity – our brains constantly adapt to and are shaped by the demands of our environment as well as the intellectual, cultural and technological tools we bring to bear in our everyday decision-making ventures

2. Zeitgeist translates from the German as "time-spirit." It is associated with the prevailing intellectual and moral tenor of a given time period for a particular group or culture. It is, therefore, always context and time specific and a product of sociocultural factors that impact the collective consciousness, social norms, and values of people leaving its mark on those who share that lived experience.

(Garland & Howard, 2009; Mundkur, 2005).

It has been suggested that while we become more adept at scanning and skimming bundles of factoids (both true and untrue), our ability for deeper contemplation and reflection has been severely compromised (Carr, 2014).

In this regard, teaching the moving target of scientific content and context to students has been a challenge for teachers. It is not unimaginable that the topic of evolutionary theory may likely bring about varied levels of cognitive conflict and dissonance for students, as well as adults. Generally, people will evoke an array of mental gymnastics and contortions to avoid inconsistency between their core beliefs and ideas that challenge those core beliefs (Cooper, 2019; Zeidler, 2001).

However, it is that very same psychological state of cognitive and moral *'imbalance'* that can be leveraged to compel students to explore, explain, resolve and learn in greater detail conceptual challenges to their epistemological worldviews.

In other words, having to confront scientific evidence or other's arguments that are inconsistent with prior beliefs and understandings can bring about a level of uncomfortable cognitive and moral tension, sometimes called a threshold concept (Land et al., 2016), necessary to create dissonance, which is a precursor to its resolution - and to novel insights and learning.

In cross-cultural SSI research (Zeidler et al., 2013), we find that a threshold model helps to explain the relationship between students' socioscientific reasoning and epistemological sophistication, moving from proximal, immediate and concrete justifications toward greater consideration of 'intangibles' consisting of distal, delayed and abstract justifications about SSI decisions (Zeidler, 2016).

We suggest that an educational SSI framework is a viable pedagogical strategy allowing science educators to strengthen their craft and subsequently lead students to deeper conceptual understanding of thematic, organizing principles in fields of evolutionary science, as well as science proper.

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Chapter 2

Using socioscientific issue approach to promote students' scientific literacy

CHAPTER 2

Using socioscientific issue approach to promote students' scientific literacy

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Abstract:

Socioscientific issues (SSIs) can be described as controversial social issues that are closely related to science and inherently dualistic complex narratives with no single solution. To better understand the historical development of SSI research, it is useful to investigate the period impacting the rise of specific SSIs. While the science, technology and society education approach focuses on the effects of science and technology on society, it does not handle these issues to promote moral development and epistemological growth. Using SSIs aims to promote individuals' moral and epistemological growth as well as awareness of social and scientific aspects of daily life issues. Socioscientific reasoning is handled as a term defining the negotiation process of dilemmatic SSIs. Socioscientific reasoning level is closely associated with one's degree of scientific literacy because it focuses on reasoning in different SSI contexts. It is also closely related to the Program for International Student Assessment's definition of scientific literacy, which states that scientific literacy relates to the ability to use scientific knowledge in real-life contexts. Two models that guide the implementation of SSIs in the classroom, the SSI TL model and the 5E model, are introduced in this study. Compatibility between the models in terms of their application in SSI-based instruction is also discussed.

KEYWORDS

Informal Reasoning, Socioscientific Reasoning, STS Education, Evolution

INTRODUCTION

1.1 Definition of SSIs

Socioscientific issues (SSIs) are topics rooted in both science and society (Ramirez Villarin & Fowler, 2019). Since an SSI is a narrative that has multiple perspectives and no clear-cut solution, it requires a negotiation process to reach an agreement (Romine et al., 2017).

Fowler and Zeidler (2016) described SSIs by using the words *'ill-structured-controversial'.* Cloning, stem cell research, gene therapy, biodiversity (Fowler & Zeidler, 2016), hydraulic fracturing, climate change and genetically modified foods (Romine et al., 2017) are some examples of SSIs.

1.2 Period Impacting the Rise of SSIs

The SSI approach emerged based on previous research about science, technology and society education (Zeidler et al., 2009). Since the 1970s, there has been an effort for science education to address topics possessing a social and technological background, and to study the effects of this approach on teaching and learning related science content (Zeidler et al., 2005). There is a consensus that placing science content in a broader context and providing social and technological discourse supports meaningful learning (Zeidler et al., 2005).

The science-technology-society movement is an effort to integrate mutual influences among technology, science and society (Sadler, 2004). In 1982, the National Science Teachers Association published the characteristics of a scientifically literate person and emphasized understanding the intersections of these three areas (Zeidler et al., 2005). In the 1990s, the science-technology-society-environment movement, which argues for also exploring environmental issues, entered the science teaching agenda (Topçu, 2017). However, there had been an agreement that both educational approaches do not particularly focus on character development as well as ethical and moral values (Topçu et al., 2010).
The argumentation and nature of science, which are not included within the scopes of the science-technology-society and science-technology-society-environment educational approaches, can be highlighted as additional weak points (Topçu, 2017).

CONCEPTUAL FRAMEWORK FOR SSIs

2.1 Scientific Literacy

Fostering scientific literacy is an important goal for science education (Kolsto, 2001; Yacoubian, 2018). Previously, comprehending connections between science, technology and society was described by the National Science Teacher Association as a characteristic of a scientifically literate person (Zeidler et al., 2005). Thus, whilst the idea of the science-technology-society movement reflects the property of being scientifically literate (Zeidler et al., 2005), it can be said that scientific literacy formed the basis for SSIs stemming from the science-technology-society movement.

Roberts and Bybee (2014) put forward two fundamental and broad views of scientific literacy (as cited in Kinslow et al., 2019). According to Kinslow et al. (2019), there are two visions of scientific literacy. Although the definitions of Vision I and II change according to the people or groups creating the definitions, Tan (2016) stated that Vision I is curriculum knowledge and Vision II is the ability to understand and criticise the impact of science on daily life. Similar to Tan (2016), Romine et al. (2017) identified Vision I as content knowledge. For Vision II, contextual knowledge, which relates to the ability to use scientific phenomena in different societal contexts, is emphasised (Romine et al., 2017).

The scientific literacy view adopted by the Programme for International Student Assessment (PISA) also includes the ability to use scientific knowledge in real-life contexts (Sadler & Zeidler, 2009). Since SSIs are used as a learning context, it can be said that they coincide with the scientific literacy view put forward by the PISA.

Additionally, in recent years, Vision III's scientific literacy concept has been defined. Vision III scientific literacy has emerged in response to the challenges and needs of the 21st century, such as injustice, growing hate against certain groups and environmental crises (Valladares, 2021).

It takes the view of scientific literacy beyond the contextual use of scientific information and additionally emphasises social engagement and citizen impact (Valladares, 2021). It adopts the perspective of using knowledge and a set of skills to reconstruct human relationships worldwide (Valladares, 2021).

Table 1
Competencies for scientific literacy visions and their relationships with SSIs.

	Vision I Scientific Literacy	**Vision II Scientific Literacy**	**Vision III Scientific Literacy**
Competencies	**Learning Science Content Knowledge (Tan, 2016; Romine et al., 2017).**	**Learning science content and ability to use scientific knowledge in real life contexts (Sadler & Zeidler, 2009).**	Learning science content, the ability to use it contextually and developing a set of skills for democratic participation and citizenship (Valladares, 2021).
SSI's Contribution	Socioscientific narratives serve as a meaningful approach **for learning science content knowledge (Sadler,2009).**	SSI offers real life contexts having social and scientific roots for science learning and **to use it contexts (Sadler, 2009).**	SSI framework offers the opportunity to become engaged in socio-political action (Bencze, Pouliot, Pedretti, Simonneaux, Simonneaux and Zeidler, 2020) and **learning democratic participation through decision making processes (Ottander & Simon, 2021).**

2.2 Informal Reasoning

Informal reasoning is a significant concept that means decision-making processes on dilemmatic issues. An SSI is defined as open-ended, multi-dimensional and dilemmatic (Romine et al., 2017).

When considering the complex dilemmas arising from the nature of SSIs, students use informal reasoning to make decisions and reach agreements (Sadler & Zeidler, 2004). The cognitive reasoning process for negotiating contentious problems (i.e., informal reasoning; Sadler & Zeidler, 2005) requires one to rely not only on scientific facts but also on the emotive features of a problem.

Accordingly, as students negotiate, discuss, debate and investigate such complex and contentious issues, they come to engage in deep discourse and the co-construction of meaning-making, which requires blending both the cognitive and affective processes that contribute to the resolution of the problem at hand. Notably, SSIs provide an appropriate platform for the use of informal reasoning (Sadler, 2004).

2.3 Socioscientific Reasoning

SSIs contribute to thinking and decision-making processes as well as position-taking (Zeidler et al., 2019). To understand how these goals are achieved through SSI-based instruction, the need for a concept corresponding to this thought process has been mentioned (Zeidler et al., 2021).

To meet this need, socioscientific reasoning is defined (Sadler et al., 2007). Socioscientific reasoning includes reasoning practices that involve students being engaged during the negotiation process of a socioscientific narrative (Sadler et al., 2007; Zeidler et al., 2021). Socioscientific reasoning is described as a concept focusing on these abilities and practices (Romine et al., 2017).

Moreover, this form of reasoning is important in terms of both its relation to scientific literacy and the practices used in the decision-making process for SSI negotiation (Kinslow et al., 2019). Different from informal reasoning, this novel concept describes the reasoning process within the scope of SSIs. However, Sadler (2004) explained informal reasoning as the thinking process involved in any complicated and dilemmatic issue.

Romine et al. (2017) investigated socioscientific reasoning and claimed that it focuses on content knowledge but also includes higher-order cognitive skills such as understanding the complex and multifaceted nature of an issue. The socioscientific reasoning concept is described based on a set of practices that students are expected to be engaged in within the resolution process of a complex SSI (Kinslow et al., 2019). These practices include understanding the complexity of the issue, analysing and expressing the SSI from multiple perspectives, noticing ongoing inquiry of the topic and being sceptical of existing or manipulated information (Kinslow et al., 2019; Sadler et al., 2007).

The first practice, *'complexity',* suggests that students should notice complex nature of SSIs, which there is no a clear-cut solution (Cian, 2019; Kinslow et al., 2019; Sadler et al., 2007). Considering multiple perspectives, which is the second practice of socioscientific reasoning, is described as a reasoning process required to understand the negative and positive sides of an SSI decision-making process for each stakeholder (Cian, 2019; Kinslow et al., 2019; Sadler et al., 2007). In this dimension of socioscientific reasoning, potential ways to negotiate the problematic context should be evaluated (Sadler et al., 2007).

The third practice can be described as an awareness of ongoing questioning (Cian, 2019; Kinslow et al., 2019; Sadler et al., 2007). Students should set questions in their minds for future inquiries (Kinslow et al., 2019). Since the solutions reached are not the only solutions to this issue, they can be re-evaluated and changed (Cian, 2019). Students should also notice that since the stakeholders' own advantages and disadvantages may affect their decision-making processes, this requires students to be sceptical regarding the produced arguments (Cian, 2019; Kinslow et al., 2019; Sadler et al., 2007). The dimension *"being sceptical"* means that stakeholders' stances and the information they provide can be manipulated based on their needs or benefits (Cian, 2019). Additionally, a fifth dimension is added to the Socioscientific reasoning (Zeidler et al., 2019), which is called the affordances and limitations of science (Zeidler et al., 2019).

This dimension involves being aware of the contributions of scientific knowledge and processes to the solution of dilemmatic SSIs and realising that they also have limitations (Zeidler et al., 2019).

A USEFUL FRAMEWORK FOR DEVELOPING SSI-BASED INSTRUCTION

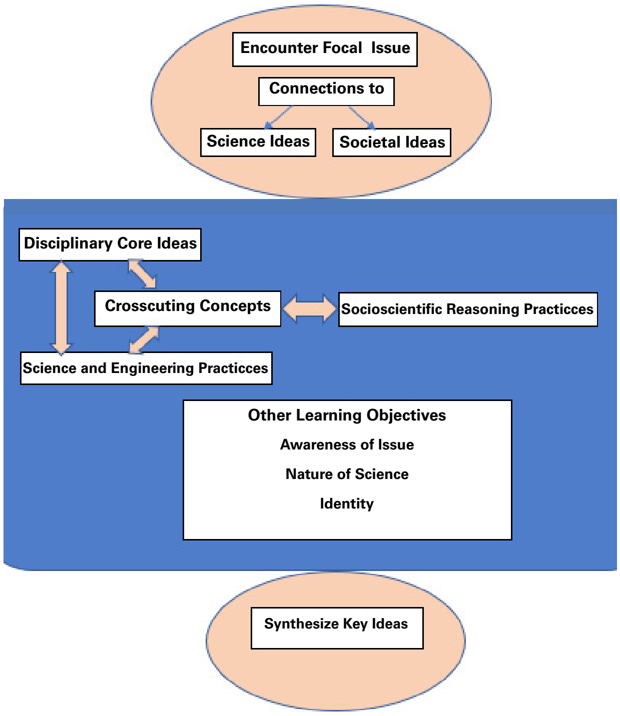
3.1 Socioscientific Teaching and Learning Model (SSI TL Model)

The SSITL model was described by Friedrichsen et al. (2016) and can be used as a guide for instructors to develop SSI-based instructional processes. The most current version of this model includes two parts: instructional design and learning outcomes (Friedrichsen et al., 2016).

The instructional part is divided into three sub-parts: focal issue, main body and culminating activity (Friedrichsen et al., 2016). In the focal issue part, the SSI is introduced (Friedrichsen et al., 2016). Students can explore the determined context as SSI (Friedrichsen et al., 2016) and notice that it has scientific and social roots (Topçu, 2017). The main body part includes activities to explore and comprehend the intended topic (Friedrichsen et al., 2016).

The an SSITL model's current version is aligned with the National Generation Science Standards (NGSS; NGSS Lead States, 2013) from the USA. The main body

Figure 1
Socioscientific teaching and learning model (figure adapted with modifications from Sadler et al., 2017).



part of the an SSITL model is coherent with its three-dimensional policy (Friedrichsen et al., 2016), which argues that science education should provide students opportunities to learn about 1) crosscutting concepts, 2) disciplinary core ideas and 3) scientific and engineering practices (NRC, 2012). Disciplinary core ideas are related to the content knowledge required according to the NGSS standards (NGSS, 2013).

For life sciences, there are four disciplinary ideas: a) from molecules to organisms: structures and processes; b) ecosystems: interactions, energy and dynamics; c) heredity: inheritance and variation of traits; d) biological evolution: unity and diversity (NRC, 2012, p. 142). Scientific and engineering practices embrace methods that are part of the scientific and engineering enterprise (NRC, 2012).

Eight scientific practices have been determined by the National Research Council (2012): i) asking questions (for science) and defining problems (for engineering); ii) developing and using modelling; iii) planning and carrying out investigations; iv) analysing and interpreting data; v) using mathematics and computational thinking; vi) constructing explanations (for science) and designing solutions (for engineering); vii) engaging in arguments based on evidence; viii) obtaining, evaluating and communicating information (NRC, 2012, p. 49).

The third dimension of the NGSS, crosscutting concepts, allows the combination of scientific and engineering knowledge across disciplines (NRC, 2012). Seven crosscutting concepts were described by the National Research Council (2012). These are *'patterns'*, *'cause and effect', 'scale, proportion and quantity', 'systems and system models', 'energy and matter', 'structure and function'* and *'stability and change'* (NRC, 2012, p. 84). Based on this vision, the main body activities should be planned so that students can learn the disciplinary core ideas, scientific and engineering practices and crosscutting concepts and develop an understanding of the nature of science (epistemology of science) and the SSI whilst also developing and their own identity (Friedrichsen et al., 2016; Sadler et al., 2017; Topçu, 2017).

The final step of the SSITL model is a culminating activity (Friedrichsen et al., 2016). This activity should involve dynamics that allow students to think about and synthesise the ideas and scientific concepts discussed in the instructional period (Sadler et al., 2017).

The SSI-based instruction guided by the SSITL model has clear instructional goals (Sadler et al., 2017; Topçu, 2017). Students are expected to learn about the SSI, develop content knowledge (disciplinary core ideas) and/or experience scientific and engineering practices whilst learning about the crosscutting concepts (Sadler et al., 2017; Topçu, 2017).

By using scientific knowledge to understand a socioscientific context in SSI-based instruction, students are also expected to improve their socioscientific reasoning level (Topçu, 2017). Addressing and discussing ethical and moral values contributes to character development (Levinson, 2008). In a study conducted by Sadler et al. (2016), the results of an experimental process were shared and discussed in the scope of SSI-based instruction and students shared and discussed experimental data like a scientific community (Sadler et al., 2016).

This allowed students to learn that *'science is collaborative'* (Sadler et al., 2017, p. 84). This is an example of how the nature of science can be addressed in SSI-based instruction.

3.1 The 5E Model and the SSI TL Model

The 5E model was developed by Bybee and is based on the constructivist education philosophy (Ergin, 2012; Scott et al., 2014). It presents a framework that can be used to guide educators whilst designing science learning outcomes (Scott et al., 2014).

The 5E model proposes that instructors develop educational activities with five stages, which include engagement, exploration, explanation, elaboration and evaluation (Bybee et al., 2006). When applying this model, teachers take a supervisory position by monitoring and supporting students with questions and materials (Bybee, 2014; Scott et al., 2014). The 5E model is compatible with the SSITL model and assists the SSI-based instructional process by providing a constructivist point of view and segmenting the main section activities (Friedrichsen et al., 2016).

Engagement is the stage in which students' curiosity and desire for learning are evoked (Bybee, 2014; Bybee et al., 2006). Asking a question, defining the problem and showing an attractive event are examples of practices that can be applied in this step (Bybee, 2014). Both the 5E and SSITL models aim to engage students by introducing the lesson topic to the students (Friedrichsen et al., 2016).

When students become engaged in the previous stage, they become ready and willing to discover the issue at hand (Bybee, 2014). For example, in the instructions prepared by Sarıkaya (in press), a video related to the collapsing of bee hives is watched to explore a socioscientific narrative: pesticide use in agriculture. Through some texts related to pesticide use, a small discussion on the SSI can be made (Sarıkaya, in press).

Exploration involves activities that allow students to explore an issue (Bybee et al., 2006; Ergin, 2012). Exploration should allow students to conduct experiments, make observations and formulate concepts and skills (Scott et al., 2014). The 5E model encourages the SSITL model to make students engaged with the exploration of scientific topics (Friedrichsen et al., 2016). Using the example of the previously described activity, (Sarıkaya, in press), arguments can be made regarding the question of *'whether pesticides should be used or not'* based on the given texts.

A food chain building game can also be played to learn the content (Sarıkaya, in press). In the explanation stage, it is expected that students will make their conceptual understandings of their exploration experiences explicit (Bybee, 2014; Bybee et al., 2006). Students make inferences based on their experiences from the exploration stage (Scott et al., 2014). Explanation allows students to describe a concept or a scientific idea (Bybee, 2014; Bybee et al., 2006).

The explanation stage is also a part of the main body activities that occur in the SSITL model (Friedrichsen et al., 2016). In the explanation stage, teachers may create opportunities for students to explain their arguments during an argumentation activity (e.g., as done by Sarıkaya, in press); however, students can provide explanations during the entire instruction period.

The following stage is an elaboration that aims to transfer the conceptual understanding and skills to different contexts (Bybee, 2014; Bybee et al., 2006). Students are expected to perform collaborative group work and be immersed in an interactive learning environment (Scott et al., 2014). In this environment, they are expected to express their understanding and comment on other students' ideas, thereby receiving and giving feedback (Scott et al., 2014).

Making connections between daily life and the content whilst extending their knowledge by attaining a deeper understanding are the goals of this stage

(Bybee, 2014; Bybee et al., 2006). In the elaboration stage, students are expected to achieve a better comprehension of the scientific topic. To achieve this goal during this stage, students are offered and led through different contexts in which they can apply relevant scientific knowledge (Friedrichsen et al., 2016). In the activity developed by Sarıkaya (in press), students create their food webs and explain energy flow. In another activity (Sarıkaya, in press), based on a marine ecosystem example, they develop their explanations in the elaboration stage.

Also, the *'pattern'* is discussed over the fact that the food chain and energy flow pattern occur in the same way in aquatic ecosystems. Thus, students are allowed to discuss patterns, which represents one of the crosscutting concepts (Sarıkaya, in press).

So, students make explanations during the instructional process (Sarıkaya, in press). The final step, evaluation, requires designing activities to measure whether the intended goals are achieved in the instructional process (Bybee, 2014; Bybee et al., 2006).

Performance activities, essays or tests can be used in this step (Ergin, 2012). Briefly, in this stage, teachers evaluate what students learned from the instruction (Scott et al., 2014). The culminating activity part of the SSITL model corresponds to the evaluation of the 5E model because both aim to summarise what students learn during the instruction (Friedrichsen et al., 2016).

A good example of an evaluation activity could be to ask students to prepare a campaign to raise awareness of the effects of pesticides on food relationships and the environment, as done by Sarıkaya (in press).

Figure 2
Compatibility between the 5E model and the SSITL model (figure adapted with modifications from Friedrichsen et al., 2016).

SSITL Mdoel	5E Model
Focal Issue	Engagement: Engaging students by introducing the topic
Social Connections **Science Ideas** + **Science Practice** Information Communication Technologies (ICT)	Exploration: Creating a design allowing students to discover a phenomenon
	Explanation: Describing a concept or a scientific idea, especially based on the experiences attained from the exploration
	Elaboration: Transferring knowledge to different contexts
Culminating Activity	Evaluation: Assessment of learning outcomes

The 5E model strengthens the SSITL model by leading it to create activities from a constructivist perspective, which is a student-centred one (Friedrichsen et al., 2016). In particular, using the 5E model as a supportive instructional framework divides the main body activities existing in the SSI TL model into sections, thereby allowing for the qualified organisation of an SSI-based curriculum (Friedrichsen et al., 2016).

CONCLUSION

SSIs have an open-ended narrative due to their dilemmatic nature, lack clear-cut solutions and require decision-making processes (Topçu, 2017). This point makes it important for us to understand the relevant decision-making processes. Informal reasoning is a cognitive process that occurs in an individual's mind during his/her engagement with SSI (Romine et al., 2017; Sadler & Zeidler, 2004). It can be said that by defining and using the new concept of 'socioscientific reasoning', the aim is to make thinking about the practices used by students in the decision-making processes of SSI explicit.

SSI-based instruction overlaps with the aims of Vision II of scientific literacy (Sadler & Zeidler, 2009). The ability to negotiate dilemmatic SSIs is one of the dimensions of scientific literacy (Sadler & Zeidler, 2004).

The socioscientific competencies students use to resolve SSIs are closely associated with their scientific literacy level (Romine et al., 2017; Sadler et al., 2007).

Thus, focusing on socioscientific competencies may allow us to achieve scientific literacy aims. Applying SSI-based instruction is important and its outcomes overlap with those required to foster scientific literacy (Sadler & Zeidler, 2009). SSI-based instruction offers a learning setting that promotes many learning gains (Topçu, 2017). SSI fosters Vision I scientific literacy by scaffolding content knowledge, Vision II scientific literacy by allowing students to use content knowledge in dilemmatic real-life contexts (Sadler & Zeidler, 2009) and Vision III scientific literacy by allowing students to participate in the decision-making process promoting democratic participation (Bencze et al., 2020; Ottander & Simon, 2021). Zeidler et al. (2019) also supported the significant role of SSIs in the development of scientific literacy and showed how this has been demonstrated through 20 years of research.

In this chapter, two models—the SSI teaching and learning model and the 5E model—were introduced to support instructors in the development of SSI-based instruction. It was also discussed how these two models can be used in combination. These models can serve as frameworks that lead a teacher to determine how SSI-based instruction can be applied.

When the contribution of SSIs to the scientific literacy concept (Bencze et al., 2020; Ottander & Simon, 2021; Sadler, 2009; Sadler & Zeidler, 2009; Topçu, 2017) is considered, the importance of SSI-based education and the developed models which allow teachers to use SSI as an instructional tool can be understood. Also, the SSITL model clearly shows the potential learning objectives in a socioscientific-based practice.

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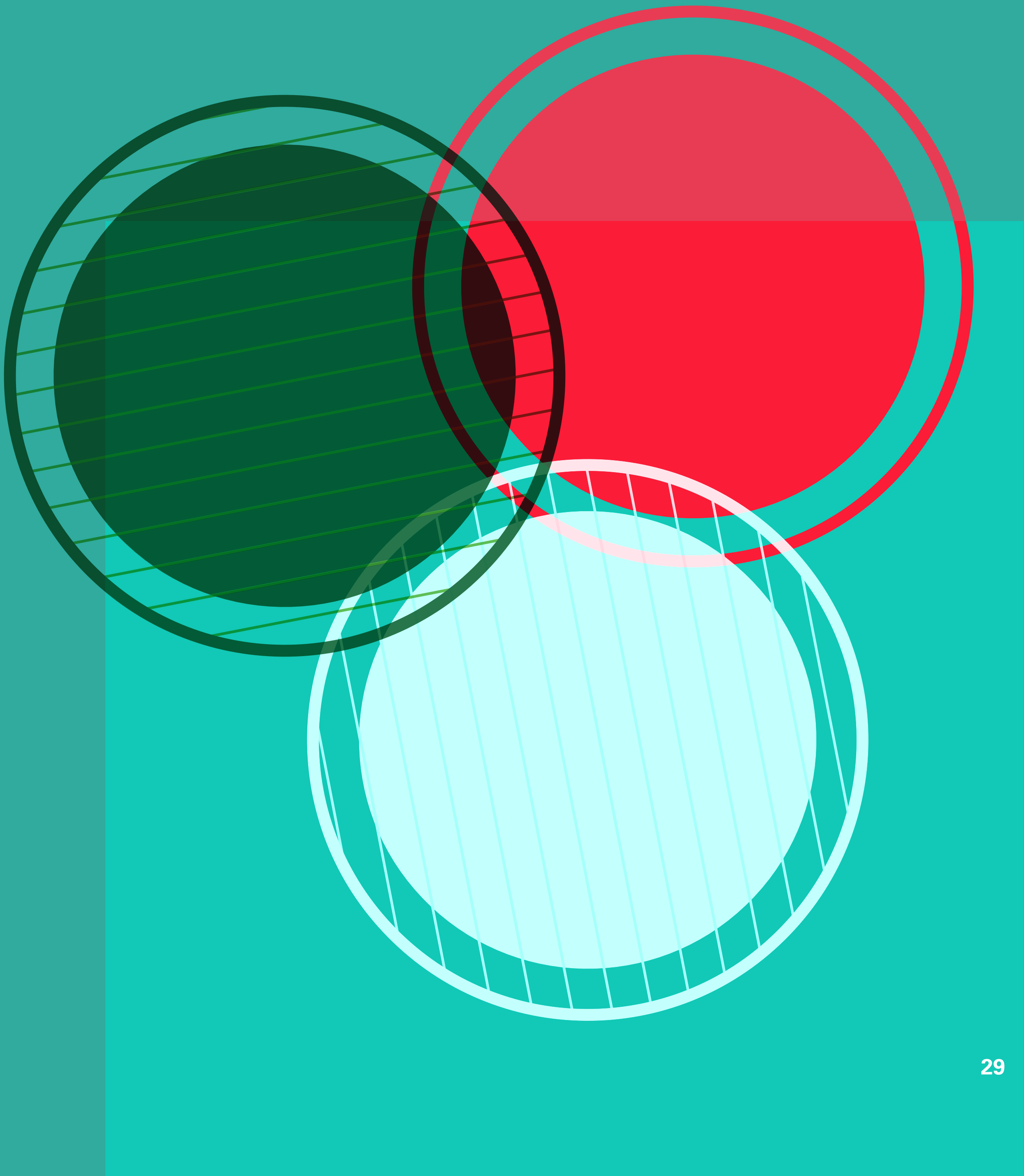
Chapter 3

Evolution education through SSI for sustainable development



CHAPTER 3

Evolution education through SSI for sustainable development

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Abstract:

Addressing the complex and controversial problems we face today requires education to empower citizens with competencies in sustainability that allow them to contribute to more just and sustainable societies. Many sustainability problems are strongly linked to evolutionary processes. When complex problems can be informed by science, these are known as socioscientific issues (SSI). Educational approaches that explore SSI have been shown to contribute to the development of functional scientific literacy and character development. Together, this suggests that evolution education through the SSI approach may contribute to the development of key competencies in sustainability. To test this hypothesis and understand how evolution education has been explored through SSI approaches, we performed a systematic literature review to identify the key competencies in sustainability developed in papers addressing evolution through SSI. Our results indicate that a few studies have addressed evolution education through SSI and support the potential of this approach since all key competencies in sustainability were found in these studies; however, some of these competencies (e.g., strategic and anticipatory competencies) were not frequently observed. Our results also support the interest in this approach to evolution education since all evolution education dimensions were found. However, the analysed studies show little diversity in terms of the explored SSI, with the majority being related to biotechnology. The implications of these findings and important highlights for educational practices and research are discussed.

KEYWORDS

Key competencies in sustainability, Sustainable Development, Evolution education, Socioscientific issues, Literature review.

INTRODUCTION

Key competencies in sustainability

According to Wiek et al. (2015), *'sustainability is the collective willingness and ability of a society to reach or maintain its viability, vitality, and integrity over long periods of time, while allowing other societies to reach or maintain their own viability, vitality, and integrity'* (p. 241). We are living in a period of immense challenges to sustainability that is seriously affecting the survival of many societies and putting the planet's biological support systems at risk (United Nations, 2015). Some examples of these challenges include (but are not restricted to) global health threats, climate change resulting in the rise of global temperatures and sea level, ocean acidification, more frequent and intense natural disasters, the depletion of natural resources and impacts on environmental degradation (e.g., desertification, drought, land degradation, freshwater scarcity and biodiversity loss).

All of these challenges are characterised by high degrees of complexity with no obvious optimal solution, high damage potential and strong urgency (Wiek et al., 2011). To address these challenges, citizens must be able to make informed choices and develop innovative and effective solutions. This requires a large-scale educational transformation that equips not only sustainability professionals but also new generations of any kind of professionals with these skills (Wiek et al., 2011).

According to Wiek et al. (2011), education for sustainable development should allow students to develop the competencies in sustainability, which are '*complexes of knowledge, skills, and attitudes that enable successful task performance and problem solving with respect to real-world sustainability problems, challenges, and opportunities'* (p. 204). These competencies are fundamental for building a more sustainable and just society for all and empowering current and future generations to meet their needs using a balanced and integrated approach to the economic, social and environmental dimensions of sustainable development (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2018; Wiek et al., 2011, 2015).

The sustainability competencies are not restricted by disciplinary boundaries or specific content knowledge (de Haan, 2006), but rather represent cross-cutting and transversal learning goals that are needed to deal with the complex challenges we face in our daily lives (UNESCO, 2018; Wiek et al., 2015).

Through a literature review, Wiek et al. (2011) identified five key competencies in sustainability:

i **Systems thinking competency**: *'Ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks'* (Wiek et al., 2011, p. 207);

ii **Anticipatory competency**: *'Ability to collectively analyze, evaluate, and craft rich "pictures" of the future related to sustainability issues and sustainability problem-solving frameworks'* (Wiek et al., 2011, pp. 208–209);

iii **Normative competency:**
'Ability to collectively map, specify, apply, reconcile, and negotiate sustainability values, principles, goals, and targets. This capacity enables, first, to collectively assess the (un-) sustainability of current and/or future states of social-ecological systems and, second, to collectively create and craft sustainability visions for these systems. This capacity is based on acquired normative knowledge including concepts of justice, equity, social-ecological integrity, and ethics' (Wiek et al., 2011, p. 209);

iv **Strategic competency:**
'Ability to collectively design and implement interventions, transitions, and transformative governance strategies toward sustainability. This capacity requires an intimate understanding of strategic concepts such as intentionality, systemic inertia, path dependencies, barriers, carriers, alliances etc.; knowledge about viability, feasibility, effectiveness, efficiency of systemic interventions as well as potential of unintended consequences' (Wiek et al., 2011, p. 210);

v **Interpersonal competency:**
'Ability to motivate, enable, and facilitate collaborative and participatory sustainability research and problem solving. This capacity includes advanced skills in communicating (...), deliberating and negotiating (...), collaborating (...), leadership (...), pluralistic and trans-cultural thinking (...), and empathy' (Wiek et al., 2011, p. 211).

In light of these key competencies in sustainability and because education for sustainability *'should enable students to analyse and solve sustainability problems, to anticipate and prepare for future sustainability challenges, as well as to create and seize opportunities for sustainability'* (Wiek et al., 2011, p. 204), we are convinced that the socioscientific issues (SSI) approach is contributing to the development of key competencies in sustainability.

Socioscientific Issues approach

Over the last two decades, the SSI pedagogical approach has been advocated by several authors as effective for involving students in learning opportunities that bridge school experiences with social contexts, thereby promoting the development of meaningful learning and encouraging functional scientific literacy and character among global citizens (Fowler & Zeidler, 2016). According to Sadler (2005), SSI *'emerge[d] from the interface of science and society, and they involve societal issues with conceptual, procedural, or technological associations with science'* (p. 68).

These issues are complex, ill-structured and controversial societal topics without a simple and clear-cut-solution since they can be informed by various ideas and perspectives, such as economic, political and ethical (Fowler & Zeidler, 2016; Sadler et al., 2017; Zeidler, 2014).

Some examples of SSI are dilemmas involving biotechnology, environmental problems, genetics, climate change, biodiversity loss and antibiotic resistance. SSI are also understood as a pedagogical approach that, according to Zeidler and Sadler (in press):

1. Use personally relevant, controversial and ill-structured problems that require scientific, evidence-based reasoning to inform decisions about such topics;

2. Employ the use of scientific topics with social ramifications that require students to engage in dialogue, discussion, debate and argumentation;

3. Integrate implicit and/or explicit ethical components that require some degree of moral reasoning;

4. Emphasise the formation of virtue and character as long-range pedagogical goals.

Over the past few years, this approach has been allowing students to become actively involved in the construction of knowledge whilst making informed decisions and analysing, synthesising and evaluating diverse sources of data and information (Lee et al., 2013; Peel et al., 2019; Zeidler et al., 2019).

Research studies have shown that this approach impacts students' i) understanding of the nature of science (Abd-El-Khalick, 2003; Khishfe & Lederman, 2006), ii) reasoning (Zeidler et al., 2009) and, more specifically, informal reasoning (Sadler, 2005), iii) argumentation skills (Kolstø, 2006; Venville & Dawson, 2010; Zohar & Nemet, 2001), iv) functional scientific literacy and character (Zeidler & Sadler, 2007; Zeidler et al., 2013), v) moral, ethical and social sensitivity and reasoning (Clarkeburn, 2002; Lee et al., 2012, 2013; Fowler et al., 2009; Hogan, 2002; Peel et al., 2019; Zeidler et al., 2019), vi) empathy and perspective-taking skills, vii) sense of socioscientific responsibility and viii) understanding of the complexity of connections inherent within contextualised science learning (Lee et al., 2013; Peel et al., 2019; Zeidler et al., 2019).

These studies support the potential of the SSI approach to developing some of the skills required for sustainable development. However, to the best of the authors' knowledge, no studies have directly related the SSI educational approach to the development of the five key competencies in sustainability proposed by Wiek et al. (2011).

Evolution education

Many of the current global challenges that threaten the sustainability of our planet and future generations are related to evolutionary processes and require solutions informed by evolutionary biology (Carroll et al., 2014).

Some of the challenges included in the Sustainable Development Goals 2030 Agenda (United Nations, 2015), for which understanding evolution is critical, include human health problems such as obesity, diabetes, cancer, cardiovascular disorders and infectious diseases (i.e. resulting from changes in our diet, environment and lifestyles, or, in the case of diseases, the evolution of new or drug-resistant pathogens), food security problems caused by the decrease in agricultural production (due to increasing resistance to pesticides) and the reduction of biodiversity caused by species' extinction (due to poor adaptation to climate change and pollution) (Carroll et al., 2014; Jørgensen et al., 2019; Matthews et al., 2020). To address these complex problems, we need citizens that can understand evolution and use this knowledge to make informed decisions and design solutions that consider important evolutionary processes.

Although evolution is recognised as a central unifying principle in biology that is essential for scientific literacy to address these social problems, and, consequently, for promoting sustainable development (Fowler & Zeidler, 2016; National Academy of Sciences, 1998; National Research Council [NRC], 2007, 2012; Sadler, 2005), many international studies have shown that most citizens do not understand and/or accept biological evolution (Athanasiou & Mavrikaki, 2014; Kuschmierz et al., 2020; Nehm et al., 2009; Sickel & Friedrichsen, 2013; To et al., 2017).

Several institutions proposed that evolution should be explored within the framework of issues related to students' current affairs and everyday life problems (Associação Portuguesa de Biologia Evolutiva [APBE], 2012; National Association of Biology Teachers [NABT], 2008; NRC, 2012; National Science Teaching Association [NSTA], 2003).

Although some studies have analysed how students use evolution to reason about some SSI problems (Fowler & Zeidler, 2016; Sadler, 2005), to the best of our knowledge, no studies have reviewed how evolution has been explored through the SSI approach.

Moreover, to the best of the authors' knowledge, there is no information available on how evolution education through an SSI approach allows for the development of the key competencies in sustainability. Through the present study, we aimed to address this lack of knowledge by answering the following research questions:

- ? How is evolution explored under an SSI approach?
- ? How does evolution education through an SSI approach allow for the development of key competencies in sustainability?

METHODOLOGY

2.1 Systematic literature review

To answer our research questions, we conducted a systematic literature review (Snyder, 2019). The Scopus database was chosen as a data source since it is one of the most widespread and multidisciplinary databases, containing one of the largest searchable citation and abstract sources of searchable literature (Falagas et al., 2008).

To search for studies on evolution education, in addition to variants of 'evolution', we used a set of keywords that were informed by the dimensions of evolution education identified in previous studies, strictly related to evolution (the categories and some subcategories were defined by Sá-Pinto et al., 2021) and detailed the evolutionary mechanisms and human evolution.

This resulted in the following search terms, which were always used in combination: *'evolution', 'evolutionary', 'history of life', 'evidence of evolution', 'mechanisms of evolution', 'studying evolution', 'natural selection', 'sexual selection', 'artificial selection', 'genetic drift' and 'human evolution'.*

To search for studies on SSI, we combined the keywords 'socioscientific issues' and 'socio-scientific issues' since both nomenclatures are used in the literature.

Finally, to look for studies related to competencies for sustainability, we used the search terms *'sustainability', 'sustainable', 'sustainable development', 'education for sustainability'* and *'competencies for sustainability'.*
We performed two distinct searches:

Search 1

To answer the first research question, we conducted a search using the keywords related to evolution education and SSI.

Search 2

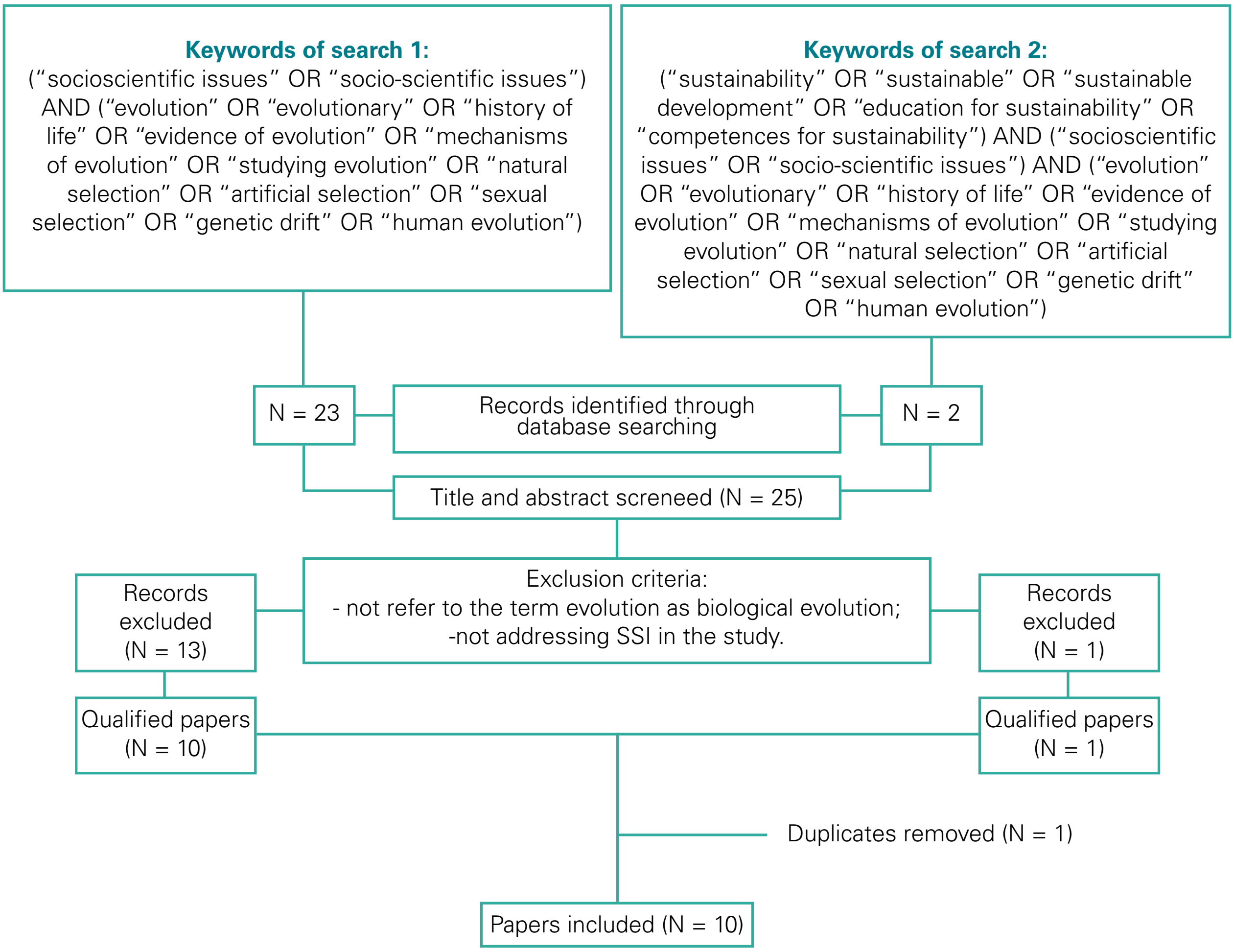
To answer the second research question, we conducted a search using keywords related to the three topics explored in this study.

The words were all searched as being present in the title, abstract or keywords. No time restrictions w ere made when conducting the search.

All abstracts of all search results were read, and all papers that did not refer to biological evolution or that did not explore SSI despite referring to them were excluded from the posterior analyses.

Figure 1 presents all of the paper selection phases for the two performed searches.

Figure 1
Phases of the systematic literature review.



2.2 Analysis of the papers

All selected papers were subjected to a content analysis (Krippendorff, 2018). This method was chosen due to its applicability to our goal of analysing text data through a systematic process of coding classification to identify specific themes (Hsieh & Shannon, 2005).

To answer the first research question, we identified the dimensions of evolution education that were covered in papers addressing evolution and SSI. Then, we identified which SSI were explored in those papers. To answer the second research question, we aimed to identify which key competencies in sustainability were covered in the same papers. To identify which dimensions of evolution were explored in the retrieved papers, we used the FACE (Framework to Assess the Coverage of biological Evolution by school curricula) categories (Sá-Pinto et al., 2021) as the categories of analysis: i) history of life; ii) evidence of evolution; iv) mechanisms of evolution; v) studying evolution.

We excluded *'nature of science'* and *'development of scientific practices'* since these dimensions may be explored under diverse disciplinary fields (NRC, 2012). To analyse which SSI were explored in the retrieved papers, we derived the categories of analysis inductively based on the floating reading of the retrieved

Table 1
Analysis framework for key competencies in sustainability.

Key competencies (categories)	Analysis features
1. Systems-thinking competency	• Recognize and understand relationships; • Analyse complex systems; • Think about how systems are embedded within different domains and different scales; • Deal with uncertainty.
2. Anticipatory competency	• Understand and evaluate several futures (possible, probable, and desirable); • Create one's visions of the future; • Apply the principle of precaution; • Assess the consequences of actions; • Deal with risk and change.
3. Normative competency	• Understand and reflect on the norms and values that underlie people's actions; • Negotiate sustainability values, principles, goals and targets (in context of conflicts of interest and concessions).
4. Strategic competency	• Collectively develop and implement innovative actions that promote sustainability (locally and in wider contexts).
5. Interpersonal competency	• Be able to learn from others; • Understand and respect other people's needs, perspectives and actions (empathy); • Understand, relate to and be sensitive to others (empathic leadership); • Handle group conflicts; • Facilitate collaboration and participation in problem solving.

Notes: Key competencies defined as Wiek et al. (2011) and further defined with the analysis features described by Juuti et al. (2021).

papers (Merriam, 2009). To study how the retrieved studies addressed the competencies in sustainability, we used the key competencies defined by Wiek et al. (2011) as the categories of analysis. To further define these categories, we used the analysis features described by Juuti et al. (2021; see Table 1).

All papers were analysed by two researchers and characterised by the presence or absence of these categories. The number and examples of evidence found in each paper were recorded. Interrater reliability was estimated as the percentage of the initial agreement between researchers (McHugh, 2012) in terms of the key competencies in sustainability found in each paper.

The interrater reliability was greater than 90% for all key competencies analysed, which is much higher than the 70% threshold that is considered acceptable for these analyses (Stembler, 2004, p. 3). Examples of evidence not equally rated by the two researchers were discussed and, failing a consensus, removed from the analyses.

RESULTS

Search 1 returned a total of 23 results. After reading all of the abstracts, 13 papers from Search 1 were excluded from posterior analysis for not referring to the term evolution as biological evolution or for not addressing SSI. Search 2 returned two results, one of which was excluded from further analysis because we noticed that the term evolution was not used to refer to biological evolution in the abstract.

The remaining paper (Fried et al., 2020) was also obtained as a result of Search 1. Thus, we will hereafter simply mention the results retrieved in Search 1. All of the papers included in this study are listed and organised in chronological order in Appendix A (available at https://doi.org/10.5281/zenodo.7323827). Of the ten papers analysed, only seven described activities occurring in the classroom environment. Of the remaining three, one described educational approaches to the teaching of evolution and their legal implications (Hermann, 2013), whilst two explored how students used evolution knowledge to individually argue about some SSI (Fowler & Zeidler, 2016; Sadler, 2005).

Of the seven described activities occurring in classrooms, one explored pre-service teachers' ideas, concerns and approaches for teaching SSI and societally-denied science (Borgerding & Dagistan, 2018), whilst three studied SSI argumentation through group activities in a high school classroom setting (Anisa et al., 2020a; Anisa et al., 2020b; Anisa et al., 2022), two described educational activities and included evolution as a central idea in biology that can inform reasoning about SSI (in high schools: Peel et al., 2019; in undergraduate education: Yacobucci, 2013) and one outlined the creation of sustainable designs in undergraduate education (Fried et al., 2020).

Our results indicate that eight papers explored the *'study of evolution'*, seven papers explored the 'mechanisms of evolution' and the *'evidence of evolution'* and six papers explored the *'history of life'* (see Table 2 and examples of the evidence assigned to each dimension of evolution in Appendix B available (at https://doi.org/10.5281/zenodo.7389841).

All evidence found for the dimension *'studying evolution'* was related to the application of evolutionary biology in everyday life. The evolutionary processes explored in the papers included natural selection (four papers), artificial selection (four papers), intrapopulation diversity generation (i.e., mutations; five papers) and trait inheritance (four papers).

Table 2
Dimensions of evolution education found in each paper.

Papers	Dimensions of evolution education			
	History of life	Evidence of evolution	Mechanisms of evolution	Studying evolution
Sadler (2005)	—	●	●	—
Yacobucci (2013)	●	—	●	●
Hermann (2013)	—	—	—	—
Fowler & Zeidler (2016)	—	—	●	●
Borgerding & Dagistan (2018)	—	●	—	—
Peel et al. (2019)	●	●	●	●
Fried et al. (2020)	●	●	●	●
Anisa et al. (2020a)	●	●	●	●
Anisa et al. (2020b)	●	●	●	●
Anisa et al. (2022)	●	●	●	●

Notes: ● Represents the dimension being found in the paper. — Represents the dimension not being found in the paper.

Concerning the addressed SSI, the topic of genetically modified organisms was the most frequently explored (three papers: Anisa et al., 2020a; Anisa et al., 2020b; Anisa et al., 2022), followed by cloning (Fowler & Zeidler, 2016; Sadler, 2005), gene therapy (Fowler & Zeidler, 2016; Sadler, 2005), antibiotic use (Fowler & Zeidler, 2016; Peel et al., 2019) and evolution (Hermann, 2013; Yacobucci, 2013) with the same frequency (two papers each).

Teaching evolution was the least commonly mentioned SSI (one paper: Borgerding & Dagistan, 2018). We highlight the fact that some authors consider evolution itself to be an SSI, whilst others emphasise that it is the teaching of evolution that represents an SSI since the existence of conflicting positions in society on whether or not evolution should be taught and the religious objections of students and their parents may create conflicts in the classroom (Borgerding & Dagistan, 2018).

Regarding the key competencies in sustainability, our results indicate that normative and interpersonal competencies were commonly found in the analysed papers, whilst strategic competency was rarely addressed in these papers (Table 3; see examples of the evidence assigned to each of the key competencies in Appendix B available at https://doi.org/10.5281/zenodo.7389841). The average number of key competencies addressed in each paper was 1.8 (see Figure 2) and the mode was one competency (four papers). In two of the papers that did not describe a classroom activity, no competencies were addressed. Moreover, four competencies were found in two other papers.

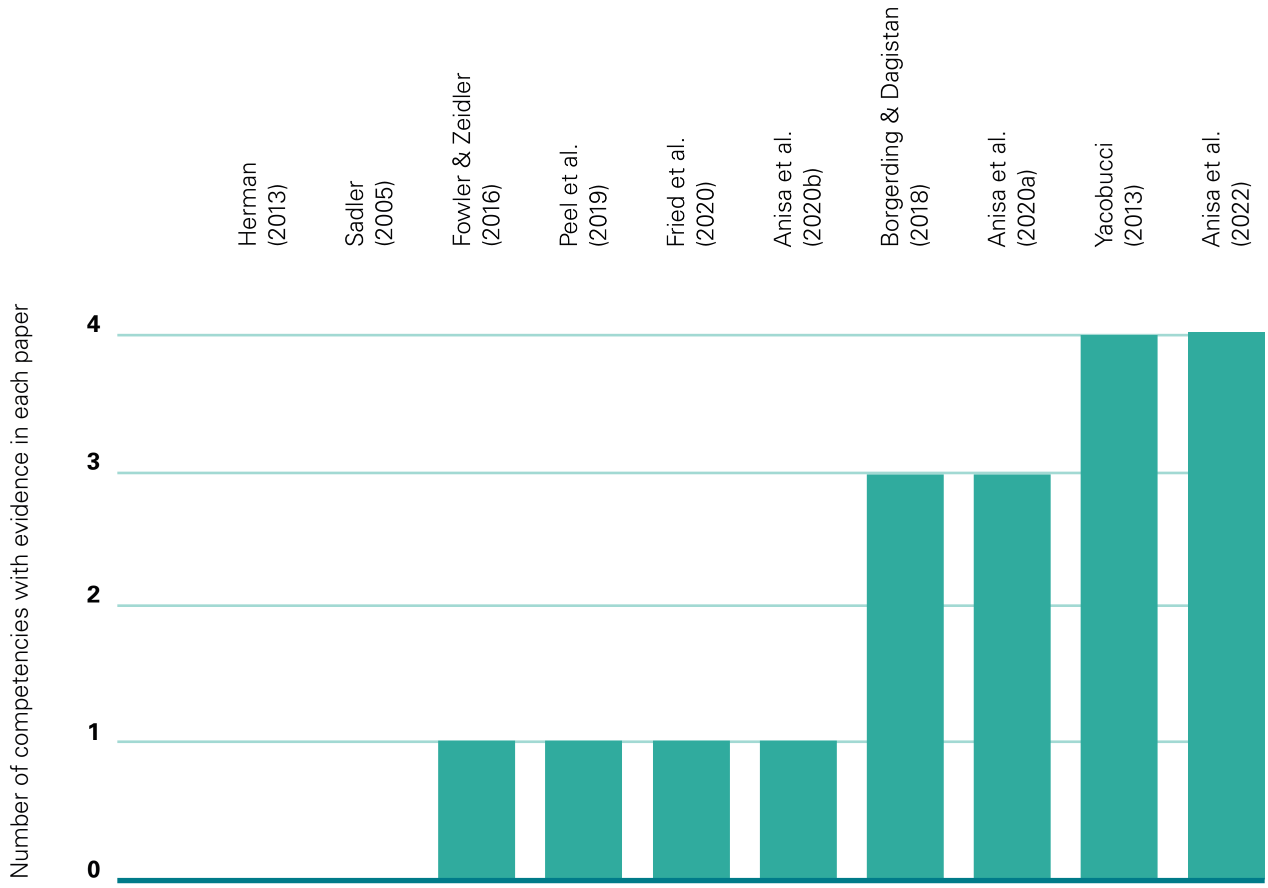
Strategic competency was only found in the sole paper obtained from Search 2, which included the three topics addressed in this study (sustainability, SSI and evolution). Notably, this competency was the only one for which we found evidence in this study (Fried et al., 2020).

Table 3
Number of papers with evidence for each key competency in sustainability and the total number of pieces of evidence found.

Key competencies	Number of papers (N=10)	Total number of evidence found	Interrater reliability
1. Systems-thinking competency	5	8	0.92
2. Anticipatory competency	3	3	0.97
3. Normative competency	4	11	0.90
4. Strategic competency	1	3	0.97
5. Interpersonal competency	5	15	0.97

Notes: N represents the total number of papers analysed.

Figure 2
Number of distinct competencies in sustainability education for which evidence was found in each of the 10 studied papers.



DISCUSSION

One of the most striking results of our literature review was the low number of papers found, especially when searching for studies that simultaneously mention education for sustainability, SSI and evolution education.

These results highlight the knowledge gap that exists around this topic and the importance of performing more studies on how to promote education for sustainability by exploring SSI from an evolutionary perspective.

Regarding our first research question, despite our overrepresentation of keywords related to mechanisms of evolution, we found evidence of all the dimensions important for evolution education (as described in Sá-Pinto et al., 2021).

Interestingly, eight papers addressed *'studying evolution'*, which was more precisely related to the application of evolutionary biology in everyday life. This result aligns with Sadler's (2005) findings and recommendation that evolution instruction should include explicit attention to how evolution can or cannot be used in the context of social dilemmas since students' understanding of evolution strongly influence their SSI-related decision making. Half of the papers presented evidence of all evolution education dimensions being explored, which supports the potential of SSI in evolution education.

Our results also reveal very low diversity among the SSI that were addressed to explore evolution. Although evolution is related to many of today's complex sustainability problems (e.g., human health, biodiversity conservation and food security) (Carroll et al., 2014), most of the topics addressed in the analysed papers were related to the biotechnology field.

According to Nehm and Rigdway (2011), students are sensitive to the surface characteristics of a situation/problem. Depending on the situation or living being presented, students may provide different ideas about evolution. Aligned with this, Peel et al.'s (2019) study on antibiotic resistance and natural selection also found that students either correctly explained antibiotic resistance or natural selection and struggled when applying their understanding of antibiotic resistance to other contexts. Accordingly, by not exploring diverse SSI from an evolutionary perspective, we may fail to support students in understanding and using strategies informed by evolution to address these problems.

A high diversity of SSI explored to study evolution would benefit students' understanding and subsequent generalisation of their concepts to other contexts (Nehm & Rigdway, 2011) and foster their ability to use this knowledge to build long-term solutions for these problems (Carroll et al., 2014). In this sense, the educational proposals presented in this book represent an important contribution since they greatly increase the diversity of SSI, including new problems such as those related to human health and evolution (Chapters 7 and 11), the management of common pool resources (Chapter 8), and the decline of pollinators (Chapter 10).

Regarding our second research question, despite the low number of available papers describing educational activities occurring in classrooms, our results support that exploring evolution through SSI can indeed promote the development of key competencies in sustainability. In fact, evidence for the pedagogical exploration of all key competencies in sustainability—as defined by Wiek et al. (2011)—was found in the analysed papers; however, some were more frequently found than others.

The high observed frequency of the normative and interpersonal competencies was expected since the SSI approach requires students to engage in dialogue, discussions, debates and argumentation and integrates implicit and/or explicit ethical components that require some degree of moral reasoning (Zeidler & Sadler, in press).

These characteristics enhance opportunities for students to understand and reflect on the norms and values that guide people's actions, thereby providing opportunities that promote understanding and respect for other people's perspectives, needs and actions. Additionally, the SSI approach emphasises virtue and character formation as a long-term pedagogical goal (Zeidler & Sadler, in press), which we consider to be strongly aligned with these competencies.

Notably, strategic competency was only observed in the activity described by Fried et al. (2020), which combined the SSI approach with design-based learning (DBL). For this competency to be developed, students need to collectively design and implement interventions, strategies and actions that foster sustainability. In fact, the combination of SSI with educational approaches in which students are expected to develop a product or a solution (e.g., DBL, project-based learning or challenge-based learning) is expected to further enhance opportunities for the development of strategic competence.

For some of the key competencies, the analysed papers described activities that—despite representing clear opportunities for developing key competencies in sustainability—were not considered evidence of those since the work was not developed collaboratively, which is a requirement for most of the key competencies (Wiek et al., 2011). One example can be seen in the work of Fowler and Zeidler (2016), who asked each participating student to individually *'identify the potential consequences of each [scenario] and determine the likelihood that each would occur before choosing the most reasonable choice'*.

Although this task shows great potential to develop anticipatory competence, this requires a collective approach (Wiek et al., 2011). A similar situation was observed in the work of Peel et al. (2019), where 'each student developed a policy to address antibiotic resistance at a local, national, or international level'. Again, although this activity has great potential to develop strategic competency, we could not consider it since it has not been performed collectively.

These examples highlight the importance of fostering collaborative work to achieve and develop key competencies in sustainability. These observations also raise the question of how much these definitions should include the dimension of collaborative work. Notably, in UNESCO's (2018) redefinition of Wiek et al.'s (2011) competencies in sustainability, the need for a collaborative dimension was removed from most of these competencies.

However, it included collaboration as a new and independent key competency in sustainability, thus reinforcing the importance of collaborative work. According to UNESCO (2018), this competency is defined as *'the ability to learn from others; understand and respect the needs, perspectives and actions of others (empathy); understand, relate to and be sensitive to others (empathic leadership), deal with conflicts in a group; and facilitate collaborative and participatory problem-solving'* (p. 44).

Additionally, as one of the methods for education for sustainable development, the same organisation proposed the involvement of real-world collaborative projects, such as a service learning project and campaigns for various sustainability topics. This split between collaborative competency and the other competencies is also observed in the experience-based learning framework for developing sustainability competencies proposed by Caniglia et al. (2016).

In this study, which focused on university students, the key competency of collaborative work has a prominent role and specific learning objectives. Whether collaborative work is included in the key competencies in sustainability or defined as an independent competency, there seems to be a general agreement on the importance of fostering collaboration in education for sustainable development. Therefore, we emphasise the relevance of this for future teaching practices.

Our work has several limitations that may have precluded us from fully identifying the potential of exploring SSI through an evolutionary perspective to promote sustainability education. A very small number of studies were identified in this study, which is likely because the literature review was performed using an academic database that is not expected to cover all the publications about educational practices written for non-academic professionals (e.g., formal and non-formal educators).

This context suggests that future studies aimed at extending the present work should cover other databases, including the resource databases used by educators. On the other hand, by using the key competencies in sustainability defined by Wiek et al. (2011)—which include a dimension of collaborative work in the definition of nearly all competencies—as our framework of analysis, we may have underestimated their presence and frequency in the studied papers.

IMPORTANT HIGHLIGHTS FOR TEACHING PRACTICES AND RESEARCH

In this study, we have shown that teaching evolution through the SSI approach could help foster the development of key competencies in sustainability.

However, regarding evolution education, our results reinforce the need to diversify the SSI explored from an evolutionary perspective to enable students to achieve a better understanding of evolution, make informed choices and develop innovative and effective solutions for daily life problems.

We also found a lack of scientific studies that explore how evolution, when explored through an SSI approach, can contribute to the development of key competencies in sustainability since very few papers simultaneously mentioned education for sustainability, SSI and evolution education. These results suggest that this research line remains under-explored, which supports the importance of developing future research and educational activities around these topics.

It is also important to pursue the development of all key competencies in sustainability, whilst paying special attention to those that are less developed and those that were only found when other pedagogical approaches were combined (e.g., anticipatory competency and strategic competency). In particular, anticipatory competence can be developed through discussions and informed predictions of expected evolutionary outcomes of certain biological contexts.

This may be achieved by discussing SSI such as antibiotic use, plagues and disease outbreak management, species conservation and food security problems. Moreover, both this competency and the strategic competency can be addressed within the frameworks of project-based learning or challenge-based learning by proposing and evaluating solutions for these problems. Furthermore, this study also revealed the importance of fostering collaborative work to promote the development of competencies in sustainability. Although this aspect may not be essential for developing all competencies, it is undoubtedly an essential aspect for fully achieving sustainability-related goals, which should be considered in the design of future educational activities.

The collaborative work can be extended outside the classroom. For this, we propose that teachers engage the research community and other stakeholders external to schools in their educational activities to promote collaborative, meaningful and contextualised learning in the resolution of real problems.

On the other hand, we also recognise that the SSI approach might not be the only one that allows the development of key competencies in sustainability.

Thus, future studies are also required to explore how other approaches can simultaneously enhance the teaching and learning of evolution and the development of relevant competencies.

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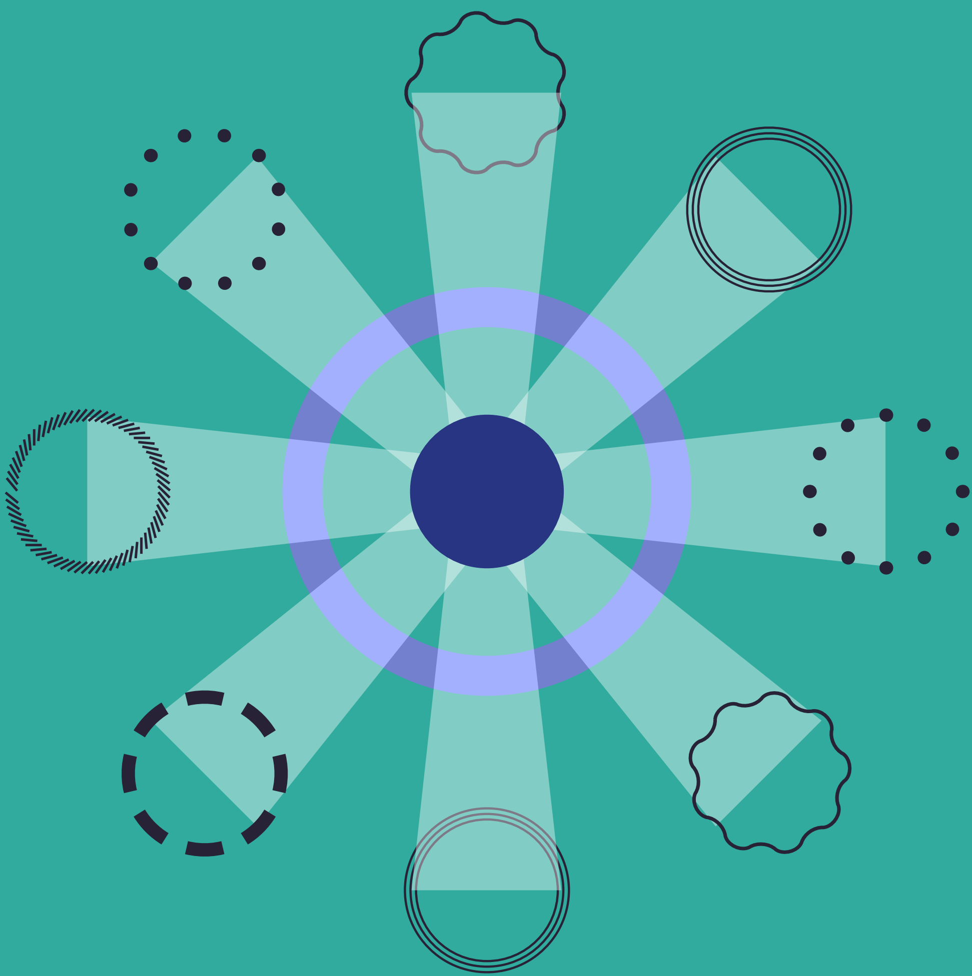
Chapter 4

SSI approach out of schools - How can these approaches be used in science museums and other non formal education contexts?



CHAPTER 4

SSI approach out of schools - How can these approaches be used in science museums and other non formal education contexts?

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Abstract:

In recent years, educational research has shown that approaching science within a socioscientific context has multiple benefits for students at the cognitive level and in terms of personality and skill development. A wealth of research has already been performed in the context of formal education on this topic; however, considerably less has been performed in the context of non-formal education. In this chapter, we seek to provide examples of socioscientific issues (SSIs) being applied in non-formal education contexts, especially in museums. Activities from the Natural History Museum of Porto, the National Museum of Natural History of Paris and the Zoological Museum of Athens are presented. The activities focus on one aspect of evolution that is becoming increasingly noticeable in the lives of modern people: biodiversity. Biodiversity is not only a biological concept that people of all ages should be aware of, but an essential component of life. Reference is also made to the integration of SSI activities in other non-formal education environments. Finally, we conclude with a critical reflection on the contribution of such environments to SSI education.

KEYWORDS

socioscientific issues (SSIs), museum education, biodiversity

INTRODUCTION

Socioscientific issues (SSIs) are at the heart of science education (Sadler et al., 2016). For this reason, many contemporary education researchers seek to create learning opportunities through SSIs and examine the corresponding learning outcomes (Evagorou et al., 2009; Ke et al., 2021).

In other words, attempts are being made to engage students through SSIs in real-life situations whilst using school knowledge to formulate their opinions, take part in dialogues and make informed decisions. Teaching through SSIs is often combined with the strengthening of argumentation skills, which is a requirement and an integral feature of today's students and active future citizens (Dawson & Venville, 2010; Georgiou & Mavrikaki, 2013; Georgiou et al., 2020; Maniatakou et al., 2020).

For the aforementioned reasons, efforts are being made to integrate SSIs into both formal and non-formal education. Since museums are excellent environments for non-formal education, they offer the opportunity to develop different SSIs to enhance learning. Although most museums have not yet integrated educational programmes using SSIs into their capacities, some have already done so.

In this chapter, we will use the concept of biodiversity directly related to evolution as an example to present different cases of non-formal education environments, especially museums, which have developed activities around SSIs with biodiversity as their focus.

SSI APPROACHES TO THE NATURAL SCIENCES: FOSTERING ACTION TOWARDS THE PRESERVATION OF BIODIVERSITY

Biodiversity loss (and preservation) is a complex topic that is informed by science but entails social, ethical and moral dimensions that make it a relevant and demanding SSI. Climate change, pollution, habitat degradation, the introduction of invasive species and the overexploitation of natural resources are among the major drivers of the increasingly rapid decline of biodiversity (Djoghlaf & Dodds, 2011).

As humans, we are one of the most inventive species, shaping our environment to our will—or at least according to our perceived needs. Although our presence on Earth is recent from a geological perspective, we managed to expand across the entire planet, creating intricate and diversified networks of cultures and tailoring our world.

Our existence has been highly eventful and our global population continues to grow. We now live longer and healthier lives than we ever have, despite well-documented geographic asymmetries. However, the fitting of our *'Human Planet'*—as Lewis and Maslin (2018) insightfully described—has come at a great cost. As we domesticate nature, shuffle species all over the world and use up all available resources in an attempt to cope with our accelerated consumption habits, we have cleared green areas, decimated wildlife, created oceans of waste, released carbon and other greenhouse gases to the atmosphere at an embarrassing rate, and disrupted natural cycles.

All these actions interfere with the practices and lifestyles of communities worldwide and add pressure to coupled systems. The scientific community believes that the cumulative effects of our actions have reached a level that matches other planetary-scale geological events in the history of our planet, which can support the definition of a new, human-driven epoch: the Anthropocene (Lewis & Maslin, 2018; Steffen et al., 2015).

The first step to overturning what can arguably be depicted as our walk towards extinction is to acknowledge the effects of our everyday actions, choices and demands. From this point on, several solutions can be envisioned—the most immediate and potentially most impactful of which involve expert knowledge and the intervention of specialised agents.

These solutions include reducing pollution (particularly carbon emissions), restoring ecosystems, recovering habitats and implementing rewilding and conservation programmes (Dinerstein et al., 2020; Science Task Force for the UN Decade on Ecosystem Restoration, 2021). Nevertheless, it is simultaneously pivotal to mobilise civil society to actively engage in change-making instead of simply raising awareness of its importance. This calls for focused educational approaches being promoted in both formal, non-formal and informal settings.

According to UNESCO[1] (United Nations Educational, Scientific and Cultural Organization), 'education is essential for the sustainable and equitable use of biodiversity and its conservation'. Only by promoting *'the global collective action of an educated society, including efforts to promote local and indigenous knowledge of biodiversity'* and by taking on 'an inclusive approach that speaks to and involves everyone' will we be able to ensure that there is a future for the life in our planet.

By now, we are all fairly familiar with buzzwords such as biodiversity and sustainability (Special Eurobarometer 481, 2019). But are we truly ready to take action? Do we have all of the necessary knowledge and emotional predisposition to do it? To fully grasp the meaning of biodiversity and make sense of the threats it faces, one must master abstract notions and scientific concepts, such as evolution and its mechanisms, genetic diversity, time and chance. Much like what happens with any other SSI, it is necessary to retrieve information from various fields and sources and assess the meaningfulness of possible implications according to a wide range of variables stemming from each context considered (Sadler, 2004).

Ultimately, a social science issue is a controversial issue that does not have a single solution but rather many different angles from which it could be viewed by assessing the pros and cons in each case (Sadler, 2004).

Thus, how can we motivate and empower people of all backgrounds and ages to protect biodiversity? In particular, what contributions can we expect from non-formal and informal learning spaces (e.g., museums and science centres) in which the nature of the established interactions is episodic and visitors' profiles are highly variable? In this chapter, we present the work of three European museums on biodiversity and in other out-of-school contexts through the lens of SSI. To this end, we present the examples of:

1. The Natural History and Science Museum of the University of Porto (MHNC-UP) and the Hall of Biodiversity, a science centre deliberately and fully dedicated to biodiversity that has been open to the public since 2017 and in which museography is used to promote critical thinking and exploratory approaches to key SSIs.

1. https://en.unesco.org/themes/biodiversity/education

2. The French National Museum of Natural History, which initiated the *'Vigie-Nature'* citizen science programme with embedded SSIs. This programme encourages everyone to participate in the scientific research process to acquire new knowledge and act rationally to protect biodiversity.

3. The Zoological Museum of Athens (the oldest and richest zoological museum in Greece, founded 150 years ago) and its educational programme *'Look around the Museum to find a friend'*, which was built around a biodiversity-focused SSI and has been offered since 2019.

4. Other out-of-school contexts that could allow learners to approach biodiversity via an SSI framework.

1. The Natural History and Science Museum of the University of Porto: The Hall of Biodiversity – A journey through life

Natural history museums have a widely acknowledged role in documenting biodiversity, fostering its study and contributing to its preservation.

The collections they hold are repositories of data that tell us the story of how life has been evolving. Yet, whilst the scientific and academic communities are well aware of the power of natural history collections, how can the wider audience become acquainted with it? How can we unlock their history, meaning, symbolic, cultural and environmental worth, and potential whilst raising awareness about biodiversity loss and mobilising visitors to develop a state of consciousness that makes them appreciate and actively protect nature and all of its diversity?

There is an increasing number of voices arguing that one way to achieve this is to spark or reignite the curiosity that we naturally have about the world around us and to embrace emotions as a key variable affecting the quality of our learning and cultural experiences (Mazzanti & Sani, 2021; Thomas, 2016). Additionally, studies on transdisciplinary approaches to science engagement have demonstrated the effective role that the arts play in conveying complex scientific messages with social and cultural dimensions (Rossi-Linnemann & Martini, 2019).

It was based on these assumptions that the Hall of Biodiversity, a unit of the MHNC-UP that is part of the national network of the science centre Ciência Viva, located in the heart of the Botanical Garden of the University of Porto, was envisioned. The Hall of Biodiversity was designed by combining architecture, art and literature whilst connecting them to biology and natural history.

Together with the Botanical Garden and its living collection, it is a place of inspiration that urges visitors to celebrate and nourish the diversity of life whilst becoming acquainted with our natural and cultural heritage.

In line with the museographic philosophy that guided its development—coined by Jorge Wagensberg (Terradas & Wagensberg, 2006)—its permanent exhibition brings together real objects, aphorisms and metaphors, setting the stage for emotionally-loaded interactions with the objects themselves, the phenomena addressed, the explainers present in the space and the visitors themselves (Wagensberg, 2005).

The goal of the exhibition is to enable visitors to have a memorable experience and lead them to become more receptive to any learning that can then take place. Most importantly, it aims to allow visitors to develop an informed opinion.[2] In the words of Wagensberg (2015), *'the relevance of a museum is not measured by the number of visitors it receives, but rather by the weight of the conversation it generates before, during and after the visit'* (p. 116).

Since the exhibition is structured around a major SSI, it makes sense to fuel conversations and reflection whenever possible. No definite answers are ever provided, with the ultimate goal being to have visitors leave the museum with more questions than they had when they entered it (Wagensberg, 2005, 2015). This also creates authentic opportunities to address the nature of science and the way scientific knowledge is built.

And whilst serious issues are at stake, a very positive outlook is maintained throughout each room, exhibit and example since the aim is to present a call to action reminding us of how remarkable nature is whilst simultaneously leading us to consider what we have to lose if we do not tend to it.

At the Hall of Biodiversity, visitors can find a set of 49 exhibition modules and installations outlined to bear strong aesthetic features and organised according to 15 major topics covering all key aspects of biological and cultural diversity whilst providing a wide range of sensory experiences.

The main natural phenomena underlying the diversity of life as we know it are showcased, challenging visitors to experience an often forgotten/overlooked feeling of amazement towards the beauty of nature whilst appreciating the intellectual enjoyment that results from understanding abstract and complex scientific concepts.

Technology is used instrumentally to avoid replacing the experience of the sense of place and diverting attention from the messages conveyed (Wagensberg, 2015). This includes a wealth of solutions, ranging from mechanical models to multimedia and audio-visual resources. As for the information provided in each exhibit, it is kept to a minimum whilst detailing key aspects to prompt cognitive engagement and interaction.

The language used, whilst scientifically valid and precise, dismisses all sorts of scientific jargon. The use of museographic metaphors pervades the communication established with visitors, confronting them with unexpected details and challenging thoughts whilst simultaneously providing a familiar core of information that scaffolds the entire process (Simon, 2016; Wagensberg, 2015).

A very flexible storyline combining literature elements with science (Ferrand de Almeida et al., 2019a) overcomes physical interactivity by upgrading it to cognitive and affective levels and taking visitors on a journey through life in which they are the active and central agents. Although biodiversity can be considered something external to us as humans, as well as something that we must protect, this can still be regarded as exogenous and something that we must act upon. In the Hall of Biodiversity, humans' dual role as shapers and targets of change is highlighted throughout the entire exhibition.

The goal is to provide evidence of the environmental, social and cultural impacts of our actions whilst especially considering the importance of promoting feelings of accountability (Lee et al., 2013). Although a detailed description of all the exhibits in the

2. https://www.cienciaviva.pt/centroscv/rede/

Hall of Biodiversity is beyond the scope of this chapter, a selection of a few of the most emblematic examples is briefly depicted in the following paragraphs.

The journey begins outside the building, with an open invitation for us to accept our place in the wondrously diverse tree of life and acknowledge how we and all of the living beings with which we share our planet relate to one another (Figure 1).

Once we enter the building, we find ourselves face to face with a giant whale skeleton, which takes up much of the main hall (Figure 2).

Straight out of the pages of a novel written by one of Portugal's most beloved poets who used to spend her summer vacation in this very same house as a child (then her grandparents' home), this single museum object provides a powerful message.

Standing as a beacon of hope, it simultaneously reminds us of all the harmful effects that our actions have on the oceans, ranging from the intensification of natural resource exploitation to the increased pollution and degradation of ecosystems.

Figure 1
The 'Tree of Life' welcomes us at the entrance of the Hall of Biodiversity. Credit: Anabela Magalhães.

Figure 2
The blue whale (Balaenoptera musculus) skeleton of the zoological collection of the Natural History and Science Museum of the University of Porto. Credit: João Ferrand.

The poet is Sophia de Mello Breyner Andresen (06.11.1919 – 02.07.2004). To learn more about this story, see Ferrand et al., 2019.

Then, as soon as we climb up the helix staircase, we are asked to answer the fundamental question: why should we preserve (bio)diversity? The full range of arguments that allows us to answer this question are organised according to four essential principles:

a) Aesthetic principle – nature is beautiful and worth saving simply because of that.

b) Ethical principle – if a species got to the present time, who are we to stop its existence?

c) Economic principle – as difficult as it may be to put a price tag on biodiversity, the foundation of our global markets lies in it.

d) Scientific principle – by destroying biodiversity, we are dismissing a wealth of resources with therapeutic properties that can help us treat problems we cannot even foresee.

Each of these principles is illustrated by what Wagensberg (2009) defined as a hypercubic display of sudden understanding—a novel way of organising objects, according to specific criteria that allow the conveyance of a museographic metaphor. By making the invisible visible, it turns complex scientific notions that scientists often cannot explain using facts and reasoning into intelligible and relatable realities (Ferrand de Almeida et al., 2019b; Wagensberg, 2009).

These four displays include the following: a collection of eggs of all colours, sizes and shapes, organised according to gradients based on these three features; a collection of all the dog breeds in the world, emerging from a single wolf (i.e., the species at the origin of their domestication); a collection of plant seeds pinned down to their place of origin on a globe representing Earth; a collection of all the pills we now have available to treat all sorts of illness, whose active compounds come from nature (Figure 3).

Each display is accompanied by an interactive module that expands visitor experience. The opportunities to engage in inquiry focusing on the countless topics worthy of debate and discussion that stem from interaction with these exhibits is endless.

The main SSI being addressed—biodiversity loss—unfolds in its multiple dimensions, each of which triggers a debate around specific SSIs. The most frequently covered topics include the respect for and appreciation of diversity, the balance between human activities and wildlife preservation, the process of domestication and its ecological and economic impacts, human evolution and mobility, the introduction of invasive species, public health and pharmaceutical research, and traditional and local vs. mass production practices, among many others.

Figure 3
A collection of eggs organised by size, shape and colour in a hypercubic display of sudden understanding. Credit: João Ferrand.

The adventure continues as we are presented with the main mechanisms of evolution and selection (natural, sexual and artificial selection) as well as the various possible ways in which an organism can vary (e.g., in its genetic profile, size, shape, colour, perception, survival techniques and genetic configuration). To address one of the most relevant and central phenomena in evolution, the Hall of Biodiversity revisits the textbook example of the phenotypic variation of the peppered moth (Biston betularia) in the UK during the industrial revolution.

An illustrated life-size interactive panel depicting birch wood and the resident population of B. betularia leads us to travel back in history and witness the effects of air pollution on these animals. This aesthetically loaded exhibit leaves us thinking about how a simple change in environmental conditions at a given time and place (in this case, introduced by human hands) can dictate the destiny of a population. Thus, it is very easy to start considering the following question: what does it mean to be the fittest?

In turn, artificial selection—a recurring topic within the Hall of Biodiversity—finds its ultimate spotlight in a 3 x 4 m display harbouring an impressive *'maize curtain'* (Figure 4). In this display, the various stages of maize domestication are visually demonstrated using real cobs. We begin with a column of wild cobs (teosinte), which is followed by a remarkably diverse column of cobs of all colours, sizes and shapes, representing cultivars that we can still find in Central and South America.

Then, a much less diverse column of cobs of local Portuguese cultivars follows. Finally, we reach a column of clones: cobs of transgenic varieties that are all identical, perfectly adapted to a specific environment and utterly incapable of adaptation.
By observing this display, we are immediately able to understand how this plant has been shaped through agricultural practices to meet our needs at specific periods throughout history. This is done by first using traditional techniques and attempting to unravel all possible combinations leading to the most luscious diversity possible.

Then, by moving on to more focused techniques (and eventually genetic engineering) driven by an intent to improve the crops produced, maize was made more efficient and homogenous whilst sacrificing diversity along the way. This seemingly simple yet very powerful metaphor ends up challenging us to reflect on the economic, cultural, social and environmental impacts of technology, including all of their highly controversial dimensions.

Figure 4
Artificial selection: The domestication of maize.
Credit: João Ferrand.

Evoking the history of natural history collections reproduced in the Hall of Biodiversity is a cabinet of curiosities. Here, a dense and neatly organised matrix of objects, pictures, illustrations and maps representing the origin of natural history museums is brought together with a visual outline of some of the most relevant geological, ecological and cultural routes projected onto a giant globe emulating our planet that takes up the centre of the room (Figure 7). This sudden voyage from past to future stimulates reflection about our natural curiosity toward the unknown and stresses the sense of responsibility that we must bear when interacting with nature and other cultures.

Finally, coming full circle, human diversity—one of our most valuable traits—is rejoiced by recalling what makes us special and unique, both as individuals and as a species, from both biological and cultural standpoints. Our cultural evolution, expressed in language, music, arts, literature and many other activities, has been prompted by our ability to move and communicate.

The action unfolds in two adjacent rooms. In the first room, we are challenged to look for patterns that disrupt the continuum in which the variation in our traits is distributed. Here, we can find the human pantone, a sample of artist Angélica Dass' Humanae Project[4].

In the second room, literature brings us an ode to our status as global citizens that are fully capable and naturally eager to interact with different cultures whilst promoting awareness of the interchange that arises from these conversations and that it enhances our ability to make sense of reality and the world around us.

However, the story does not end here. In addition to its permanent exhibition, the Hall of Biodiversity supports very dynamic and transdisciplinary temporary exhibitions, as well as cultural and educational programmes. Notably, the latter always favour active learning approaches. Although these focus on a wide range of themes and topics, the preservation of biodiversity and sustainable development are always present, either explicitly or implicitly. The Hall of Biodiversity's educational programme includes activities specifically intended for the school community (all instructional levels as well as pre- and in-service teacher training), which facilitates a deepening of the work around certain contents in the context of medium- to long-term projects.

In line with this goal of achieving a long-lasting audience engagement, even the programmes targeting audience segments other than the school community are structured to ensure recurrence.

These programmes are cross-sectional, involving all units of the MHNC-UP and its various teams (educational services, communication and collections), as well as external partners in various fields.

2. From citizen science to the socioscientific empowerment of students: The impetus of the French National Museum of Natural History

Protecting biodiversity requires social choices based on sustainable ecosystem management. For effective action, it is necessary to protect not only current biodiversity but also the evolutionary process at its origin. In other words, it is

4. https://angelicadass.com/photography/humanae/

important to know that humanity is part of biodiversity and that it can contribute to its evolution. In Europe, natural history museums play an important role in the implementation of citizen science within the European Citizen Science Association (Sforzi et al., 2018). Thus, data collected by volunteer citizens can be analysed by scientists to produce indicators that help describe the impact of human activities on biodiversity (e.g., climate change, urbanisation, pollution) and can also open educational perspectives on SSIs.

In 2006, the French National Museum of Natural History (Muséum national d'histoire naturelle - MNHN) created a citizen science project called *'Vigie-Nature'* (Couvet et al., 2008) to inventory the biodiversity of the French territory. For this purpose, scientific protocols designed by the museum's researchers that could easily be implemented by citizens provide data on various species. In 2012, *'Vigie-Nature'* created a variation for schools called '*Vigie-Nature École'* (VNE).

This project is based on the voluntary participation of primary, middle or high school teachers and students who wish to raise awareness of biodiversity loss through their contribution to a real research project. Ten protocols are available for implementation in schools, thereby allowing the monitoring of a wide variety of groups (e.g., birds, snails, wild plants, pollinating insects, etc.). With these protocols, students can directly observe the species living in their immediate environment. During the 2021–2022 academic year, 460 school classes from elementary to high school (10,898 students) contributed to the project. In total, since the launch of this project, the students have carried out 12,672 observation sessions that allowed them to count more than 43,000 birds and 10,500 snails. The data collected by school classes are sent to the museum researchers via the VNE website and analysed by them to obtain indicators of the biodiversity levels in French territory. Thus, VNE is a citizen science project that Bonney (2009) described as *'public participation in scientific research'* (PPSR) by collecting data on a large spatial and temporal scale within the French territory. The indicators of biodiversity level and the other results are sent to participants in the form of newsletters explaining the results. Students can also meet the researchers during conferences, where they can ask questions about their observations.

In relation to the French biology curriculum, VNE is used for students to mobilise scientific practices and knowledge (Bosdeveix et al., 2018; Conversy et al., 2019) but also to address the SSI (Sadler et al., 2016) concerning the anthropogenic impact on the loss or maintenance of biodiversity.

For example, some teachers can go beyond data collection and involve their students in the preservation of local biodiversity. To do this, the teacher can rely on the results of VNE data collection in connection with scientific knowledge in ecology whilst also relyingon socio-environmental considerations related to the social implications of biodiversity protection (Mueller et al., 2011). By combining these two educational approaches, students can participate in decision-making to promote concrete actions to protect biodiversity (Philipps et al., 2020).

Here, we present an ecology-focused SSI involving a decision-making process related to the conservation of biodiversity in a local context: urban bird habitat destruction in connection with the VNE citizen science tool. The *'Garden Birds'* protocol illustrates this connection between the citizen science VNE project and the SSI of bird biodiversity loss in urban areas. The first step is to identify and count the birds in a schoolyard, public park or garden around the school. The protocol is simple, yet accurate and effective. Bird observations can be performed with binoculars and/or using bird feeders. Observations must be done in 15-minute intervals (if the observation time is not the same, the data cannot be compared). In this protocol, participants count the maximum number of individuals of each species seen simultaneously.

The observation can be conducted at the same site, but at different dates and times to understand when and why birds visit the site. To assist teachers and students in identifying the observed birds, an identification key (Figure 5) is provided. For each bird, one or more symbols show some specific characteristics of the observed species.

There is also an application called *‘BirdLab’*[7], which can easily be downloaded to phones or tablets. Through BirdLab, researchers are interested in the interactions between birds at feeders. To analyse this, participants will have to replicate the activity of different species at the feeders in real time for 5 minutes via a simple *‘drag & drop’* action.

Observations should be made on two identical feeders with the same amount of food, separated by 1 to 2 metres. Automatic geolocation allows the type of environment (e.g., urban, peri-urban, rural) to be determined. For example, by participating, students can realise that blackbirds come

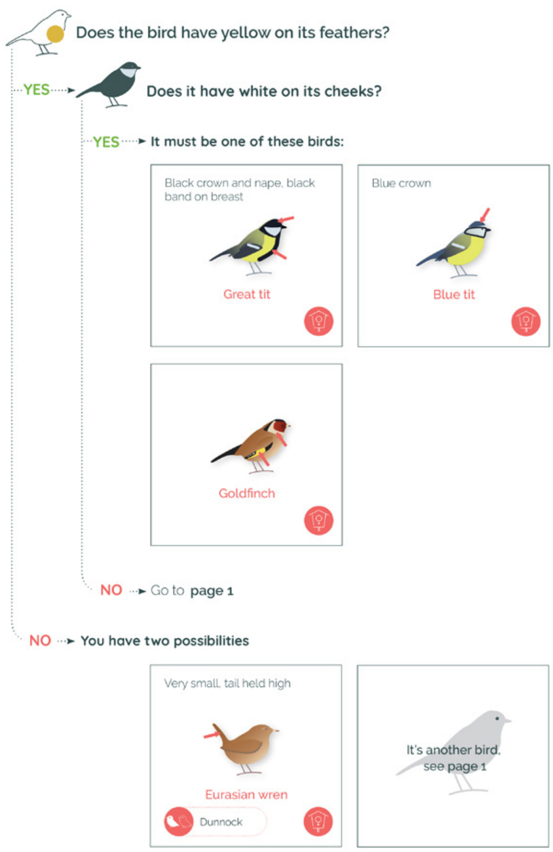

Figure 5
Example of a determination key to aid in the identification of bird species. © Vigie-Nature – MNHN.

and go to the feeders many times, whilst other birds prefer to stay longer[5] (Figure 6).

In the second step, VNE can engage students in a decision-making process to protect biodiversity at the local level based on the data collected.

For example, students can compare the biodiversity (abundance and diversity) of birds in a wasteland and a mowed lawn (Figure 7) through the analysis of collected data and realise that there are four species in the wasteland and only two on the mowed lawn.

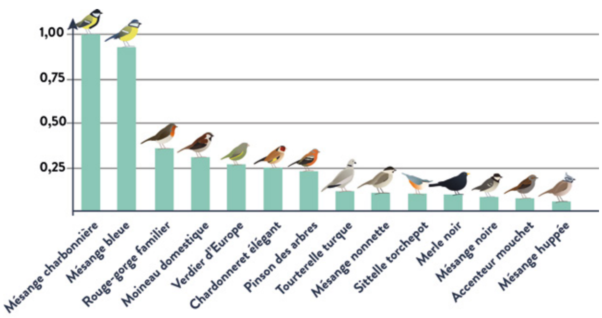

Figure 6
Example of BirdLab tool: Graph of the relative frequency of the 14 most present species (compared to the great tit). The blue and great tits are the most frequently observed feeders. © Sébastien TURPIN – MNHN.

In this situation, students mobilise both the results obtained in the two environments and the local SSI of biodiversity loss in urban areas.

Hence, they suggested that some areas in gardens and public parks should not be mowed to promote the growth of plants that produce the seeds consumed by birds. This proposal can be formulated as a recommendation from the students to the school, neighbourhood and even

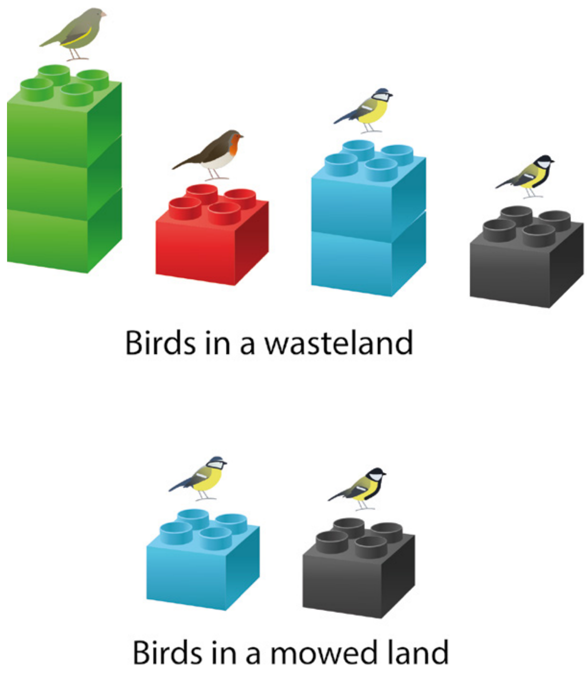

Figure 7
Results of the collected data (abundance and diversity of bird species) in two environments (wasteland and mowed lawn). © Sébastien TURPIN - MNHN.

city authorities. This seemingly simple suggestion is not popular because it is not self-evident. Indeed, not mowing the lawn is often taken by the public and authorities as a sign of neglected areas by garden owners or by the gardening services of the city's public parks.

Therefore, it is up to the students who participated in the VNE citizen science project to provide the data they collected to municipal authorities and the local population in order to demonstrate the ecological interest in leaving areas of the city uncultivated to combat biodiversity

5. https://www.birdlab.fr

loss. Therefore, based on the scientific data generated by the students' participation in the *'VNE'* project, a collective informed decision-making dynamic in favour of bird biodiversity conservation can be developed through engagement in the corresponding SSI. Thus, students can implement positive human activities by empowering their immediate environment because they are actively engaged in citizen action and contribute to the transformation of gardening practices in the city. Moreover, it is well known that SSIs consist of excellent contexts for argumentation development (Duschl & Osborne, 2002; Zeidler & Nichols, 2009).

In conclusion, based on this simple result, students can use and generate resources to think about actions to protect biodiversity. They are both members of a school community and members of the scientific community of the VNE citizen science project.

Thus, in addition to its scientific objectives of assessing biodiversity, this project can also produce a social impact based not on common opinions but rather on scientific data. It also represents an opportunity to work with students on the link between ecology, evolution, climate change and the role of natural selection and genetic drift in the process of species extinction.

Therefore, Vigie-Nature and VNE are citizen networks that promote scientific ecology as well as the SSI of biodiversity conservation in order to change our individual and collective attitudes in a social context and highlight the contribution of museums towards this end.

3. The Zoological Museum of the Biology Department of the University of Athens: In search of biodiversity

As mentioned earlier, biodiversity is not just a biological concept that people of all ages should be aware of, but an essential component of life. Thus, Greece's largest zoology museum could not leave out this scientific dimension, which also has a social impact. For this purpose, the design of educational programmes that could function either as a complement to the main science curriculum of the school (and specifically biology) or independently has recently started in the Museum of Zoology of the Department of Biology of the University of Athens.

Here, we present the programme entitled *'Look around the Museum to find a friend',* which was designed around the topic of biodiversity for secondary school students (Deroungeri, 2022)—and more specifically for the first years of secondary education (K7–K8; 13–14 years old)—in the context of the SSIs on the topic of biodiversity. It was based on the presentation of different (endemic and non-endemic) animal species living in Greece in a playful and fun manner for the students whilst also being designed with clear objectives (e.g., name endangered animal species in Greece, distinguish animals according to their category of danger, compare different categories of animals and relate them to their causes of endangerment, etc.).

Thus, by the time students leave the museum, they have gained knowledge and have not merely toured the museum's premises. The ultimate goal for the students was to make sure they would be able to decide on a hypothetical deforestation scenario. The following is a summary of both the objectives of the project and the methodology implemented, as well as some initial impressions from student groups who visited the museum and followed the biodiversity project. However, the presentation and analysis of the learning outcomes are outside the scope of this chapter.

'Look around the museum to find a friend'

As previously explained, the design of the programme places biodiversity at its heart. It highlights the place of humans among other living organisms, emphasising that human beings are just one of them. Simultaneously, knowledge about biodiversity is not only an ecological constant, but a way of understanding why it is important for every living organism (in this case, especially humans) to respect nature and all that it contains.

Due to Greece's particular topography, variety of habitats resulting from the land areas, and the numerous and very different islands, biodiversity is particularly rich. Like other countries, Greece has endemic and non-endemic species that can be classified into different risk categories. The causes of risk can be pointed out, including anthropogenic effects.

Thus, a key aim of this project is to familiarise students with the risk categories of species as defined by the IUCN (International Union for Conservation of Nature). Non-endangered, endangered, critically endangered and vulnerable species were chosen for this project so that students can come in contact with and observe how these terms differ and what cases of each risk category can be found in Greece.

Moreover, another objective of the project is for students to identify the causes that lead to the extinction of endangered species and how this can be reduced or eliminated. After all, based on the IUCN categorisation mentioned above, it is known that not all endangered species disappear despite their decreasing numbers.

Thus, it is important to understand how each of these cases may occur. Apart from the IUCN categorisation, an important objective was to correlate the conservation (or not) of species (as a key dimension of biodiversity) with the impact of anthropogenic activities. In this way, the project aimed to foster an attitude of respect for the environment and an awareness of the consequences of students' present actions on future situations. Furthermore, as previously mentioned, the SSI that the programme concluded with sought to have the students decide on a human intervention in the natural environment (deforestation) whilst considering as many parameters as possible. This activity is described below.

To implement this project, accompanying materials were designed for students. Tour guides, quick response barcodes (QR codes) and an information recording form were designed. More specifically, the museum space was divided into four routes, each of which was assigned a tour guide. Each tour guide took the form of a small book of puzzles.

By solving a puzzle, the students were taken to a point in the museum (different for each puzzle) where a QR code was waiting for them. Once scanned with the help of tablets (which were given to the students on arrival at the museum), the QR code reveals information about the animal under study. In other words, each QR code provided more information about the animal in the puzzle that the students had solved.

They would then have to solve the next puzzle to reach the next animal exhibit in a similar manner. Thus, all the information collected by the students was recorded in certain columns on the information recording form (animal name, habitat, threat, etc.). Therefore, each group of students was asked to fill in all the columns on the form based on the exhibits on the trail until they had filled in

the information for all the animals.
At the end of this process, a short discussion with a member of the museum staff followed for the students to summarise their findings and be assigned the final activity (i.e., the completion of a *'comic strip'* on the subject of deforestation). In fact, the students were given two pictures (Figures 9 and 10), which constituted a short story. The protagonists of the story were the animals of the forest, which had to decide how and whether to act if they had to face a human intervention in their natural environment.

Therefore, the students had to complete the animals' dialogues. Through these dialogues, they should come to a decision regarding this particular SSI. The dialogues that students develop can demonstrate whether they realise that there is a threat of extinction and for which animals (i.e., based on the animal images depicting all IUCN categories). Their final decision can also show whether they were able to reach a decision through a multifaceted consideration of the issue. This would be aided by the information they had previously collected as well as the final summary that had been made.

Although the learning outcomes are not the subject of this chapter, it is important to mention that at the end of the entire process, the students completed a short questionnaire to express their impressions of the project and evaluate any knowledge they may have gained. It was found that the majority of the evaluation questions were answered correctly.

More striking, however, were the results of the answers relating to the students' impressions. They reported no difficulties in following the programme, with 95% stating that they would not have preferred any other way of engaging with the programme (e.g., a traditional tour). In fact, several noted that they liked having to *'put their minds to work'* rather than just walking through the museum.

Additionally, the same percentage of students reported that they would like to

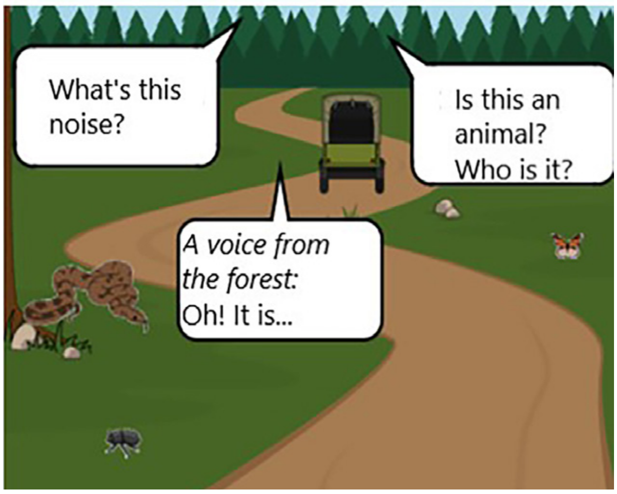

Figure 9
Life in the forest and the arrival of the 'stranger' (first part of the short story; Deroungeri, 2022).

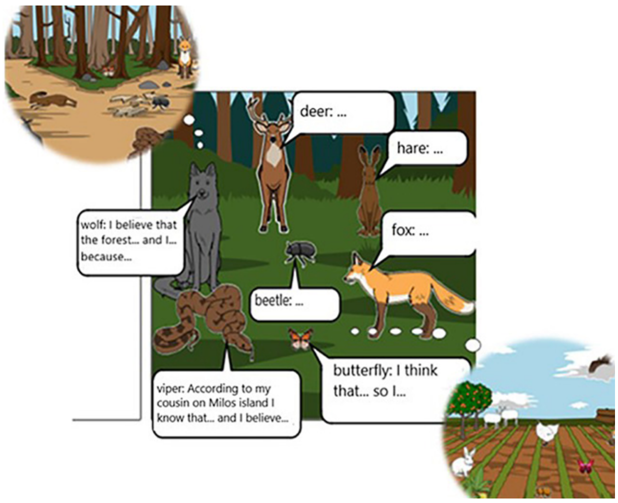

Figure 10
The council of forest animals meets to make decisions (second part of the short story; Deroungeri, 2022).

attend similar programmes again in the future. It was also particularly encouraging that students even responded positively to metacognitive questions. For example, they noted that this programme helped them learn about biodiversity and the risks it faces.

Overall, students seemed to enjoy this way of approaching biological concepts. Moreover, the design and integration of the programme in an SSI context gave a boost to learning about biodiversity issues through the possibilities and opportunities that a museum can offer.

4. SSIs in other out-of-school contexts

Museums are unquestionably powerful environments that can be used to engage with SSIs. Also, in addition to the specific content, activities and projects they promote, to some extent, this potential results from the situational interest that can be prompted by them.

Research has shown that place-based education can provide relevant outcomes due to the authenticity of the settings in which interactions occur (Wattchow, 2021). This feature is common to other out-of-school contexts, such as natural parks, botanical gardens (which are often perceived and presented as living museums), zoos and aquariums, which have also been shown to create fruitful opportunities to tackle pressing societal issues with a scientific and technological underpinning (Dean, 2022; Papoulias, 2022; Reyes, 2020). These contexts appear to be particularly suitable for addressing environmental issues given the (more or less) direct contact with nature that can be fostered.

Researchers have argued that experiencing the natural world in more or less controlled settings—namely by exploring places with which one is familiar and that are readily available—allows people to understand the complexity of variables at play when discussing real environmental challenges, especially those related to biodiversity preservation and sustainability (Austin, 2021; Herman et al., 2019).

By becoming immersed in nature, one can embrace the complex network of elements upon which the delicate balance of natural phenomena is based, instead of having to deal with them as abstract concepts (Austin, 2021). This arguably makes it easier to fully grasp the main dimensions that typically characterise SSIs.

A recent research study (Herman et al., 2020) on students' emotive reasoning about an environmental SSI whilst visiting the Greater Yellowstone Area has demonstrated that place-based SSI instruction can scaffold their emotional and affective responses towards an issue and the agents involved and affected by it, which can act as triggers to pro-social and pro-environmental behaviours. Additionally, the bioblitz—an increasingly popular tool in environmental (and especially biodiversity) education—has been proven to support the development of practical and conceptual learning of nature-related scientific concepts in a more authentic, immersive way, with students reporting an increased sense of appreciation of nature and an improved readiness to act in favour of environmental preservation (Gass et al., 2021).

The potential of these other out-of-school contexts can be further boosted by exploring active learning strategies that have been trialled and tested in museums, science centres and schools.

DISCUSSION - CONCLUSION

There are various ways to address different SSIs in museums and science centres through either exhibitions or activities. The examples presented herein represent only some of the available solutions; however, they embrace this commitment from the core. Overall, the advantages of an educational approach using SSIs are well known (Zeidler & Nichols, 2009). Moreover, the combination of using SSI-based educational approaches within non-formal education environments could offer even more opportunities for students and future citizens to engage with a wide range of topics, including biodiversity.

More than standing as a serious ecological issue, the preservation of biodiversity demands a concerted effort by multiple actors in social, cultural, economic, political and scientific fields. Based on the most recent scientific data, an estimated 2.4 million species face the risk of extinction within a timeframe of years due to human activities (Raven, 2020).

At a time when our knowledge of and impact on the world is as deep as it has ever been—and when we control technology like never before—all efforts must be placed on disrupting the destruction of nature and building a future we can be proud of. Each of us, as individuals and as a community, has a role to play in this regard, whether by taking immediate and direct action or by creating the conditions required to foster positive change. Hence, it is obvious why these three museum activities have been developed with the common denominator of presenting biodiversity as a socioscientific issue and not only as an exclusively scientific issue. At the interface between the scientific and social worlds, these activities contribute to rethinking the educational contribution of museums. They offer the possibility to go beyond the informative and popularising perspective of scientific knowledge by initiating a critical perspective through a strong interaction between the activity and the student. Furthermore, to some extent, it could even be said that it is a matter of offering the pupil a *'thought experiment'* in which he or she becomes an actor in a decision-making process involving both scientific knowledge and values.

Far from the expert's perspective of imposing from the top down and prescribing the *'right decision' to be made, these three examples emphasise the students'* ability to express arguments. But the most important point is undoubtedly their contribution to *'doing science in society'.* Indeed, it is not about telling evolutionary and ecological stories as a grand science tale about the dangers threatening biodiversity. Instead, it is about proposing activities that go beyond raising awareness or improving one's understanding of scientific products.

Indeed, the three descriptions of activities in the museums of Porto, Paris and Athens include a different proposal for approaching biodiversity through SSIs. In the first case, a novel approach based on a museographic philosophy that brings together art and science by harnessing the universal power of aesthetics whilst favouring emotions, affective engagement and ultimately intellectual enjoyment has been trialled and tested by the experts of Porto's museum.

In the second case, a modern citizen science project (i.e., VNE) in combination with an SSI demonstrated how students could engage in results-gathering processes by acting as young scientists that are willing to contribute to the research of mature scientists and ultimately want to make suggestions for improving their local communities in the context of conservation and biodiversity enhancement. In the latter case, through a tour of the Zoological Museum of Athens, an idea was given for how to integrate fun and adventure in the management of a biodiversity-focused SSI.

Through puzzles and *'comics'*, students were ultimately asked to make decisions. Notably, they left the museum not only excited after an atypical visit but also gained knowledge after real engagement with the SSI.

These three activities reflect new educational orientations based more explicitly on a commitment to science education for citizens. This is a major challenge that implies new responsibilities for 'scientific action in society' and invites students to participate in democratic decision-making processes, particularly concerning the protection and conservation of biodiversity in the face of global changes caused by the anthropogenic activities that threaten it (climate change, urbanisation, pollution, etc.).

Nevertheless, the loss of biodiversity is among the most pressing environmental and societal challenges at both local and global scales. It concerns every single one of us in each stage of our lives and has been at the forefront of the United Nations agendas for sustainable development (Roe et al., 2019). Whilst being explicitly covered in the 15th Sustainable Development Goal to *'protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss'*—it unquestionably stands as an underlying concern when endeavouring to attain most of the other 16 SGDs.

Consequently, in complementarity with formal education, these museum activities and other similar outdoor proposals (e.g., in zoos, botanical gardens, exhibitions and festivals) could soon become an inevitable step more than an optional step since they contribute to the development of critical thinking and real empowerment for the protection of biodiversity in both the individual and collective dimensions.

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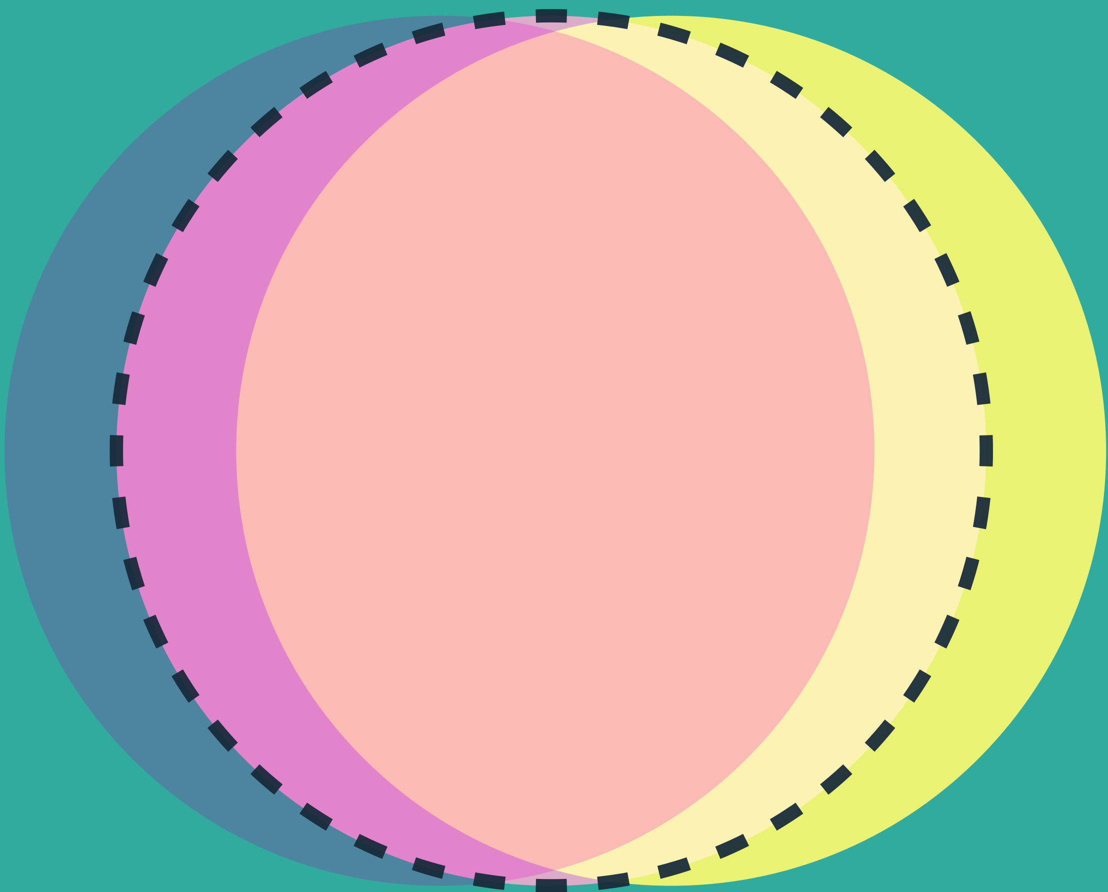
Chapter 5

How is evolution impacting our lives



CHAPTER 5

How is evolution impacting our lives

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Abstract:

Teaching evolution can be challenging because it often appears to lack context or real-world relevance. Therefore, a problem in evolution education is identifying and maintaining interest in the subject that can facilitate and enhance engagement with the teaching. There is a wide range of potential 'hooks' for evolution education and this chapter presents a few of these in an attempt to provide inspiration. Starting somewhat speculatively is a discussion on how having a proper understanding of phylogenetics may provide an ethical perspective on humanity's place in nature. This is followed by a discussion of how evolutionary research is helping us to predict biodiversity changes occurring as a result of climate change. Evolutionary medicine is then discussed using cancer and new methods of treatment as its focus. Finally, a discussion of the evolutionary underpinnings of COVID-19 is presented within the context of an individual's responsibility to society.

KEYWORDS

ethics, phylogeny, climate change, biodiversity, cancer, COVID-19

1. WHY IS IT IMPORTANT TO EXPLORE EVOLUTION IN REAL CONTEXTS?

All educators know, if only through personal experience, that students are best engaged when they have an interest in a subject (see Silvia, 2006 and Silvia, 2008 for reviews of the psychology of interest). *"When interested, students persist longer in learning tasks, spend more time studying, read more deeply, remember more of what they read, and get better grades in their classes"* (Silvia, 2008). Interest is often elicited and/or maintained when one has a frame of reference for a subject (i.e., how it fits into a wider context).

Additionally, subjects that have direct relevance to students, or are tangibly relatable to students' everyday lives, are likely to engender more interest (Silvia, 2006). Although curiosity is also a generative force for interest, it is fragile and often stymied by the subjective arbitrariness and constraints of school curriculums and the pressures of assessment (Silvia, 2006, 2008). Notably, problem solving is tightly linked to interest and curiosity.

Humans appear to be naturally drawn toward problems as a source of interest as long as the problems appear to be tractable (Silvia, 2006). If a topic can be posed as a problem to be solved or involves problem solving, this often adds to a student's motivation to learn and underpins 'pr*oblem-based learning'* pedagogic approaches (Harackiewicz et al., 2016).

Therefore, it is natural that in an attempt to maximise student engagement, teachers can place significant effort into finding *'selling points'* or *'hooks'* for topics by providing comprehendible examples, drawing out the context, posing relevant problems, making appeals to curiosity, etc. This is a deep and broad topic of research for cognitive psychology, pedagogy and andragogy in general (for a very approachable review, see Willingham, 2009).

Unfortunately, for many, evolution is a topic that can appear distant from everyday life and is thus considered abstract and incomprehensible, even boring. Appeals to curiosity and novelty can be used by educators to capture the attention of students. Palaeontology is a natural and effective entry into evolution because of the novelty of unfamiliar organisms.

This often relies heavily on dinosaurs (Salmi et al., 2016) due to their unusual appearances, whilst also leaning on violence in the hope of getting students' attention (with Tyrannosaurus rex and Velociraptor featuring prominently in this regard). Additionally, since fossils are difficult objects to interpret and imagine as living creatures, there is often a heavy reliance on speculative artistic portrayals, which is something that computer animation has excelled at.

On this scale, human evolution, which includes our extinct sister species such as Neanderthals and Denisovans (Callaway, 2016), is another topic that students often relate to for obvious reasons. However, there are limitations in placing palaeontology, and therefore evolution, into context since the objects of study are both figuratively and literally distant from students' lives.

Moreover, the timescales involved are typically in the millions or hundreds of thousands of years and thus beyond intuitive grasp (Cately & Novick, 2009), giving the subject a somewhat esoteric and irrelevant feel. As a gateway to evolution, this may backfire if students get the impression that the subject is all about long-dead things that only make gory appearances in films.

What is needed are examples, contexts and problems for evolution that are more easily relatable to students. Something in the *'here and now'* that can be recognised as relevant or useful to the individual. The problem of finding such *'hooks'* is far from solved, partly because interest is highly subjective and idiosyncratic, which makes it difficult to find clear universal examples or principles (Borgerding & Kaya, 2022; Jördens & Hamman, 2019).

A further challenge is that, although evolution is the underlying cause or explanatory principle of biological entities and phenomena, this linkage often lies hidden below the surface, is subtle to appreciate and is not necessarily required for a functional understanding of the subject. The title of Theodosius Dobzhansky's influential essay, *"Nothing in biology makes sense except in the light of evolution",* is often put forward by those who are already knowledgeable about the area as a kind of argument for studying evolution.

However, it is rarely the case that knowledge and understanding of a biological system necessarily require an evolutionary perspective. For example, one can quite effectively learn anatomy without ever knowing anything about the evolution of the homologous forms.

Therefore, the challenge for the educator is to find and present examples of evolution from different perspectives, which places it into contexts where it impacts our lives today in the hope that this garners sufficient interest in pupils and allows them to better engage with the topic.

2. EVOLUTION AND ETHICS

Based on the preceding discussion, it may seem odd to begin with the topic of evolution and ethics. However, consider that the concepts of ethics, morality, justice and fairness, among others, are often strong preoccupations for people, especially school-aged children and adolescents, even if they are not aware of the semantics or lack developed knowledge of the concepts (Malti et al., 2021). How evolution intersects with and informs ethics is a wide-ranging area with a long history of thought dating back to Darwin (for reviews, see Oldroyd, 1983; Ruse & Richards, 2017).

Evolutionary theory has been used as an explanatory principle for a wide range of human behaviour, from how market economies work to how men and women relate to each other and family dynamics. Such explanations have typically been summarised as *'social Darwinism'* or *'Darwinian psychology'.*

As one would expect, these philosophical, sociological and psychological investigations are often highly controversial and contentious. This is mainly because they stem from observational studies out of necessity. It is impossible, or at least extremely difficult, to design robust interventional experiments to investigate these hypotheses in the same manner that one could for a biological system in the laboratory.

Rather than go down the rabbit hole of social Darwinism, one less controversial example of evolutionary theory intersecting with ethics deals with the philosophical perspective on humanity's place in the natural world. We are increasingly becoming aware of and formally taught about climate change, habitat and ecosystem encroachment, and threats to biodiversity, among other challenges. As inheritors of the world, there is a keen self-interest among people in these topics, which greatly helps with engagement in studying them. Therefore, giving youth a sense of perspective about their place in the natural world is a vitally important topic that is likely to resonate favourably since they generally want to do their best as global citizens (e.g., Kuo & Jordan, 2019).

Calls to change our perspective on humanity's place and role in the natural world are increasing (e.g., Hulme, 2020). Changing the perspective of humans as the evolutionary *'top of the pile'* (anthropocentrism) by correcting a common misinterpretation of evolution could partly help to address our hubris.

Evolutionary adaptation is often incorrectly portrayed as a linear progression of creatures from ancestral *'primitive'* forms through to more *'advanced'* forms. Most will have seen evolution memes based on a series of images (typically presented from left to right) of increasingly upright figures, starting with an ape and ending with a modern-looking human.

Occasionally, a humorous version of this image adds a final human figure hunched over a computer, suggesting *'regression'* to a more primitive form. Unfortunately, these images are completely incorrect in their portrayal of evolutionary change since they present it as a linear chain of events and as a progression in terms of primitive to advanced. A linear progression is also common in many other portrayals of evolution and is sometimes even made by biological scientists (Schramm & Schmiemann, 2019).

Instead, the path of evolutionary adaptation and diversification follows a branching tree-like pattern technically called a phylogenetic tree or simply a phylogeny. This hierarchical structuring of evolutionary history is one of the fundamental understandings that has come from the study of evolution (Gregory, 2008). Although the concept predated Darwin, he brought it into a coherent concept and that was instantly appreciated for its explanatory power (Ragan, 2009). The phylogenetic tree has survived the test of time, being greatly corroborated via multiple sources of evidence in the molecular biology era (Page & Holmes, 1998).

Despite being a relatively simple and elegant concept, a phylogenetic tree has subtle depth when it comes to interpretation (Gregory, 2008; Schramm & Schmiemann, 2019). Again, a misleading bias often seeps in when a tree is presented on the page. Very often, especially for simplified trees used in education, a phylogeny is organised from apparently more primitive forms on the left-hand side of a page/screen through to apparently more advanced forms on the right-hand side of the page/screen.

This subtlety in presentation subconsciously embeds the idea that ancestral *'primitive'* forms evolve into more 'advanced' forms and that there is a progressive hierarchy to organisms, with something being *'on top'* or at the *'end'*. The *'top dog'* is usually a human (or at least an animal or multicellular organism), which reinforces an anthropocentric bias (Baum et al., 2005; Baum & Smith, 2012; Sandvik, 2009). So pernicious is this biased presentation and incorrect interpretation, even amongst many scientists, that the Tree Thinking *'organisation'* (tree-thinking.org) was formed in an attempt to educate and counter it (Baum et al., 2005; Meisel, 2010).

For those who wish to go into depth textbook by Baum and Smith (2012) provides an excellent and extensive overview of phylogenetics whilst emphasising proper *'tree thinking'.* A phylogeny can be likened to a hanging mobile that turns about in the breeze. Whilst all of the threads retain the same linkages, the elements of the mobile can move about each other to present multiple different appearances. Thus, a phylogeny with humans in the middle or at the left- or right-hand side can be equivalent and perfectly valid representations of evolutionary relatedness (for examples, see the figures in Baum et al., 2005).

Evolutionary knowledge and the correct interpretation of phylogenetic trees are important for students to learn so that they can appreciate that there is no *'top dog'* in the natural world. All extant organisms are equally ranked, with every individual, including yourself, having an independent unbroken line of descent extending as far back as approximately 4 billion years (Javaux, 2019; Krishnamurthy, 2020).

From this evolutionary perspective, humans have no more 'right' to or place in the natural world than any other organism. This should be a humbling perspective and may help future generations take a more balanced approach to the natural world and their place in it.

3. BIODIVERSITY CHANGE

As discussed in 2. above, some of the most pressing global concerns today include climate, habitat and ecosystem change and the many and various impacts that these forms of change will have on our lives through their effects on the biosphere. As average regional and global temperatures rise, there is a knock-on effect in the landscape that can significantly impact biodiversity from the individual to whole-ecosystem scales and from microscopic unicellular organisms through to the largest multicellular ones. If the environment changes too rapidly without sufficient time for organisms to adapt or move to more suitable environments, there is a real risk of extinctions occurring (Carroll et al., 2014).

Sufficient extinction events, or even the extinction of certain keystone species alone, may result in large-scale ecosystem collapse and unpredictable, but most likely negative, implications for humanity (Ceballos et al., 2015). The periodic report on global biodiversity and ecosystem services published by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (https://ipbes.net) provides depressingly voluminous information on the scale and accelerating rate of extinctions. Thus, there should be no argument that this is a pressing problem for all.

Assessing biodiversity for the benefit of basic knowledge and as a means of monitoring the impacts of climate and other habitat changes has become a staple of evolutionary research (Lankau et al., 2010). The power of biodiversity monitoring has been greatly increased with the development of genetic *'barcoding'* methods, which have been greatly expanded using next-generation sequencing technologies to become *'metabarcoding'* methods (Taberlet et al., 2012). The greatly increased specificity and sensitivity of molecular methods have assisted taxonomists and phylogeneticists in gaining far more nuanced understandings of biodiversity's composition, to monitor it in real-time, and enhanced evolutionary knowledge in general (Waldvogel et al., 2020).

For instance, by using environmental polymerase chain reaction (PCR) techniques, we now appreciate that microbial biodiversity is far greater than we can culture in the laboratory. These unculturable microbes have become known as the unexplored *'microbial dark matter'*, and likely constitutes 99% of microbial species (Jiao et al., 2020). Whilst this untapped biodiversity holds great potential for biotechnological applications (Alam et al., 2021), it remains uncertain how it will respond to climate change.

In this domain, there has been a paradigm of gradualism in evolution that originated with Darwin, who was inspired by Lyell's book on geology, which itself was instrumental in establishing the age of the planet and its rate of change (i.e., the geological scale). In many respects, the gradualism of evolution has been accepted and not challenged robustly until recent times. Interestingly, the textbook example of the natural selection of the peppered moth as a result of changing pollution in the landscape demonstrates the relatively rapid adaptation of phenotypes (Cook & Saccheri, 2013).

More recently, further examples of species adapting in sync with ecological changes have been observed (Hairston et al., 2005; Hoffmann & Flatt, 2022; Holt, 1990), including the iconic Darwin's finches (Lamichhaney et al., 2018). Although sustained incremental evolutionary changes over long time periods are likely to be the normal tempo of evolution, instances of rapid change may be underestimated and could offer a more nuanced understanding of biological evolution as a whole (Bonnet et al., 2022).

The rate and pattern of species adaptation in response to climate change has become an important area of evolutionary research because it may help us assess the risks to biodiversity dynamics and anticipate preventative and/or mitigating strategies. Although recent research has shown that natural selection and adaptation in some instances may occur much quicker than previously thought, just how widespread this phenomenon is remains unclear. Therefore, research from the palaeontological deep past (e.g., Benton, 2009; Cohen et al., 2022; Tang et al., 2018) through to the present and immediate future (e.g., Thuiller et al., 2011) and from local to global scales remains ongoing.

This type of research is providing us with a greater understanding of how biodiversity might respond to climate change. Although it is tempting to hope that biodiversity will *'survive'* in one form or another due to rapid adaptation, and with-it humanity's fortunes, the jury remains out on whether this will be sufficient.

4. CANCER

One of the most rapidly growing areas in which evolution is having a direct impact on society is evolutionary medicine, which is now approaching a coherent discipline of study in its own right (Perry, 2021). Increasingly, our understanding of the causes and progression of both non-communicable and infectious diseases, together with their prevention and treatments, is being significantly informed by evolutionary knowledge.

Direct links can be made between disease and evolution because these systems are the result of evolutionary processes. Alternatively, such linkage may be indirect or analogous where an evolutionary perspective is used as a conceptual framework for studying and treating a disease.

Evolutionary medicine uses both approaches and is rich in opportunities to generate students' interest in evolution since both disease and medicine can have a direct personal appeal. Additionally, there are many practical problems and challenges to be solved with the promise of improving healthcare. The process through which normal cells are transformed into cancerous cells (oncogenesis) has been characterised and organised by scientists using a set of *'hallmarks'* (Hanahan & Weinberg, 2011). The overarching hallmark is that cancerous cells lose control over their cell cycle and proliferation leading to unchecked growth.

This occurs through the accumulation of mutations in the DNA of cells that make up organs and *'drive'* them towards cancer (Stratton, 2011). Cancer cells ignore the normal signals that control replication and division and thus divide when they should not. Furthermore, they ignore the signals that should stop replication. Additionally, normally when something goes wrong with a cell, there are systems that eliminate it (i.e., programmed cell death, also known as apoptosis). These self-elimination systems are largely ignored by cancerous cells. The result of uncontrolled cell division leads to the formation of large clumps of cells (tumours) within tissues that can then disrupt the normal functioning of the relevant organs.

Moreover, cancer cells can break off from a tumour and spread throughout the body to numerous distal sites (metastasis) where they form more tumours, which is another hallmark of cancer. Since tumour cells originate from the host itself, the normal immune responses that protect our bodies from foreign invaders find it difficult to recognise the cancer cells as foreign; thus, unchecked proliferation continues. As the disease progresses, there is an increasing risk of organ failure and death as a result.

Cancer is necessarily a phenomenon of multicellular organisms but does not affect all organisms equally. An evolutionary perspective has been used to investigate cancer prevalence among different animals in the hope that insights from this can inform treatments in humans (Merlo et al., 2006). From a non-evolutionary perspective, one would predict that the larger and longer-lived an organism is, the more likely it will be to develop cancer simply as a probabilistic inevitability of the number of cells it is composed of.

Although this is true for individuals within a species (e.g., Albanes, 1998), it was discovered that there is almost no correlation between body size or longevity and cancer susceptibility when comparing different species of animals (i.e., what has been called Peto's paradox (Caulin & Maley, 2011)). This paradox has been explained using an evolutionary perspective. If the above prediction were true, large animals would likely develop cancer frequently and could even die from it before they could grow to reproductive age. This would be a negative, or even toxic, fitness effect on the lineage and would thus be selected against.

Therefore, if natural selection is the explanation for Peto's paradox, one would expect that larger and longer-lived organisms would contain evolved mechanisms for either preventing cancer from developing in the first place or effective mechanisms for dealing with cancers once they do arise. Such mechanisms should provide useful insights for human oncology (Kattner et al., 2021).

This evolutionary perspective on cancer is starting to provide tantalising insights. For instance, there appears to be a positive correlation between the number of tumour suppressor genes and the size of animals. Tumour suppressors normally function in the cell in ways that help prevent oncogenesis; for instance, they are often DNA repair proteins.

Therefore, when a tumour suppressor gene is mutated and becomes dysfunctional, its protective function is compromised, leading to a higher probability of oncogenesis. Having multiple copies of these genes provides redundancy against mutation (Lynch & Conery, 2000), which appears to convey increased protection against cancer. Redundancy through the use of multiple gene copies is a concept known as evolutionary or mutational robustness and is an evolved strategy of many organisms (Masel & Siegal, 2009).

Apparent genetic redundancy correlating with body size and longevity has been observed with the pivotal tumour suppressor gene, TP53. The protein product of this gene, p53, helps control DNA repair, cell cycle regulation and apoptosis (Lindström et al., 2022).

Large organisms, such as elephants, have higher numbers of the TP53 gene when compared to humans, which may explain why they do not have elevated cancer rates as their size would suggest (Nuwer, 2022). This insight, among others, has led to increased research on the role of p53 and its potential as a therapeutic target for cancer. Some organisms appear to be curious exceptions to Peto's paradox. The most celebrated example is the naked mole rat (Heterocephalus glaber), which is the longest living of the rodents (up to a 30-year lifespan) and appears to not suffer from cancer, neurodegenerative diseases and a wide range of other illnesses (Pamenter & Cheng, 2022).

Due to these features, they have rapidly become a popular model system for researchers (and benefit from the *'appeal'* of their unusual appearance for teaching purposes!). Since the use of this novel model organism is in its infancy, it remains to be seen what useful discoveries will come from them. However, their unexpected ability to resist oxidative stress has already been suggested as a potentially useful research direction (Saldmann et al., 2019).

Evolutionary theory can also have a significant impact on our understanding of biological systems that are not, strictly speaking, the normal or familiar units of evolution (i.e., individuals, populations of individuals, species, etc.). The progression of cancer in the body on a cellular scale has similarities to evolution because the oncogenic mutations are passed on to descendant cells. Furthermore, the phenotypic characteristics of a cancer cell are determined by the particular set of mutations in the genome (i.e., the genotype) (Stratton, 2011).

Although this has been complicated by the discovery of epigenetic modifications (Kanwal & Gupta, 2012), the picture of heritable variations remains the same. Lastly, the fate of descendant cells is dependent on how well they survive and pass on their mutations (fitness). Therefore, a process with striking similarities to the natural selection of whole organisms is thought to occur within tumours.

Therefore, cancer cells can be viewed as distinct genetic lineages with complex histories of nested sub-populations within a tumour, akin to a phylogeny (Stadler et al., 2021). This evolutionary insight into cancer has led to a more sophisticated understanding of its progression and the distinctiveness of particular tumour types. Cancer cells are no longer thought of as a uniform whole from start to finish, but rather as nested lineages that accumulate different sets of mutations and thus characteristics as cancer progresses.

One of the main cancer treatments involves the use of anticancer drugs (chemotherapy). These medicines typically disrupt cell replication and or division and thereby aim to prevent the unchecked growth of tumours and/or prevent metastasis. Therefore, chemotherapy represents a threat to the cancer cell lineage, and as in a normal evolutionary process, this selection pressure weeds out the less fit, often resulting in the selection of new mutants that can resist the particular drug(s) in question (Hanahan & Weinberg, 2011). Cancer cells are aided in this by having hypermutable genomes leading to high genomic heterogeneity within a tumour (Stratton, 2011).

In addition to this, the lifespan of a tumour in terms of cell division (analogous to whole organism generations) is equivalent to hundreds of thousands of years or the span of a whole species, which allows plenty of opportunities for novelties to arise and be selected for (Fortunato et al., 2017; Johnson, 2021; Merlo et al., 2006). Furthermore, a small but important sub-population (less than 2%) of tumour cells are cancer stem cells, which were unknown until 1994. These cells have characteristics that allow them to survive chemotherapy and then renew cancer growth (cancer relapse) once chemotherapy has been discontinued (Nguyen et al., 2012).

An evolutionary perspective on cancer progression has led to innovative chemotherapy strategies that attempt to balance the selective pressure on cancer cells and prevent drug resistance from evolving (Aktipis, 2020). Rather than the traditional approach of attempting to kill all cancer cells as quickly as possible, adaptive therapy aims, somewhat counterintuitively, to manage the cancer by preventing the selection of more aggressive or drug-resistant cell types (Labrie et al., 2022).

Oncology is just one example where evolutionary understanding is making a direct impact on day-to-day medical practice and will only increase in its effects as time goes on.

5. COVID-19 AND INFORMED CITIZENSHIP

Cancer is a good example of a non-communicable disease whose origins, progression and treatment are being widely and productively investigated through the lens of evolutionary biology. Arguably more worthy of an evolutionary perspective is the wide range of infectious diseases. An evolutionary perspective is directly relevant to clinicians, allowing them to readily understand the origins, progression and treatments of infectious diseases.

However, with infectious agents, which are passed from one individual to another by definition, there is an added dimension of personal responsibility for the public at large. In addition to the desire to avoid being infected ourselves, we should also be interested in preventing the spread of infections from ourselves to others. This is the domain of good citizenship, which relates to how individuals behave for the greater good of the human population.

As of the writing of this chapter, the COVID-19 pandemic caused by the coronavirus, SARS-CoV-2, is still progressing globally. This pandemic will certainly go down in history as a major one due to the loss of life and the general harm it has caused. It has also been a truly unprecedented pandemic in terms of the global response and rapidly available breadth, depth and volume of information (and misinformation) about the disease, as well as its prevention and treatment. A significant problem for the public has been understanding the science behind the pandemic, which has directly informed the medical and public health interventions implemented by various governments (Strydhorst & Landrum, 2022).

At the very centre of public health strategies has been the evolution of this virus, though that is not always immediately apparent. Therefore, a better understanding of evolutionary processes by the public could arguably have resulted in better individual responses to the various public health interventions.

Once SARS-CoV-2 infected enough people and was declared a pandemic, the challenges related to controlling it, let alone the hope of eliminating it, increased exponentially. Of particular concern was predicting how the virus might evolve, take on different phenotypic characteristics and potentially escape our public health efforts and/or become a more damaging disease (Callaway, 2020). This is a quintessential evolutionary phenomenon in which a reproducing organism is placed under strong selective pressure.

A viral lineage will only continue if it can arrive upon a phenotype through mutations that makes it more fit (i.e., capable of maintaining or even increasing its number of offspring by propagating itself). Without the generation of mutations, there is no hope of a variant arising that can either escape the immune system (primed through either natural infection or vaccination) or become more transmissible, no matter which mechanisms effect this. A key to evolving is mutation and key to that is the replication of the genome. Accordingly, places or situations in which there are uncontrolled outbreaks of disease are ideal for the emergence of new mutations, some of which can be more dangerous than previous variants.

From the start of the COVID-19 pandemic, virologists and epidemiologists closely monitored the rate and diversity of mutations of the virus in as many dimensions as possible, an enterprise that was taken up to varying degrees in different countries but overall represents the greatest molecular surveillance effort in history (Oude Munnink, 2021). As predicted by evolutionary theory, it did not take long before viral variants arose (*'variants of concern'*), which had significantly different disease characteristics and impacts on health interventions. Many commentators argued that virulence would eventually decrease and thus called for the moderation of public health efforts. However, the argument that a pathogen will inevitably evolve into a less virulent form is a persisting hypothesis for which no evidence has been conclusively found thus far (Bull & Lauring, 2014). The only clear example where the natural evolution of virulence has been studied over time is the myxoma virus, which causes myxomatosis in rabbits (Alves et al., 2019; Kerr et al., 2017).

The path of this virus's evolution over many years shows that virulence is maintained and does not diminish. The fact that we are still living with many serious diseases that originated long ago in the past is also indirect evidence that pathogens do not inevitably become less virulent (Bull & Lauring, 2014).

Most viruses, and particularly viruses with RNA genomes, have high mutation rates during genomic replication (Domingo et al., 2021a). Therefore, every replication of the viral genome is an opportunity for a new mutation to arise. Within an individual cell and the host as a whole, a truly vast number of viral sequence variants typically arises; cumulatively called a quasispecies (Domingo et al., 2021b). Considering the vast number of genome replications that will occur within each infected host, it is likely that all possible sequence variants of SARS-CoV-2 have arisen multiple times during the pandemic. Therefore, it is only a question of probability that eventually one will spread to sufficient new hosts and become a new variant that spreads through the population.

Due to the probabilistic and evolutionary inevitabilities of variation and selection, the only way to prevent new variants from arising is to prevent replication. Although completely preventing replication is not possible (we currently do not have a sterilising vaccine), limiting it as much as possible through vaccination and appropriate behaviour (masking, social distancing, etc.) would limit the chances of variants arising and thus becomes an ethical imperative for each individual.

Appreciating this evolutionary context would arguably result in informed decisions about personal behaviour being easier to make. The moral of this story is that although diseases are inevitable, pandemics need not be inevitable in the age of vaccinations and other modern public health interventions.

6. CONCLUSION

The breadth, depth and volume of our understanding of evolution and its domains of influence are so large as to completely defy summarisation in a single book chapter. Evolutionary processes, outcomes and knowledge impact our lives in a virtually uncountable number of ways. Mostly, the systems impacted are evolved biological entities themselves; however, others are not and may benefit from evolutionary principles through analogy.

For instance, evolutionary algorithms, in which computer programs go through cycles of *'mutation'* and *'selection',* are an important methodology in computer science (for an overview, see Sloss & Gustafson, 2016). Another example is phylogenetic methods being used in linguistics and literary analysis to investigate how languages and texts have *'evolved'* (e.g., Barbrook et al., 1998). Some impacts of evolution are far more obvious and comprehensible than others, thereby serving as good inspiration for educators and learners. Other impacts are subtle and lie hidden from casual consideration.

The challenge for the teacher is to identify engaging contexts and real-world examples for the topics being taught that will work best for their particular students.

For further inspiration and broader coverage of this topic, see Oldroyd (1983), Losos and Lenski (2016) and Johnson (2021).

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Chapter 6

Evolution education and outreach - important things to know about how to teach about evolution

CHAPTER 6

Evolution education and outreach - important things to know about how to teach about evolution.

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Abstract:

Although evolution is widely acknowledged as one of the most valuable scientific theories, it is also one of the most challenging subjects to communicate and teach effectively. This chapter provides a brief overview of some of the most significant topics relevant to effective teaching and communication about evolution. These topics include worldviews, the nature of science, the language of evolution, cognitive biases and misconceptions, reasoning about evolutionary phenomena, cases and curricula, pedagogical practices, and assessment and learning. Since the breadth of prior work is extensive, readers are encouraged to use this chapter as an entry point into the rich literature on evolution education.

KEYWORDS

evolution, teaching, misconceptions, curriculum, pedagogy

INTRODUCTION

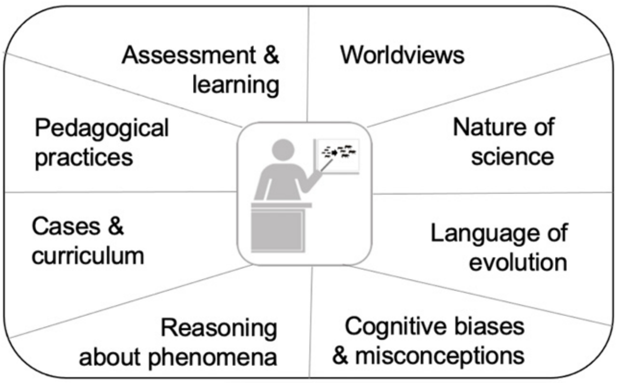
Although evolution is widely acknowledged as one of the most valuable scientific theories (Mayr, 1994; U.S. National Research Council, 2012), it is also one of the most challenging subjects to communicate and teach effectively. Hundreds of studies have documented a variety of sociocultural, linguistic, cognitive and epistemic factors that impact evolution understanding and acceptance (Figure 1).

Far fewer studies have integrated this expansive body of work or leveraged it to design interventions to help students and citizens overcome these obstacles and develop deep evolutionary understanding.

As such, addressing as many of the aforementioned factors as possible is likely to enhance outcomes. While much in evolution education remains to be known and accomplished, one unambiguous conclusion from prior research is that a robust understanding of human thinking and reasoning about the science of evolution—not just knowledge of evolution—is essential.

This chapter provides a brief introduction to some of the core challenges and solutions for teaching and communicating evolutionary ideas.

Figure 1
Major factors impacting effective evolution education and outreach (note: this figure is organised like a clock, with worldviews as the starting point).



WORLDVIEWS

Globally, religion is inextricably interwoven with culture, identity, family and personal epistemology. Therefore, religion must be considered when teaching or communicating about evolution. This consideration does not necessarily have to involve conflict.

Although it is easy to perceive controversy when it comes to evolution and religion, we agree with the suggestion of Reiss (2019) that there is a more fruitful way to approach this relationship: to think of it as a sensitive rather than a controversial topic. Despite the lack of controversy among scientists about the facts of evolution, it makes many people feel uncomfortable because they perceive that it challenges their worldviews, with some even thinking of evolution as a nihilistic idea that deprives human life of deeper meaning.

Therefore, evolution should be approached as a sensitive topic. Such an approach requires respect for students' worldviews and a careful discussion about how evolution is not inherently atheistic or irreligious per se. There are numerous examples of people who have managed to accommodate both religion and evolution.

Notably, studies from the USA and beyond have found that approximately half of the scientific community adopts some form of religious affiliation (Ecklund et al., 2019). An effective way to engage with worldviews is to avoid conflict narratives and begin by presenting the evidence just cited about scientists and their religious affiliations. Once students realise that they do not have to feel threatened by evolution, they will be more likely to consider the science itself without worrying about its implications. This should be done to respect students' beliefs and to refrain from distracting them from the scientific concepts themselves. For some, evolutionary theory does have implications for worldviews. However, this is dependent on the inferences one draws from the theory, not the theory itself. Therefore, we suggest that such implications should be left out of any discussion until the scientific content is presented.

An analogy with morality may be useful for introducing the limits of science. Consider the termination of pregnancies for medical or other reasons. Science can tell us what happens in the fertilised zygote, in the implanted embryo and when the development of the nervous system begins.

But whether an embryo should be considered a human being or not, and whether it has rights, is not a decision that can be made on scientific grounds alone. Science generates facts about phenomena that occur at each of these developmental stages. Which of these we consider a rights-bearing living entity is a decision that can be informed by such facts but cannot be made based on them alone. Other philosophical considerations are also important.

Although moral decisions can be enriched by science in various ways, science cannot guide them because decisions about what is bad or wrong are made on a culturally/socially shared subjective basis. Overall, engaging with worldviews is an essential first step in evolution education and outreach because it can serve as an effective approach for reducing conflict and clarifying common misunderstandings (e.g., evolutionary biologists cannot be religious, or science answers all questions).

NATURE AND PRACTICE OF SCIENCE

In public debates about evolution, if one looks closely at the arguments of anti-evolutionists, it becomes evident that much of the debate is not about evolution per se but about the nature of science itself: how science works, what kind of questions it can answer and how these answers are developed. For instance, a common argument against evolution is that it is *'just a theory'* (Miller, 2008).

This reflects a common confusion about the meaning of the word *'theory'* in everyday life and in science. In everyday language, the word *'theory'* refers to a hunch or speculation, whereas in science it refers to the most robust set of principles and models that scientists can use to arrive at explanations and predictions. Therefore, in such cases, anti-evolutionists must understand the structure and nature of scientific theories in general. Only once they do so might they be able to realise the many virtues of evolutionary theory (Kampourakis, 2020a).

Another example relates to the reasoning processes of scientists. Creationist Ken Ham argued in a debate with Bill Nye *'the Science Guy'* that the battle between evolution and creation is about interpretations of the same evidence. However, this is not accurate. In some cases, evolutionists and creationists do look at the same data and interpret them differently. However, their methods of doing so are strikingly different.

Creationists approach the data with predetermined conclusions (e.g., whatever religious documents suggest is true) and look for evidence to support these conclusions. When the data do not fit their conclusions, they find ways to make them fit or dismiss them altogether. This is not what scientists do. Instead, scientists do not have pre-determined conclusions. Although they may have hypotheses that they could test, and should be open to rejecting or modifying them if they are not supported by the available data, scientists arrive at conclusions based on the evidence they have. In short, for scientists, it is the conclusion that must fit with the evidence, not the evidence that must fit with the conclusion (as is the case for creationists). Scientists are prepared to dismiss long-held theories if their growing understanding of nature reaches a point that these theories can no longer hold.

Another aspect of the nature of science relates to the explanatory practices of scientists. They are interested in explaining phenomena in the natural world, which is the realm of science. Whenever they fail to do so, anti-evolutionists often invoke quasi-scientific arguments involving God—a reasoning pattern that has been described as *'God in the gaps'.* However, the explanatory aims of scientists differ in an important way.

Scientists attempt to explain nature alone, which includes the entities and phenomena in the natural world, but not those outside it (i.e., the supernatural). Notably, science is a method of studying nature (known as methodological naturalism). Whilst this perspective does not deny the existence of the supernatural, it nevertheless recognises that one cannot study it. Consequently, there is no reason to use science to study it. Science is certainly concerned with the metaphysics of nature (i.e., the causes of natural phenomena).

This stands in contrast to the view described as metaphysical naturalism, which is also known as philosophical or ontological naturalism. These perspectives suggest that only natural entities exist, thus denying the existence of anything supernatural. This is the kind of argument that often confuses (and frustrates) anti-evolutionists; however, it is not an argument that most scientists make. The perspective that only natural entities exist is a view that characterises scientism, not science.

Scientism argues that the explanatory scope of science is not limited to the realm of the natural world and that science is the only way of knowing in general (see also Kampourakis, 2020a, Ch. 7).

In summary, addressing the nature of science is an essential early step in evolution education and outreach.

THE LANGUAGE OF EVOLUTION

Language is the primary means through which scientific ideas have been communicated and transmitted throughout history (Rector et al., 2013). Like other scientific fields, evolutionary biology has a language of its own. Although some terms are unique (e.g., autapomorphy), many others are not and have scientific meanings that differ from everyday meanings (e.g., fitness, adaptation, mutation, theory).

For example, although biologists consider mutations to be randomly occurring genetic changes that can be neutral, beneficial or detrimental to an organism, in common use, the term mutation is often envisioned as a visible, harmful monstrosity at the phenotypic level. Moreover, fitness is often associated with physical health and strength as opposed to the number of offspring surviving and reproducing in the next generation.

Navigating the many meanings of terms like these makes effective communication challenging, particularly when multiple terms are used together in teaching or conversation. The situation is made much more challenging when teachers and scientists switch back and forth between *'everyday'* and scientific meanings (Betz et al., 2019). Assuming *'they know what I mean'* is a common mistake made by teachers. Simply put, language must be deployed carefully and addressed explicitly in evolution education and outreach.

Two general approaches may be used to address this challenge. First, learners can be introduced to evolutionary ideas and concepts using non-technical language that does not overlap with technical terms. This minimises interference with prior knowledge and definitions. Only after concept understanding is achieved is the scientific term attached to the concept.

For example, rather than introducing *'natural selection'*, teachers can explore many aspects of object sorting and the patterns that result from it (e.g., sorting objects with and without a blindfold, sorting for one feature but finding that another feature piggybacked along with it). Thus, one's understanding of different sorting processes and patterns can subsequently be tied to evolutionary terms and concepts (e.g., natural selection, genetic drift). A second approach lays out the linguistic challenges prior to any instruction or communication. In this approach, learners are explicitly informed of the dual meanings of evolutionary terms and how they differ in everyday and scientific contexts (Table 1).

Testing for the understanding of language mastery is crucial in any approach. Ambiguity *'alerts'* must also be made repeatedly during communication. In this regard, evolution educators have much to learn from foreign language teachers.

Table 1
Common and problematic terms that must be explicitly addressed prior to and during evolution education and outreach.

Word	Everyday meanings that must be distinguished from scientific meanings
Mutation	Visible, harmful deformity or monstrosity at the phenotypic level. Must be contrasted with invisible variants that can be harmful, neutral or beneficial depending on various factors.
Fitness	Physical fitness, strength and outward phenotypic health. Must be contrasted with reproductive output (i.e., the number of individuals or genetic contribution to the next generation).
Adapt/ adaptation	Gradual acclimation or adjustment by an individual to a circumstance and the end point of a period of adjustment. Must be contrasted with population-level changes in the distribution of variation caused by natural selection. Emphasising what the environment can and cannot cause is also helpful here.
Selection	A conscious 'selector' making an intentional choice among entities. Must be contrasted with non-intentional sorting due to differential survival and/or reproduction (e.g., by abiotic conditions).
Natural selection	Multiple ideas (e.g., 'adapting to environmental change', 'survival of the fittest') that do not conform to the tripartite scientific theory (i.e., variation + heredity + differential survival/ reproduction).
Environmental pressure	The 'force' that causes evolutionary change, including phenotypic and genetic differences. Must be contrasted with what the environment can and cannot cause (e.g., the environment cannot typically cause heritable mutations or new phenotypes).
Evolutionary theories	The guesses and speculations intrinsic to a field that cannot establish any 'facts' or know 'what really happened' (see also Nature and Practice of Science above). Must be contrasted with robust, tested and evidence-based explanations that have held up to intense scrutiny.

The media and popular culture exacerbate this challenging situation. For example, individual cartoon characters and superheroes *'evolve'* and *'mutate'*, whilst viruses *'adapt to try to evade immune systems'*, representing everyday discourse that works against scientific understanding. The average person is bombarded with evolutionary language that is discordant with scientific meanings and scientific understanding.

There are at least two key elements that one should keep in mind when considering popular culture representations of evolution. The first element is that evolution is a process of change that occurs at the population level and not at the individual level. Individuals cannot evolve new features; instead, populations evolve because of the variation in the characteristics of their individuals and differential survival and/or reproduction through natural processes.

The second element is that this process of differential survival and/or reproduction is an unconscious, unintentional process that may lead to adaptation but also extinction. Understanding these two key elements is necessary for avoiding some common misunderstandings that often result, some of which are reviewed below.

COGNITIVE BIASES AND MISCONCEPTIONS

Evolution is not simple or easy to understand, with claims to the contrary not being based on evidence. One must grasp many different fundamental biological concepts to be able to understand evolution. Evolution is also counterintuitive since it goes against our everyday intuitions about the natural world. Therefore, engaging with intuition is a necessary component of effective evolution education and outreach.

Consider the following example: ask anyone the simple question '*Why do birds have wings?'* The intuitive response most would give is *'To fly'.*

This is a rational and reasonable response because many common birds, such as pigeons, hawks and crows indeed use their wings to fly. However, if one thinks more carefully about this, examples of birds that do not use their wings for flight come to mind (e.g., swimming penguins and running ostriches). Therefore, the intuitive response, *'To fly'* to the question *'Why do birds have wings?'* does not work for all birds.

Now consider aeroplanes. When asked *'Why do aeroplanes have wings?'* all would answer *'In order to fly'.* What is different in this case? Since aeroplanes are artefacts designed by humans for the sole purpose of flight, their parts serve this exact purpose. Of course, there exist other aircraft that fly without wings, such as helicopters. However, when it comes to aeroplanes, there is no exception.

All aeroplanes have wings in order to fly because this is what they were designed for. This is not the case for birds, which have not been designed but are rather the products of natural evolutionary processes. This is a distinction that is not immediately apparent to many. Since we are surrounded by artefacts in our everyday life experiences from a very early age, we could become accustomed to intentional creation for necessary functions and the existence of parts to serve particular roles. Applying *'artefact thinking'* to organisms could be a result of this scenario.

Therefore, evolution education and outreach require attention to the distinctions between artefacts and organisms. Artefacts have fixed essences that relate to the purpose they are intended to serve, whilst organisms may have developmental essences that result in relatively consistent outcomes (e.g., the adult phenotype of each species); however, there is always variation that serves as the raw material for evolution. All parts of artefacts serve a specific role. In contrast, this is not the case for all parts of organisms. Moreover, those parts of organisms that do serve a function are the outcome of evolution by natural processes (not by design).

Thinking about the parts of organisms as if they were parts of artefacts is the result of particular cognitive biases or intuitions—spontaneous ways of thinking that in turn form obstacles to a scientific understanding of phenomena. Two very important biases are design teleology and psychological essentialism. These can be interpreted as stemming from our understanding of artefacts, which have fixed essences (essentialism) because they are designed to serve a purpose (design teleology).

These intuitions can lead to thinking about the features of organisms in the same manner (i.e., their unchanging parts are designed for a purpose).

These cognitive biases make the idea of evolution counterintuitive. Table 2 summarises cognitive biases that are relevant to teaching and communicating evolutionary ideas.

Table 2
Cognitive biases to consider when teaching and communicating about evolution.

Cognitive bias	Description and relevance to evolution
Design-based reasoning	An external agent (e.g., God, nature) guides the evolution of individual organisms towards a particular end so that they change to be able to survive. This idea is flawed because it assumes that an agent external to organisms themselves has designed them or their futures.
Intentionality	Individual organisms undergo modifications because they have particular intentions that have to be fulfilled. This is a flawed idea because the will of organisms or their wishful thinking (if they have any) cannot influence the course of their evolution. However, this does not mean that the intentions of organisms are irrelevant. Organisms have intentions (eat, mate, etc.) that are expressed in their behaviour, which might affect the course of their evolution—but not a specific, desired evolutionary end.
Essentialism	Individual organisms have fixed species essences and cannot undergo significant modifications, which makes evolution impossible. The problem here is that the robustness of development (e.g., a pig embryo will develop into a pig and not a dog) makes people think that there are essential species properties due to species essences that cannot change. However, even small changes in development can bring about large changes in adult forms, which can result in evolution.
Need-based reasoning	Individual organisms unconsciously undergo modifications to fulfil their needs in a particular environment and thus survive. This idea is flawed because any favourable traits emerge by chance and not because organisms need them. This is why the majority of species that have lived on Earth have gone extinct.

Misconceptions about evolution are also important (see Gregory, 2009 for a review). Whilst these may be due to the aforementioned cognitive biases, they may also be due to misunderstandings. In general, all the knowledge that we have takes the form of concepts, which are mental representations of the world. Scientific concepts, such as those related to evolution, are systematic representations of entities and phenomena that scientists use in their explanations and predictions. For any concept, it is natural for people to form different conceptions.

For example, although there is a dog concept, the conception of a dog that each one of us has may be different. When it comes to science, it is natural to form conceptions of phenomena and entities before we are taught about them since we encounter them in everyday life (consider a *'plant', 'animal', 'microbe,'* etc.).

These are described as preconceptions. When these are inaccurate, they are described as misconceptions. Ultimately, teaching aims to address these misconceptions and destabilise them for students to restructure them and adopt scientifically legitimate conceptions (Kampourakis & Nehm, 2018).

A requirement for this is that students are brought into conceptual conflict situations in which their conceptions are contrasted to the concepts and taught in a manner that helps them realise that the latter are more accurate than the former. Table 3 summarises some common misconceptions that must be explicitly addressed when engaging in evolution education and outreach. Pedagogical approaches for addressing these misconceptions are discussed in the section on pedagogy.

Table 3

Misconceptions commonly held by students and the general public. These are often combined with one another or with normative ideas to produce 'mixed' ideas (normative + non-normative).

Misconception	Brief description of misconception
Use or disuse of traits is a causal factor central to evolutionary change.	The lack of utility of a trait is a direct cause of the decrease or loss of a trait over generations, or, conversely, the utility of a trait is the direct cause of an increase or addition of a trait. The use/disuse idea is often linked to the inheritance of acquired characteristics (see below).
Traits acquired during a lifetime are inherited and passed on to the next generation.	The character states of the traits of individuals, populations or species acquired during their lifetimes are commonly inherited and passed on to the next generation. This misconception interferes with the scientific concept of adaptation.
Environmental pressures are a direct cause of difference, change and/or evolution.	Environmental pressures (i.e., changes in the intensity or type of environmental condition) 'force' or directly cause living units (i.e., individuals, populations and species) to change their genetics and/or phenotypes. This idea is often a product of scientists using 'shortcut' language involving pressures causing changes. This idea is also linked to inappropriate teleology.
Acclimation or simultaneous adjustment of all biotic units to change.	Gradual adjustment by units (i.e., individuals, populations and species) to the environment is a pattern explained by the incorrect processes of trait use/disuse, acquired inheritance and/or environmental pressures (rather than by the differential sorting of heritable variants).

REASONING ABOUT EVOLUTIONARY PHENOMENA

The central aims of evolutionary biology include documenting patterns of evolution and building explanations for them. Documenting evolutionary patterns is complex and painstaking work that can take decades. Most students and citizens engage with evolution through the exploration of the following previously documented phenomena: patterns of change within a taxon (e.g., SARS-Co-V2 over a year), patterns of change in a larger lineage (e.g., non-avian dinosaurs and modern birds over millions of years) or patterns of change in phenotypic traits across many lineages (e.g., monogamy across mammal clades). Discussions often centre on what caused these patterns (e.g., Why did the new variants of SARS-Co-V2 documented by biologists start appearing?).

Therefore, our discussion of education and outreach focuses on thinking about previously documented evolutionary phenomena (e.g., patterns) rather than the scientific approaches used to generate them. Cognitive biases and misconceptions (see above) are not the only factors impacting reasoning about evolutionary phenomena.

Although the remarkable diversity of evolutionary phenomena is what gives evolution its widespread appeal, recent studies have shown that such diversity is a ‘double-edged sword’ when it comes to promoting evolutionary understanding (Nehm & Ha, 2011). Although many factors come into play when thinking about evolution (e.g., knowledge, cognitive biases, misconceptions, representational competencies), the types of ideas that are used to make sense of situations are not randomly evoked; instead, they depend quite heavily on the features of the cases in question (Figure 2).

Students tend to focus their attention on the unique, observable features of such cases and, as a result, knowledge retrieval from memory is driven by these features rather than by fundamental (often unobservable) causal principles (e.g., extensive heritable variation produced via mutation, differential reproductive success). In other words, the unique features of each example tend to eclipse thinking about general causal processes in living systems.

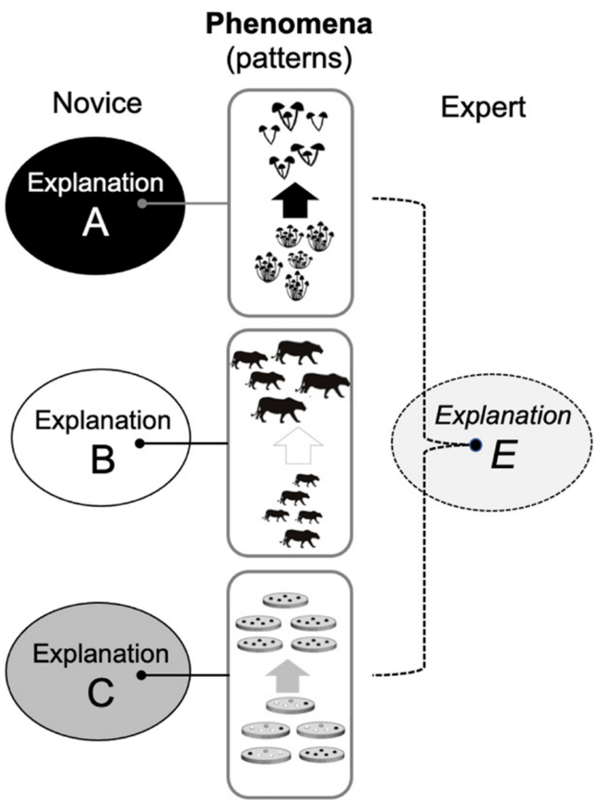
The result is that separate and unique explanations are constructed for each type of evolutionary example or phenomenon (Figure 2). For novices, the functional and ecological consequences of peppered moth colouration appear to have little in common with bacterial susceptibility to the drugs manufactured to kill them. Yet, both cases are explained in part by the differential survival of hereditary phenotypic variants produced by random genetic processes. Notably, understanding evolutionary phenomena requires the integration of causal and concrete elements.

One approach to addressing this challenge is to help students balance specificity, generality and causality when thinking about evolutionary phenomena or patterns. The first step in this approach (known as *‘cross-case comparison’)* involves creating pairs of evolutionary phenomena or patterns that differ in their concrete features (e.g., lactase persistence in humans vs. the loss of tusks in elephants; Darwin’s finches’ beak thicknesses vs. the loss of thorns in blueberry plants).

Rather than teaching cases sequentially or having students build explanations for a single case, students should work collaboratively to simultaneously identify the salient biological and causal similarities and differences between two cases (Nehm, 2018).

In general, learners have an easier time finding differences than similarities; thus, this step should come first. Many students will only *‘see’* superficial aspects of the cases (‘one is a plant and the other is an animal’, *‘one lives in location X and the* *other in location Y')* that often have little to do with causation and hence explanation. Pushing students to consider differences at a deeper level is often required.

Figure 2
Novice and expert reasoning about evolutionary phenomena.



Many superficial or concrete features of evolutionary problems (e.g., plant thorns, animal fur colour, lactase persistence, antibiotic resistance) activate different suites of conceptions and misconceptions during novice problem solving (Nehm, 2010; Nehm et al., 2012). A student may utilise misconceptions (e.g., evolutionary pressures cause mutations in response to the needs of the species) in one situation, and normative ideas in another (e.g., existing variation in a population was sorted and only some individuals survived). Sensitivity to evolutionary problem features is associated with idiosyncratic knowledge activation and the generation of multiple solutions to what experts consider the same problem (Nehm & Ridgway, 2011).

An important next step is to ask students to consider whether the features of the phenomena or patterns that they have identified relate to biological causes (e.g., *'Which of the differences that you have identified are of a causal nature?'*). This is not only an opportunity to discuss the nature of science in general but also to emphasise that causation is an essential feature of explanation. This is the point where students should begin to realise that there are few biological causes unique to a single phenomenon or pattern. Summaries of the differences—both superficial and deep, causal and noncausal—that student groups (or individual students) identify can be presented in a worksheet, group whiteboard or class chalkboard and discussed as a class.

Once the differences between cases have been identified and discussed, it is time to begin exploring similarities between the evolutionary phenomena or patterns. These similarities might encompass basic features (e.g., *'They have cells and use oxygen to metabolise food.'*) or more advanced ones (e.g., *'Heritable mutations constantly occur in both cases and can cause differences in the proteins that form parts of their phenotypes.'*). Guiding questions can also support thinking; for example, *'Do genetic differences among individuals relate to phenotypic differences in both cases?', 'Do endless resources and habitats characterise both cases?'*. Similarities across evolutionary phenomena or patterns should be summarised in parallel ways to the differences identified in the first part of the exercise.

Once the similarities and differences between the cases have been identified and discussed, the more challenging work of connecting process and pattern begins (e.g., the processes causing patterns of elephant tusklessness, or processes causing lactase persistence in humans).

This step will require scaffolding tools, such as lists of possible (normative and non-normative) ideas for students to discuss and evaluate as potentially relevant to both evolutionary situations. For example, since need-based explanations are commonly used by students (Table 2), they could evaluate the degree to which *'needs'* could explain the biological patterns in the two cases. Would the lack of food in a human population, as well as an associated need to consume and digest milk, impact the frequency of individuals with lactase persistence? How would this happen? Would poachers that differentially seek out elephants based on their phenotypes, as well as the elephants' need to lack tusks, cause individual elephants to lose them? A variety of causes could be evaluated as contributors to the patterns documented in the cases.

Scaffolding can also promote normative ideas (e.g., *'Do mutations occur in humans and elephants?', 'Do mutations contribute to phenotypic differences in humans and elephants?', 'How does that work?', 'Do phenotypic differences impact survival in humans and elephants under certain environmental conditions?').*

Cross-case comparisons must emphasise the similarity of process (e.g., mutation and genetic recombination generate large quantities of heritable variation; variation in genomes relates to variation in phenotypes; variation in phenotypes impacts competition for mates and securing resources) and dissimilarity of pattern (e.g., elephant tusk distribution, lactase persistence patterns). Evaluating potential causal contributors to different evolutionary scenarios focuses attention on how patterns might relate to processes.

The method of engaging students with multiple evolutionary phenomena or patterns and then gradually fading cognitive scaffolds (e.g., summary tables with similarities, differences and their causal natures) provides a test of preparation for future learning (i.e., '*Can students reason effectively about novel evolutionary patterns and phenomena?').* Using contrasting cases provides an opportunity for students to build abstract and causal models of evolutionary change that transcend specific cases.

This helps to address the well-documented fragmentation and context specificity of novice evolutionary reasoning (Nehm, 2018). This approach will help to counteract the largely unproductive approach in schools and outreach programmes of presenting interesting single cases (or in some cases, sequential ones) in detail.

Students and citizens must be prepared for making sense of future evolutionary phenomena or patterns.

CASES AND CURRICULA

Employing interesting and relevant examples to illustrate evolution principles and practices is an important feature to consider when designing an evolution curriculum.

All too often, students learn about the same examples during their secondary and university education (e.g., Darwin's finches, peppered moths). The types of evolutionary examples are a central consideration because (i) students have difficulty reasoning across evolutionary examples and about novel evolutionary phenomena (see above), (ii) students often view evolution as personally unimportant, uninteresting or useless (Heddy & Sinatra, 2013) and (iii) the perceived utility of evolutionary topics is strongly associated with evolution acceptance (Borgerding & Kaya, 2022).

Recent work has explored what evolution topics students find interesting and reported that the evolution of HIV, avian flu and bacteria is viewed as more interesting than the evolution of humans (e.g., lactase persistence, high altitude adaptation) and other animals (e.g., elephants, fish, sheep; Jördens & Hammann 2019). Aligning the curriculum with student interest could increase students' motivation to learn about evolution.

The curriculum should also consider perceptions of the utility of evolutionary phenomena. Borgerding and Kaya (2022) studied the utility value of evolution learning topics and found that microevolutionary examples (e.g., disease transmission, genetic variation, antibiotic and pesticide resistance) were viewed as more useful than macroevolutionary examples (e.g., the relatedness of particular organisms and coevolution). Notably, maximising interest and usefulness is an important feature of curriculum design. Prior to discussing the specifics of the evolution curriculum, it is valuable to step back and consider how curriculum design should be envisioned in the first place.

Many countries have been working to shift their science curriculums away from focusing on large amounts of factual information and towards learning about fewer core ideas in greater depth (i.e., '*less is more'*).

In the United States, for example, the fundamental ideas that deserve the greatest focus are termed disciplinary core ideas (DCIs). DCIs are valuable because they help to make sense of a wide array of natural phenomena. However, effective engagement in the natural world requires much more than knowledge.

Students and citizens must understand the approaches, principles and frameworks that scientists use (along with DCIs) to make sense of natural phenomena (see also Nature of Science above). Such knowledge-building approaches (e.g., making observations, developing models, engaging in arguments about evidence and building explanations) are called 'science practices'. Science practices are the approaches that scientists across many disciplines have found to be essential for sense making. In addition to DCIs and science practices, scientists also make use of general ideas known as *'cross-cutting concepts'* (CCCs) to structure their work. For example, these include framing phenomena in terms of their pattern, structure-function, and cause and effect.

Three-dimensional learning (e.g., DCIs, science practices, CCCs) provides the tools for helping people make sense of and explain phenomena. Although the evolution curriculum should encompass all three aspects (Figure 3), this is often not the case.

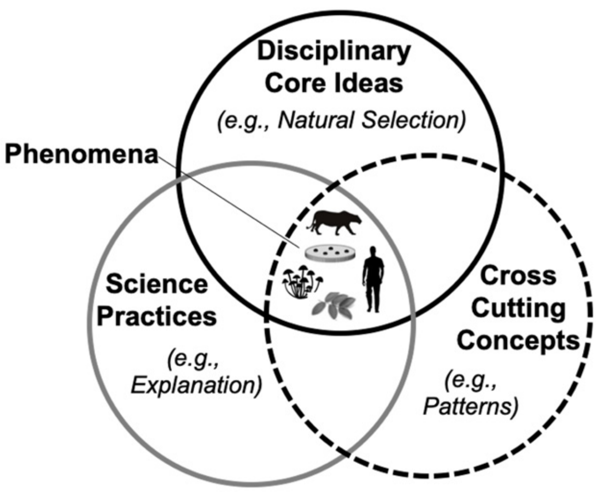
Unfortunately, there is considerably less research exploring how thinking about evolution intersects with science practices and CCCs. This raises the following questions: What do students think a meaningful evolution explanation should include? How do cognitive biases and misconceptions impact argumentation practices (and vice versa)?

Can students identify the salient features of an evolutionary pattern? To a large extent, the evolution curriculum in many countries has focused too heavily on the outputs of science (e.g., natural selection, phylogenies, extinction) at the expense of knowledge building competencies (e.g., how to approach explaining an evolutionary pattern, how to build a robust evolutionary explanation, how to establish a cause for an evolutionary pattern). Prior research suggests that fostering knowledge building competencies is a challenge.

For example, we know that students favour descriptions over causal explanations when engaging with evolutionary phenomena, that recognising the salient features of patterns when building explanations is a struggle and that argumentation too often lacks articulation with evidence.

A synthesis of prior findings in evolution education using a three-dimensional learning lens is needed alongside more curricula focused on teaching evolution using this approach.

Figure 3
DCIs, science practices, and CCCs. Three-dimensional learning, as exemplified by the US Next Generation Science Standards (NGSS), encompasses DCIs, science practices and CCCs. These three strands of science are used as an integrative framework for exploring phenomena in the natural world. In other words, these tools allow students to engage in science, not just learn about the outputs of science.



PEDAGOGICAL PRACTICES

Active engagement in the learning process (e.g., collaborative learning, active learning) is a general pedagogical approach known to be effective for many science disciplines (Freeman et al., 2014). Interestingly, large-scale studies have raised questions about whether active learning by itself can promote evolutionary understanding (Andrews et al., 2011) and whether explicit attention to misconceptions in active learning settings is the essential element (Nehm et al., 2022). In addition to active learning and explicit attention to misconceptions, many other pedagogical approaches have been proposed (see Table 4).

Many of these approaches on their own have shown promise in small-scale studies. However, combinations including multiple strategies will likely generate the greatest impact. Despite the absence of robust, large-scale, evidence-based guidelines to inform pedagogical practices for teaching evolution, it is important to emphasise that understanding student thinking and reasoning about evolution is a prerequisite to any pedagogical implementation.

Many studies have shown that teachers are unable to identify limitations in students' evolutionary reasoning and often harbour misconceptions themselves (e.g., Hartelt et al., 2022).

Table 4
Pedagogical approaches for addressing misconceptions.

Pedagogical approach	Description of how to address misconceptions
Direct instruction	Explicit discussion of misconceptions and why they are inaccurate in evolutionary contexts (e.g., Nehm et al., 2022).
Cognitive conflict	Present examples or situations that contradict expectations or cannot be explained by current mental models or misconceptions (e.g., Kampourakis, 2020b).
Metacognitive strategies	Introduce metacognitive opportunities for students to reflect upon, regulate and apply ideas across everyday and scientific situations (e.g., Gonzalez Galli et al., 2020).
Metaknowledge discussions	Foster the development of metaknowledge about types of explanations in biology and evolution (e.g., functional and mechanistic) (e.g., Trommler & Hammann, 2020).
Historical examples	Discuss how scientists previously struggled with the same concepts and illustrate how science helped to resolve confusing phenomena (e.g., trait loss) (e.g., Kampourakis & Nehm, 2018).

ASSESSMENT AND LEARNING

Having clear learning objectives and assessing them is of critical importance to effective teaching, with evolution education being no exception.

The first consideration when thinking about assessment is identifying what learners should know and be able to do with their knowledge after instruction is complete; in other words, education should always begin with the end in mind. Given that the curriculum should seek to foster growth in proficiency in the language of evolution, the nature of science and three-dimensional learning (DCIs, science practices and CCCs) across a variety of evolutionary case examples, what forms of assessment can be used to measure learning, and what pitfalls should be avoided?

Partly due to the rich information they generate about student thinking and reasoning, written explanations of evolutionary patterns have been used as an assessment approach for more than 30 years (e.g., Bishop & Anderson, 1990; see Ha & Nehm, 2018 for a review). Explaining patterns of change is also a realistic and authentic activity because most citizens will engage with patterns of biotic change at some point.

As new viruses evolve, new organisms are seen, new fossils are found, new taxa are named and new evolutionary phenomena are documented, people will try to make sense of these patterns (i.e., explain them). The COVID-19 pandemic is a case in point.

The general public's (and students') weak understanding of this phenomenon is reflected in common questions: Why did a new virus evolve? Why do new variants of the virus keep appearing? When will the virus stop changing? Of course, evolutionary change is the norm and it never stops occurring. Being introduced to Darwin's finches and peppered moths in secondary school has clearly not instilled abstract, generalised evolutionary understanding that extends beyond these cases.

One outcome of evolution education and outreach should be to prepare citizens for future learning. As such, it is as important to be able to make sense of future patterns as it is to make sense of those that one has been taught. The Assessment of Contextual Reasoning about Natural Selection (ACORNS) instrument (Nehm et al., 2012;

see www.evograder.org) was designed for this purpose. Specifically, the instrument was developed to help teachers and researchers understand thinking across a variety of scenarios, including different lineages (e.g., animals, plants, fungi), different trait polarities (e.g., loss vs. gain), different trait and taxon familiarities (porcupine vs. prosimian), different scales (within- vs. between-species) and different trait functions (e.g., colouration vs. locomotion).

Different types of patterns provide educators with information about how prepared learners will be when encountering new cases in the future. ACORNS results often show that students lack a robust model of evolution that generalises across phenomena.

This is a significant problem if we wish to prepare students for future discoveries and societal challenges. Other assessment formats (e.g., multiple choice) are more effective at determining whether students have mastered particular pieces of evolutionary theory. Explanation tasks assess the integration of understanding that reflects real-world applications.

Determining whether students have learned evolution is a remarkably complex process due to the factors discussed above. For example, if students lack a robust understanding of the nature of science (e.g., what questions science is best able to answer and those it is not), students may misunderstand what belongs in a science class and what types of knowledge are suitable for an explanation of evolutionary events (e.g., the origin of a new virus or disease). If students are confused about the

Table 5

Examples of possible assessment targets and associated learning objectives. Different assessment formats (e.g., true-false, multiple choice, open-ended writing, oral communication) can be used to measure proficiencies.

Assessment target	At the end of evolution instruction, students should be able to…
Nature of science	…explain the boundaries or limits of science; refute common misconceptions about evolution and religion and the nature of science; illustrate how science practices are used to generate evidence-based understanding; differentiate everyday and scientific meanings of nature of science words and terms.
Language of science	…differentiate everyday and scientific meanings of evolutionary terms; use evolutionary terms accurately in scientific communication; identify ambiguous evolutionary language in a newspaper or online source and rewrite the news story to accurately reflect evolutionary concepts.
Evolution knowledge (e.g., core ideas)	…refute common misconceptions about evolutionary concepts and theories; explain how both random and non-random processes impact evolutionary phenomena; explain why environmental change is not necessary for natural selection; explain the role that mass extinctions play in the evolution of life on Earth.
Science practices	…build a single causal model lacking misconceptions that explains several novel evolutionary phenomena or patterns; construct a written scientific argument that integrates claims, evidence and reasoning about the sources of evidence most relevant to an explanation of an evolutionary pattern; develop a scientific explanation for a novel evolutionary phenomenon.
Cross-cutting concepts	…use a previously developed phylogeny to document patterns of character state changes in lineages; be able to identify cause and effect relationships in an evolutionary phenomenon.

dual meanings of evolutionary terms, it will be difficult for them to understand what is being asked in an assessment question. If students are presented with a question about a single evolutionary scenario, it will be impossible to know whether they can use their knowledge to tackle another. If students are administered assessment tasks using different taxa, different types of traits or different polarities of change before and after instruction, it may not be possible to unambiguously isolate context effects from learning outcomes.

For these reasons, it is essential to assess a variety of targets (Table 5) and have items that are parallel in form and difficulty. In other words, all of the topics discussed in this chapter should be included in the gathering of evidence to determine whether communication and education have been effective.

CONCLUSION

This chapter provided a brief overview of some of the most significant topics relevant to effectively teaching and communicating evolutionary ideas.

These topics include worldviews, the nature of science, the language of evolution, cognitive biases and misconceptions, reasoning about evolutionary phenomena, cases and curricula, pedagogical practices, and assessment and learning. Since the breadth of prior work is extensive, readers are encouraged to use this chapter as an entry point into the literature.

Focused attention on all of these topics is required for effective evolution education and outreach.

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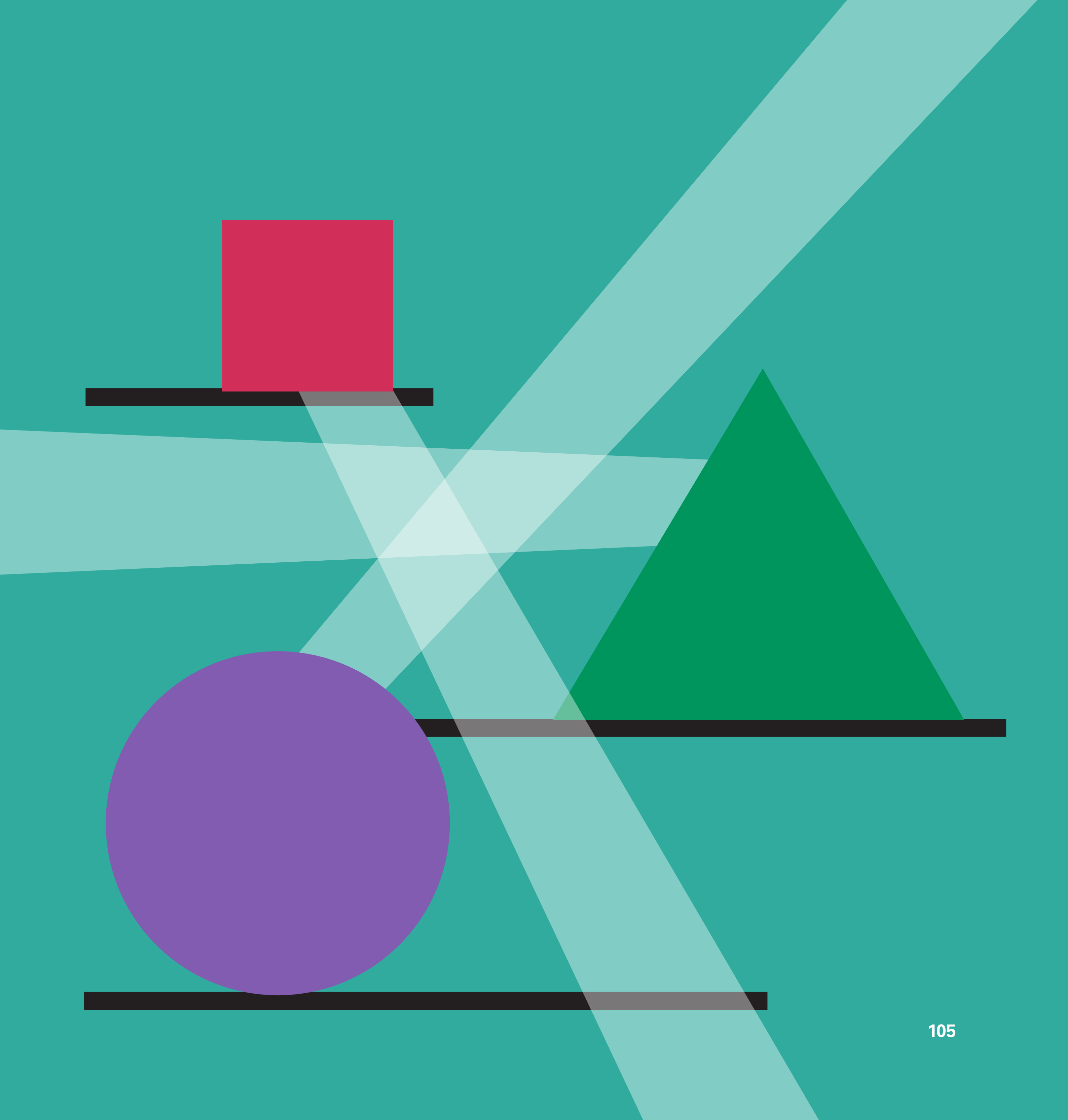
Chapter 7

Opportunities to deal with human evolution



CHAPTER 7

Opportunities to deal with human evolution

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Abstract:

Since knowledge about evolution—and especially human evolution—is insufficient, we aimed to design three student-centred online activities. These activities deal with human evolution and are intended to expose high school biology students and pre-service science teachers to issues concerning human evolution in order to enhance their knowledge of evolution and human evolution whilst also potentially enhancing their acceptance of evolution. The activities deal with lactose tolerance, celiac disease and starch consumption affecting diabetes. Additionally, we describe the principles that guided the design of these three activities: issues connecting to students' lives; non-contentious topics regarding human evolution; human evolution examples that occurred in the not-too-distant past; unambiguous genetic frame stories including simple genetic mutations that affect known traits; and examples that expose students to basic bioinformatics tools for facing authentic scientific issues dealing with genetic evidence of evolution. Furthermore, we present the results of pre-service science teachers' experiences with one of the activities, which demonstrate that a significant proportion of these teachers used more evolution key concepts after experiencing the activity. Notably, a significant proportion of these teachers showed an increase in evolution acceptance. In-service teachers who experienced one of the activities recommended the introduction of genetic evidence of human evolution via the activity and did not predict opposition among their students. Thus, we recommend the use of these activities among high school biology students since dealing with a relevant topic that includes clear and straightforward evidence of evolution may lead to better knowledge, a greater acceptance of evolution and human evolution, and the improved negotiation of evolution-related sociscientific issues (SSIs).

KEYWORDS

online activities, genetic evidence, religious pre-service teachers

INTRODUCTION

Although evolution is a controversial topic (Deniz & Borgerding, 2018), the evolution of animals and plants is more commonly accepted than the evolution of humans (Asghar & Wiles, 2007). This is likely because many societies consider humans to have a soul and an ethical code. Thus, some theologians do not accept the concept that an evolutionary process is occurring in humans (Alter & Webb, 1996). A study conducted in 2009 revealed that only 48% of Americans agree that evolution is the best explanation for the origin of human life on Earth (Moore et al., 2010).

This controversy also resonates in the field of education. In UK universities, it was found that 9% of students do not accept evolution by natural selection, with 16% not accepting human evolution by natural selection (Betti et al., 2020). In Israel, the situation is similar. Approximately half of surveyed high school science teachers saw a conflict between the theory of evolution and religion. For some of them, the random nature of the theory of evolution contradicted the belief in creation directed by the 'hand of God', whereas others opposed the possibility of man evolving from apes (Dodick et al., 2010).

Another study conducted on science teachers in Israel showed that human evolution was one of the most unfamiliar topics for them (Siani & Yarden, 2022b). Nevertheless, there has been some change in this regard over the last decade. When comparing the time spent on teaching creationism and the time devoted to human evolution and evolutionary processes in biology classes in the US, there was a substantial increase in the amount of time that teachers devoted to teaching human evolution between 2011 (Berkman & Plutzer, 2011) and 2019 (Plutzer et al., 2020). In the second survey, only 14% of teachers reported that they discussed creationism in high school biology classes —in comparison to 23% in the first survey (Plutzer et al., 2020). Despite this change, human evolution remains a sensitive and controversial issue in most countries, which might explain why it is not included in the science curricula and textbooks of many countries (Zer-Kavod, 2018).

Since evolution is a controversial topic, it is considered a socioscientific issue (SSI). SSIs are defined as controversial issues that involve the use of scientific topics and require students to engage in dialogue and debate (Zeidler & Nichols, 2009). The process of dealing with SSIs requires decision making based on scientific knowledge whilst also being influenced by societal factors such as ethnicity and religion. This implies that the negotiation of evolution-related SSIs is linked to the knowledge and acceptance of evolution (Fowler & Zeidler, 2016).

In this chapter, we introduce three online instructional activities that address the topic of human evolution by dealing with genetic evidence. All three activities aim to familiarise high school biology students and pre-service teachers with human evolution cases that are relevant to students' lives. We strive to raise the knowledge and acceptance of human evolution, which are not high in Israel and worldwide—especially among religious populations. Additionally, we present findings regarding the experiences of Jewish religious pre-service science teachers with the 'lactose tolerance' activity and interviews held with them a few months after experiencing this activity.

The target audience for this chapter is high school biology teachers, curriculum developers in the field of biology as well as biology education researchers. In light of the experience of the pre-service teachers, we recommend the use of the proposed activities with high school teachers and curriculum designers. Additionally, we recommend that biology education researchers examine the evolution knowledge of their students after experiencing the activities.

1.1 Religious controversy around evolution

Evolution has been a controversial issue for many years. Most of the doubt and disputes surrounding evolution stem from the conflict between evolution and creationism, which has been detected in countries such as Britain, where Muslims and conservative Protestant Christians show low levels of evolution acceptance. This is also true for Muslims worldwide (Edis, 2008), as well as among people from 34 other countries (Miller et al., 2006). It was previously shown that in some cases, as the level of religiosity rises, the level of evolution acceptance lowers (Unsworth & Voas, 2018). Also, among students, religious beliefs and religious cultures are among the most important factors predicting whether they will accept evolution (Hill, 2014; Truong et al., 2018). One of the central factors relating to the acceptance of evolution is that one should become an atheist in order to accept evolution (Lyons, 2010). Although some religions have allowed their believers to accept evolution alongside their religiosity, the theory of evolution is rejected despite the readily available scientific evidence (Coyne, 2012). Moreover, it has been found that acceptance of evolution positively correlates with attitudes towards science and the understanding of the concepts of evolution, whilst negatively correlating with religious faith (Eder et al., 2018). One problematic topic related to evolution with which people feel hesitation across both religious and non-religious groups is the Earth's age (Unsworth & Voas, 2018).

Among the Jewish people, the complete rejection of core parts of the theory of evolution mainly exists in the ultra-orthodox sector. Other religious sects accept the main parts of the theory of evolution, including species transformation. For them, science complements religion, with evolution being an ongoing process driven by God (Dodick & Shuchat, 2014; Swetlitz, 2013). This approach has been accepted by rabbis such as Abraham Isaac Kook (Cho et al., 2011; Pear et al., 2015), with additional rabbis claiming that evolution can even support Jewish beliefs (Pear et al., 2015). In contrast, the ultra-orthodox Jewish community strongly opposes the theory of evolution (Pear, 2018), so much so that well-known ultra-orthodox rabbis told teachers to remove pages from textbooks that introduced the theory of evolution, which seemed like heresies regarding the creation of the world to them (Pear et al., 2015). The opposition to evolution states that the scientific evidence for evolution is weak and that the Earth is young and has been created by God in its present form (Swetlitz, 2013).

Jewish religious science teachers in Israel were asked about their conflicts regarding evolution. Notably, they mentioned the age of the Earth as a controversial issue alongside the clash between the theory of evolution and biblical creation. For some of the teachers, the randomness of evolution opposes their belief in creation directed by God *'as is'.* In fact, some of the teachers who mentioned the controversy lacked complete knowledge of the theory of evolution (Dodick et al., 2010). Recent research has found that Israeli science teachers admitted that they and their students have difficulties with the religious controversy surrounding evolution in addition to a lack of scientific knowledge regarding the theory (Siani & Yarden, 2022b).

In addition to religion, other factors

have been shown to influence the acceptance of evolution. Among UK secondary school students, evolution understanding significantly increased after learning evolution (especially when teaching evolution after genetics) since there is a strong correlation between evolution understanding and acceptance (Kampourakis & Strasser, 2015; Mead et al., 2017). More research from the UK has shown that students' prior acceptance of evolution is an important factor that influences acceptance. Those with a low acceptance of evolution before learning about evolution respond poorly to evolution learning (Mead et al., 2018). Among Greek science teachers, it was found that acceptance of evolution can be enhanced by explaining the theory of evolution through practical and understandable examples such as geological arguments, fossils and information about Earth and its environments (Katakos & Athanasiou, 2020). These examples and others show that the influence of religion on evolution acceptance is complex and that it is important to consider the range of perspectives among studied individuals (Elsdon-Baker, 2015).

1.2 Human evolution in curricula worldwide

Although it is clear that evolution is controversial worldwide, it is part of the science curricula in many countries. However, the situation is different when discussing human evolution. Even in countries where science curricula include evolution, the topic of human evolution is frequently missing. A recent review comparing high school biology curricula in Australia, England, Virginia and California in the US, New Zealand, Singapore, Scotland, Finland and the Canadian province of British Columbia showed that the topic of evolution was part of all curricula; however, human evolution was only mentioned in two of them (Australia and New Zealand) (Zer-Kavod, 2018). Human evolution is also omitted from curricula in Hong Kong (Cheng & Chan, 2018), Iran (Kazempour & Amirshokoohi, 2018) and France. (Quessada & Clément, 2018). Moreover, US textbooks also make little mention of human evolution. Prior to the 1960s, biology textbooks placed little emphasis on human evolution. In the 1970s and early 1980s, textbooks reduced their coverage of human evolution even further. However, in the 1990s, the coverage became quite comprehensive (Skoog, 2005). Upon comparing textbooks from 18 countries (12 European and 6 non-European), 6 of them had no chapter dealing with the topic of human evolution (Quessada et al., 2008). In 2004, the state science frameworks of only three states in the US had standards relating to human evolution (Skoog, 2005).

1.3 Human evolution in the Israeli science curriculum

The presence of the topic of evolution in the Israeli junior high school science and technology curriculum and high school biology curriculum has recently been addressed (Siani & Yarden, 2020). Since 2016, both of these curricula included the topic of evolution, but not human evolution. Notably, in Israeli high schools, biology is an elective topic that is studied by approximately 15% of high school students. Human evolution was only included in the 1990 and 2010 biology curricula as part of evolution, which was an elective topic chosen by approximately 5% of the students who studied biology in high school. In the 2010 curriculum (Israeli Ministry of Education, 2010), it was recommended that human evolution be learned for 1 out of the 30 hours dedicated to the topic of evolution. As previously noted, human evolution is no longer included in Israeli curricula. However, the Israeli biology curriculum is undergoing yet another change, with the curriculum writing committee planning to reinstate human evolution (personal communication, Chief Supervisor of High School Biology Education in Israel). Since this topic has not been part of the curriculum for a few years now, there are hardly any related educational activities for students — especially online student-centred ones.We set out to prepare such activities in order to be prepared when this topic once again becomes part of the curriculum. One of our considerations in preparing learning materials on this topic was that if the principles of evolution were to be connected to the students' lives, it might be easier for students to accept and identify with them (Pobiner, 2012, 2016; Pobiner et al., 2018, 2019).

1.4 Why should we teach human evolution?

As can be understood from examining various curricula worldwide, human evolution is less commonly addressed than other topics in evolution. Nevertheless, focusing specifically on examples from human evolution has been shown to raise the enjoyment, engagement and enthusiasm of students studying evolution (Pobiner, 2012, 2016; Pobiner et al., 2018). Notably, human examples have helped students gain evolution knowledge as well as acceptance (Kaloi et al., 2022). In this chapter, we introduce three activities that deal with contemporary research-based examples in which genetic evidence of human evolution is presented. These activities could enable students to better understand the evidence of evolution, which may lead learners to accept evolution as a scientifically valid and meaningful tool in the study of biology (Pobiner et al., 2018).

1.5 Rationale for the human evolution education activities

In previous research, we interviewed educational stakeholders regarding the theological tensions surrounding the implementation of evolution in Israeli curricula. The interviewees articulated the need for more learning materials that include evidence of evolution as a possible way to avoid theological tensions among students (Siani & Yarden, 2020). To fill this need, a chapter regarding evidence for evolution was included in an online teacher guide (Siani, 2018). One of the subchapters included in this guide was *'Uniformity in cell structure and chemical composition'*. This subchapter deals with the following genetic evidence for evolution:

> **By comparing DNA sequences of different species, we can check how similar they are to each other and give them a numerical score reflecting that similarity. With the help of the scores given to the DNA sections from the different species, we can tell who split from whom, and even estimate how long ago it happened. The greater the difference between the DNA sequences, the longer the estimated time since the split. (Siani, 2018, p. 16)**

This guide was a first step in developing teaching and learning materials about evolution. However, we have since understood that student-centred online materials calling for students' active participation are better than teachers' guides that suggest making materials accessible for teachers and students. Since educational stakeholders have noted that evolution evidence is an important issue—and even though we knew that human evolution is currently not mentioned in the Israeli biology curriculum—we decided to design online activities that deal with human evolution.

1.6 Student-centred online pedagogy

In addition to the pedagogical content involved in teaching human evolution, continual changes in our surroundings pose a challenge for teaching in the 21st century. The educational system plays a major role in enabling students to take part in these changing challenges (Jan, 2017). One way of coping with these changes is technology, which is integrated into schooling to achieve the best quality pedagogy and effective learning by competent teachers who have new sets of resources and techniques (Jan, 2017). Interactive computer-based simulations have successfully improved learners' understanding of biological concepts and reduced common learner misconceptions about evolution (Abraham et al., 2009; Perry et al., 2008). Moreover, traditional teaching methods are not suited for teaching complicated topics such as evolution, which often include misconceptions (Nelson, 2008). Rather, inquiry-based teaching units have improved college students' explanations and acceptance of modern evolutionary theory (Robbins & Roy, 2007). Indeed, it was shown that, on average, student-centred pedagogy leads to greater learning outcomes for students than frontal teaching of evolution (Grunspan et al., 2018).

PROBLEM

In this chapter, we describe three student-centred online activities dealing with human evolution. These activities intend to expose high school biology students and pre-service science teachers to issues concerning human evolution to enhance their knowledge regarding the evidence of evolution (which may lead them to accept evolution and human evolution) since evolution knowledge and acceptance are important for SSI argumentation. We describe the principles that guided the design of all three activities and present the results of the experiences of pre-service science teachers with one of the activities.

METHODOLOGY

Design principles considered when designing the activities

All three activities that we designed are part of the free-of-charge Personalised Teaching and Learning (PeTeL) environment developed by the Weizmann Institute's Department of Science Teaching. PeTeL is a Moodle-based interactive online learning management system that enables educators to manage their students' learning in a single online environment. PeTeL includes a variety of diagnostic and evaluation interactive units for the use of science, technology, engineering and mathematics teachers.

In addition to aiding in teaching, PeTeL also enables the evaluation of students' actions since it follows and records their answers, their number of attempts and the time they spent in the environment (Bar et al., 2022). Information regarding the PeTeL environment in which these activities are included, can be found at: https://stwis.org/kwfrqy

We were guided by a few design principles when designing the following three online activities: i) lactose tolerance; ii) celiac disease; iii) starch consumption and diabetes. Below, we list each of the design principles that guided the design of these three activities (Siani & Yarden, 2022a) and provide examples to demonstrate how these principles are reflected in the activities:

a. Choosing a medical issue that is connected to nearly every student or his/her family.

This principle can be demonstrated in all three activities. All students are likely familiar with friends or family members who deal with one or more of the phenomena/diseases that are the focus of the activities.

b. Choosing a non-contentious topic of human evolution that will not raise protests from different sectors of the population.

Since human evolution is a contentious topic—even more than the evolution of plants and animals—we chose to trace the genetic evidence of traits that are known to us and part of our lives. These do not include topics that might raise controversy among certain sectors of Israeli society (Siani & Yarden, 2020), such as the evolution of skulls and the human-ape common origin (Pobiner, 2016). This is the case for all three activities.

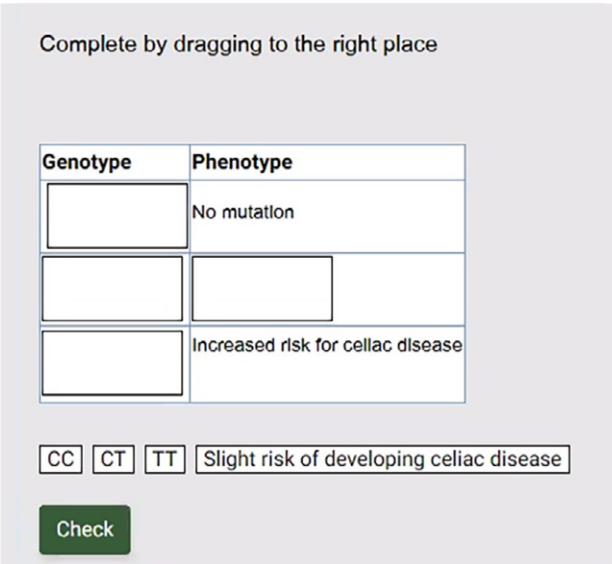
c. Choosing a human evolution example that occurred in the not-too-distant past.

The time when the evolution of a trait likely occurred was also a central issue in designing the activities since educational stakeholders have stated that the time dimension is a difficult aspect of learning evolution (Siani & Yarden, 2022b).
One of the positive mutations that led to lactose tolerance likely occurred when humans started the transition from nomadic hunter-gatherer societies to sedentary, productive agricultural communities approximately 10,000 years ago—a short time scale in terms of evolution.

d. Choosing a clear, unambiguous genetic *'frame story'* that includes a simple, one-step genetic mutation that affects a known trait—a mutation that can easily be explained to 15- to 18-year-old biology students whose knowledge regarding the control of gene expression is limited.

All three human evolution activities deal with a point mutation. For example, in the activity dealing with celiac disease, students are taught about the point mutation that leads to celiac disease and are asked to complete an immediate response question (see Figure 1).

Figure 1
A question regarding the point mutation that leads to celiac disease.



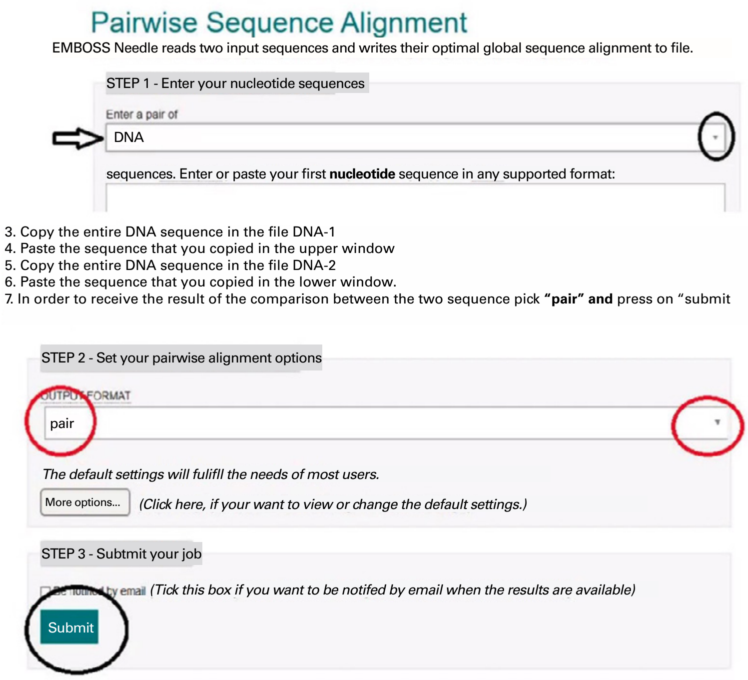
The unifying theme of all three activities is that they demonstrate genetic evidence of human evolution. In previous studies, science teachers have shown that one way to reduce tension among their students is by teaching them about the scientific evidence of evolution (Siani et al., 2022). Thus, we understand that teachers are seeking activities that deal with evidence. We specifically focused on genetic evidence since genetics is a topic that students have difficulty studying (Dzidzinyo, 2020; Fauzi & Mitalistiani, 2018). When designing these activities, we aimed to aid students in studying evolution within the context of genetics to enable them to understand the genetic evidence of evolution.

e. Choosing an example that exposes students to basic bioinformatics tools through which they can catch a glimpse of authentic science that deals with the genetic evidence of evolution.

Bioinformatics tools enable students to catch a glimpse of authentic science dealing with the genetic evidence of evolution, which shows them how scientists work in this field. By using these tools, students can understand that evolution is an evidence-based scientific field.

Figure 2 presents a screenshot from the activity dealing with lactose tolerance. This demonstrates the use of the EMBOSS tool (Madeira et al., 2022), with which students can compare two DNA sequences to determine where a mutation has occurred and which type of point mutation it is.

Figure 2
Use of the EMBOSS bioinformatics tool in the lactose tolerance activity.



In addition to the design principles that we were initially guided by, during the development of the second and third activities, we identified an additional design principle:

f. Dealing with human evolution topics to enhance students' knowledge whilst also potentially enhancing their acceptance of evolution so that they might better negotiate evolution-related SSIs.

Since negotiating SSIs has been correlated with developing knowledge and acceptance of evolution (Fowler & Zeidler, 2016) and because we aim for students to use socioscientific reasoning in the field of evolution, we wanted to design these activities to improve students' evolution knowledge whilst also raise their acceptance of human evolution.

Detailed descriptions of the three activities

i) Lactose tolerance: The story of a trait (Activity 1 description)

The first activity we designed consists of four units dealing with the activity of the enzyme lactase in our intestine, the differences in lactose tolerance in people from different origins, the genetic foundation of lactose tolerance (Ségurel & Bon, 2017) and an extension unit dealing with the control of lactase gene expression. Practical and experiential elements, such as the historical foundation of the mutation leading to lactose tolerance, are included in this activity.
We have previously described this entire activity in detail (Siani & Yarden, 2022a). The entire activity is openly available free of charge at:
https://stwis.org/q5czkm
For a demo version without registration:
https://stwis.org/k01jx8

ii) Does our diet affect our genes? (Activity 2 description)

The second activity we designed consists of two units. The first unit deals with the nutritional characteristics of different populations and the connection between their diet and the human genome. The second unit deals with the difference between the amylase gene in the human genome and the amylase gene in chimpanzees whilst attempting to help students understand why these differences exist. The entire activity is openly available free of charge at:
https://stwis.org/xyg8u6
For a demo version without registration:
https://stwis.org/48aohg
We describe the main items of each unit as follows.

1. Diets in different populations

This unit aims to teach students about the different starch compositions of diets around the world and become familiarised with the amylase gene and its functions. Then, the students can comprehend that the number of copies of the amylase gene is different in tribes such as the Biaka tribe, which eats small amounts of starch in their diet, which is mainly based on meat and fruit—in comparison to Western nutrition, which is based on carbohydrates.

Figure 3 presents a comparison between the different populations examined (Perry et al., 2007). This figure is followed by questions referring to the research skills that can be obtained from it. This section continues with an open-ended question: What might be the biological benefit for people who have multiple copies of the amylase gene? The section ends with a possible explanation of the current advantage of a low-starch diet (summarised in Figure 4).

Figure 3
Number of amylase copies in two populations that eat either high- or low-starch diets.

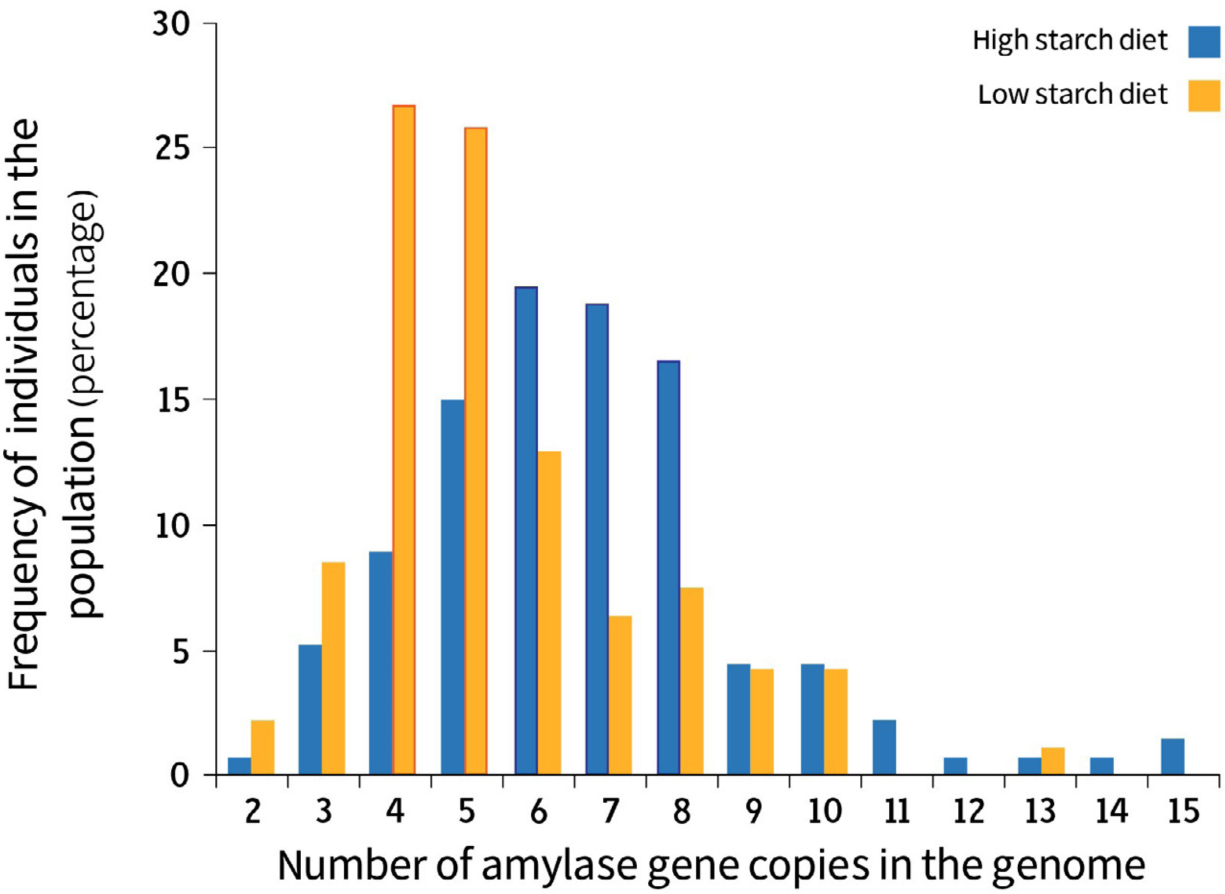


Figure 4
A summary question.

When blood glucose levels remain high, diabetes and obesity can develop.

It is possible that in populations that consume a diet with a high amount of starch, in which there are more pople with many copies of the amylase gene,

not only does starch efficiently break down starch into glucose, insulin effectively puts glucose into cells, and blood sugar levels remain at a normal level.

It turns out that people with multiple copies of the ______ gene in their genome also have high levels of ______ in their blood.

Therefore, they are able to break down the starch into ______ and with the help of insulin the monosaccharides enter the cells efficiently.

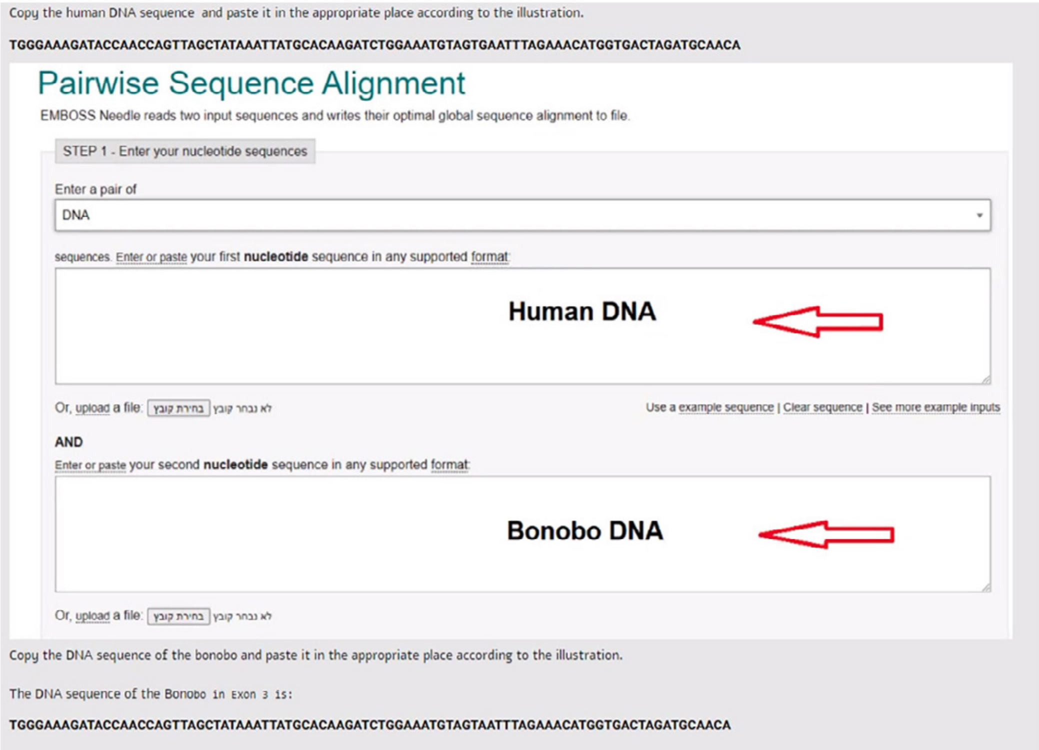
If this condition **does not** occur, the blood sugar level ______ and thus the ______ disease and even ______ may develop.

insulin | amylase | diabetes | rise | obesity | monosaccharides

Check

In this unit, the consequences of eating high starch diets (in terms of diabetes and obesity) relate to the first design principle listed—i.e., 'choosing a medical issue that is connected to nearly every student or his/her family—since metabolic diseases concern all modern societies worldwide.

Figure 5
Instructions for using the EMBOSS tool.



2. The relationship between evolution and the genetics of the amylase gene

This unit aims to use a bioinformatics tool to analyse the two point mutations that cause a difference between the amylase gene in the human genome and the amylase gene in chimpanzees, as well as how this genetic difference has influenced the function and diet of humans in comparison to chimpanzees.

Figure 5 presents part of the instructions that the students receive in order to find the genetic differences. The design principle used in this unit is the fifth one: *'An example that exposes students to basic bioinformatics tools through which they can catch a glimpse of authentic science that deals with the genetic evidence of evolution.'* By using the EMBOSS tool (Madeira et al., 2022), students can use an authentic tool commonly used by scientists.

The unit ends with questions that help students apply their knowledge of the genetic differences they learned about, to the field of human evolution: '*Compare the evolutionary process of the amylase gene* *in humans with the evolutionary process of the amylase gene in the bonobo.'*

This question uses the fourth design principle: *'Includes a simple, one-step genetic mutation that affects a known trait.'* After the students have learned about the mutation, they form a connection between it and human evolution.

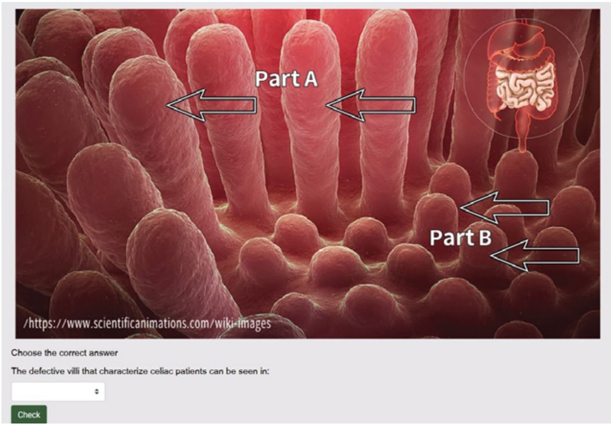
iii) Celiac disease: An evolutionary advantage? (Activity 3 description)

The aim of this activity, which includes one unit, is to enable students to understand the symptoms of celiac disease and one of the genetic mutations that cause it. The activity is openly available free of charge at:
https://stwis.org/0mu3kf
For a demo version without registration:
https://stwis.org/rkwxgb

A short video clip introduces this topic. Then, students answer questions regarding the symptoms of celiac disease to continue the clip (Figure 6). Following the video clip, the difference between the small intestine villi of healthy people in comparison to people with celiac disease is shown (see Figure 7) and includes a short question.

Figure 6
Interactive video clip dealing with celiac disease.

Figure 7
Illustration of normal and defective villi.
Image source: Scientific Animations Inc, 2019.



The design principles used in this unit are the first and second ones. The first principle is *'A topic connected to the lives of the students'* since approximately 1% of the global population has celiac disease (About Celiac Disease. *Celiac Disease Foundation.*, 2021). The second is *'A non-contentious topic of human evolution'* since celiac disease does not usually connect to human evolution but rather to health and nutrition.

The mutation that raises the incidence of the disease (Zhernakova et al., 2010) is shown next, with students being asked to add an idea to a *'forum discussion'* regarding the possible advantage that people with this mutation have over others since this mutation has been conserved for many years.

This forum discussion relates to the sixth design principle: *'Dealing with human evolution topics to enhance students' knowledge whilst also potentially enhancing their acceptance of evolution so that they might better negotiate evolution-related SSIs.'* Through the students' comments in the forum discussion, the teacher can observe the knowledge and level of acceptance among students related to principles of evolution and human evolution. This forum might be an opportunity for discussion and debate regarding the acceptance of evolution, advantageous mutations and human evolution.

The activity ends with a description of research that assumes that the celiac disease mutation enables sick people to cope with infectious diseases, which might explain why it has been advantageous for thousands of years.

RESULTS

Religious science pre-service teachers' experience with the lactose tolerance activity

The activity *'Lactose tolerance: The story of a trait'* was experienced by 23 religious Jewish pre-service science teachers during the 2019–2020 academic year. Four months after experiencing the activity, we interviewed 11 of the pre-service teachers via Zoom. The main aim of the first interview, known as the *'knowledge of evolution'* interview, was to probe the pre-service teachers' evolution knowledge.

The interviews lasted 20 to 30 minutes and included six knowledge questions. Questions 1 and 5 deal with human evolution and were adapted from Pobiner et al. (2019). The remaining questions were adapted from Nehm & Ha (2011). Questions 2 and 3 deal with animal evolution: Question 2 deals with the formation of a trait, whilst Question 3 deals with the loss of a trait. Question 4 deals with artificial evolution and Question 6 deals with the evolution of bacteria. The analysis of interview data showed that in all the questions except for the one dealing with the loss of a trait (i.e., Question 3), the pre-service teachers used more key evolution concepts (Nehm & Reilly, 2007) than alternative (naïve) concepts (Nehm & Ha, 2011) to explain evolution situations. This could mean that experiencing the human evolution activity was meaningful and resulted in the pre-service teachers finding it easier to explain human evolution phenomena even a few months after the activity (Siani & Yarden, submitted).

At the beginning and end of the activity, the pre-service teachers completed the I-SEA evolution acceptance questionnaire (Nadelson & Southerland, 2012), in which one of the three subscales deals with human evolution. The analysis of the questionnaire showed a significant difference ($p=0.0291$) between the mean score of the items dealing with human evolution in the pre-questionnaire (3.283 ± 0.877) versus the post-questionnaire (3.572 ± 0.922), meaning that the average acceptance of the items in this section rose after engaging in this activity. Additionally, the average score of evolution acceptance (according to the I-SEA three-part questionnaire) shows that among the 23 pre-service teachers, 13 showed a clear picture of additional acceptance of evolution after the activity than before it, whilst 3 showed no change and 7 showed a decline in their acceptance (Siani & Yarden, submitted).

Nine months after they had experienced the activity, we interviewed four of these pre-service teachers via Zoom for 20 to 30 minutes. At the time of the second interview, the interviewees were already in-service teachers and had completed most of their college studies. The main aim of the second interview, known as the *'acceptance of evolution'* interview, was to follow the teachers' acceptance of evolution, willingness to teach evolution and clarify whether there was a change or retention in their acceptance of evolution and human evolution. Both of the interviews' questions are detailed in a recent paper by our group (Siani & Yarden, submitted).

In this chapter, we focus on the way that pre-service teachers (now in-service science teachers) stated that they will deal with the issue of evolution and human evolution 9 months after they experienced the '*lactose tolerance'* activity.

Most of the teachers said that in the schools in which they teach, they have already faced the rejection of evolution. Others said that they presume they will face it:

> **I think I will not teach evolution if I teach in a religious school because it may arouse there, hmm... because their view is very negative towards evolution. Even if I present it in a very non-negative way, they will think I am bringing a secular spirit to a religious school that does not fit the place. (S10)**

Although S10 understands that evolution is a theory accepted by scientists, she argued that she would not teach evolution as a random process, but rather as a directed one:

> **We as religious people think that evolution happens because there is something that directs it, making it easier to accept it. I look at the evolutionary process as something that is directed. In my perception as a religious person, it does not just happen by itself. (S10)**

Another in-service teacher emphasised her own argumentation for evolution and noted that when she introduces the topic to students, it is based on both the Bible and scientific evolutionary principles:

> **It is impossible to understand the book of Genesis without the evolutionary perspective: first, the sunlight has to develop; then, the animals in the water and then the birds. Had there been a contradiction between the Bible and the theory of evolution, it might have made me sceptical of either the Bible or evolution. Yet, evolution works out for me with the Bible perfectly. (S11)**

Most of the pre-service teachers did not differentiate between human evolution and the evolution of plants and animals, yet some of them emphasised their students' problems as follows:

> **'I don't think there is a difference between different living creatures. I think all populations are changing over the years. All creatures have evolution.' (S9).**

> **I do not make a distinction between humans, bacteria, etc. I will teach about all the creatures. There is a philosophical statement here. That man is not the centre of the world. But what will mainly concern students is the contradiction between creationism, evolution and the origin of man. Students can say that we are actually animals, and this is perhaps a philosophical question that can also be discussed, as well as whether the origin of man is really from the ape. (S5)**

Yet, some pre-service teachers did differentiate between human evolution and that of other creatures:

> **Human evolution? It is different from that of plants and animals. I can accept micro-evolution but not macro-evolution. The subject of lactose does not conflict with religion. What conflicts with religion is something that has not been proven yet. The creation of the world clashes with religion because one does not know things for sure, like the evolution of the human being. (S8)**

Thus, we can understand that human evolution is still more controversial than other topics in evolution. Also, more activities in this field are essential and might aid teachers and students alike.

DISCUSSION

In this chapter, we have described the theoretical considerations and design principles that have led us to design three online activities dealing with human evolution. Additionally, we have described the experience of pre-service science teachers using one of these activities. This experience might have led the pre-service teachers to better understand and accept human evolution.

Why should we deal specifically with human evolution and put effort into activities dealing with this topic? Previous studies dealing with human evolution activities have claimed that it is important to teach human evolution at the school level to develop a scientifically literate society that can effectively discuss and debate issues regarding human evolution (Sutherland & L'Abbé, 2019). Moreover, understanding human variation, which is reflected in activities dealing with human evolution, is an important step in respecting the diverse nature of societies (Donovan et al., 2019; Strkalj et al., 2007), such as the multicultural society of Israel.

In addition to the importance of understanding and accepting the diversity of society, another main aim when designing the human evolution activities was to introduce students to genetic evidence, which is mainly taught via the comparison of DNA sequences using bioinformatics tools. The importance of teaching evolution evidence is consistent with previous studies noting that an important factor influencing knowledge and acceptance of the theory of evolution is discussing evidence that supports evolution and natural selection (Bravo & Cofré, 2016). Thus, by discussing genetic evidence with students, we might enhance their knowledge—and perhaps also their acceptance—of evolution.

Another aim when designing the activities was to expose students to the fact that evolution occurs for humans like every other organism. Previous research has shown that students consider human evolution as a separate evolutionary subject (Trevisan & Santovito, 2015). Notably, it was important for us to overturn this concept through the activities we designed. Thus, the pre-service science teachers who experienced the 'lactose tolerance' activity reflected on the fact that the evolution of humans is a part of the theory of evolution.

Furthermore, common misconceptions regarding evolution are teleological explanations, which usually refer to the purpose of a trait (Hammann & Nehm, 2020) and are common among both high school and elementary school students (Brown et al., 2020). When designing the activities, we made an effort to design them so that students will not interpret mutations as being an intentional attempt by an organism to adapt to its environment. Rather, we emphasised the fact that the mutations occurred randomly and gave an advantage to those who had them.

Since prior studies have shown that religiosity is an influential factor when considering topics such as human origin (Silva et al., 2021), it was important for us that religious pre-service teachers experienced one of the activities and allowed us to assess their reactions to human evolution a few months thereafter. From their reactions, we can conclude that their experience with the activity might have added value to their knowledge—and perhaps also to their acceptance—of human evolution.

In addition to religiosity, another factor influencing the acceptance of evolution is having an understanding of the nature of science (NOS) (Dunk et al., 2019). Pre-service science teachers with a high level of understanding and acceptance of the theory of evolution also had a high understanding of the NOS. They understood that the scientific theory is reliable since it has been validated by accumulated evidence and that it might also change as a result of new research (Akyol et al., 2012). Notably, the importance of the NOS has been emphasised in all three activities described in this chapter. We aimed to show students the importance of genetic research as evidence for human evolution to raise their understanding of the NOS, thereby increasing evolution knowledge and perhaps also evolution acceptance.

Finally, open-minded thinking has also been found to be significantly correlated with the acceptance of human evolution (Sinatra et al., 2003), implying that a positive correlation has been found between characteristics of open-minded thinking and evolution acceptance. This means that evolution acceptance can be higher among pre-service teachers whose cognitive flexibility and openness to belief of the evolution theory are higher (Athanasiou et al., 2012).

The three activities designed and described in this chapter aim to develop the open-minded flexible thinking of students by showing them the genetic context of everyday phenomena that are connected to their lives.

IMPORTANT HIGHLIGHTS FOR TEACHING PRACTICES

After analysing the impact of the '*lactose tolerance'* activity among pre-service science teachers, we can conclude that dealing with human evolution via an interactive student-centred activity might increase knowledge of human evolution, especially since we saw that pre-service teachers used more scientific concepts and less alternative concepts when dealing with the theory of evolution. This may imply that even a short activity dealing with a topic in evolution that has elements relevant to the lives of students and deals with clear and straightforward evidence of evolution, may be impactful and lead to better knowledge —and perhaps a rise in the acceptance—of evolution and human evolution.

Another use of the *'lactose tolerance'* activity occurred in 2020 when 117 in-service teachers experienced the activity. Their reflections regarding this activity could aid other teachers around the world by helping them understand how to use it. On average, the amount of class time teachers recommended spending for each of the first two units was one lesson, whilst for the third unit, most teachers recommended spending two lessons. Overall, 88% of the teachers said that the first unit was easy or reasonable, whilst 77% said the same about the second unit and 68% said that the third unit was reasonable to difficult. Notably, they were not asked about the fourth unit.

When the teachers were asked about how they would combine the activity during teaching evolution, some of them recommended using the activity after developing a basic familiarity with natural selection, selective pressure and mutations. Other teachers recommended being familiar with DNA, RNA transcription and protein translation before using the activity.
The in-service teachers also suggested using the activity since it is a simple and relevant example of human evolution that does not involve studies of the bones of ancient people or dinosaurs, which may be unclear or problematic to some students. They further suggested using the activity as a way to stimulate students' curiosity in the field of evolution.

Thus, the main aims of the design principles we used in all three activities—i.e., a medical issue that is connected to the students' lives and a non-contentious topic of human evolution that will not raise protests —were mentioned by the teachers, which enabled them to teach human evolution with no special controversy. None of the teachers mentioned any controversy experienced whilst dealing with human evolution, nor did they assume controversy would rise among their students. Similarly, the in-service science teachers who experienced the *'lactose tolerance'* activity suggested using the activity to enable students to feel like researchers when using the bioinformatics tools. Thus, the design principle related to *'exposing students to authentic scientific tools'* was also suggested by the in-service science teachers.

Overall, we can conclude that the use of these activities in classes might improve evolution knowledge and could thus increase the acceptance of human evolution. Additionally, the use of human evolution examples was recommended by all in-service and pre-service teachers —and is likely also preferred by students —since both groups recommended using it and did not predict any opposition to the introduction of genetic evidence of human evolution via these activities.

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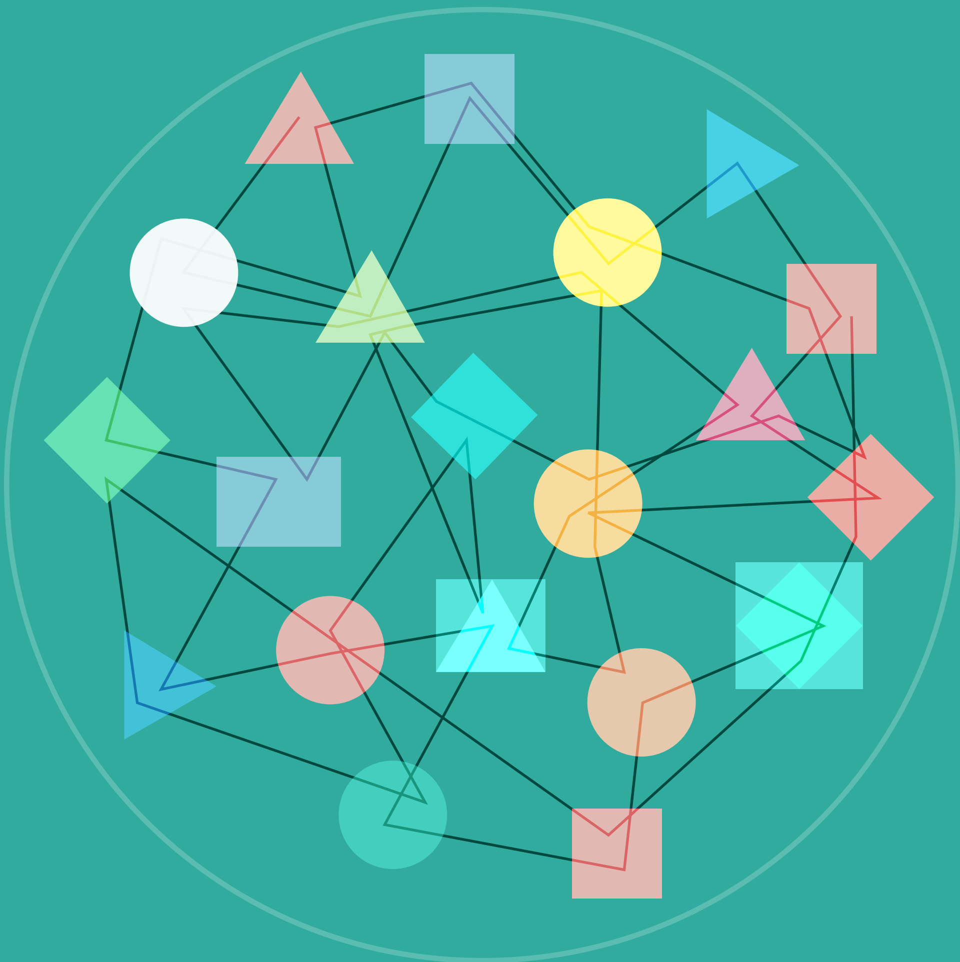
Chapter 8

Evolving cooperation and sustainability for common pool resources



CHAPTER 8

Evolving cooperation and sustainability for common pool resources

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Abstract:

Sustainable resource management is often a matter of managing common-pool resources (CPRs), which include the social and material resources shared by groups of individuals. CPRs can be prone to overuse through competition between resource users who are motivated to maximise their resource use (or contribute little to the maintenance of the resource) for individual gain and at the expense of group-level sustainability—an outcome known as the Tragedy of the Commons. CPR dilemmas are pervasive in human contexts, ranging from mitigating climate change to sharing public spaces, fighting a pandemic or tackling antimicrobial resistance. Since CPR dilemmas are also found across the non-human living world, sustainability scientists, economists and evolutionary biologists are interested in the dynamics of competition and cooperation around resources. In this chapter, we argue that students' conceptual understanding of CPR dilemmas through exploration and critical reflections on human and non-human examples is central to developing a basic understanding of sustainability issues more broadly, as well as of evolutionary dynamics that can help explain the evolution of cooperative social behaviours and conflict resolution mechanisms. We provide an overview of the science of CPR dilemmas in the evolution of living systems and human natural resource contexts. Moreover, we present a flexible set of resources that educators in secondary school biology or environmental science can employ to help students engage in cross-cutting concepts, scientific ideas of the life sciences and a range of scientific practices to develop understandings and socioscientific reasoning skills surrounding real-world issues of sustainable resource use.

KEYWORDS

sustainable development, behaviour, cooperation, common-pool resources

1. INTRODUCTION TO THE SOCIOSCIENTIFIC PROBLEM

1.1 The Tragedy of the Commons: A central model in sustainability science

In a 1968 article, ecologist Garret Hardin popularised the model of the Tragedy of the Commons (ToC; Hardin, 1968). Using the example of a common village pasture, he theorised that the self-interest of individual herders to maximise their own gain from the shared pasture by increasing their herd size will inevitably lead to the overuse of the shared pasture.

The ToC relates to a specific type of social situation called a social dilemma, which is a situation in which individuals behave in a way that benefits them individually in the shorter term (in terms of evolutionary fitness, wealth or other outcomes); however, collectively, this behaviour leads to the least benefits for everyone over the longer term.

Many societal problems, such as mitigating and adapting to climate change, reducing social inequality, wearing face masks to fight a global pandemic, and the responsible use of antibiotics to tackle antimicrobial resistance, can be conceptualised as social dilemmas—and hence as problems related to overcoming the ToC. The resolution of all of these problems requires individuals to cooperate for the common good at more or less expense to their own short-term benefit. Therefore, the challenges and solutions to such cooperation problems have been an area of research scholarship in sustainability science (e.g., Dickinson et al., 2013; Meinzen-Dick et al., 2018; Messner et al., 2013; Waring et al., 2015, 2017).

Hardin (1968) proposed that given our purportedly selfish human nature, the only solutions to this tragedy would be the privatisation of resources or top-down governmental control. However, in the 1990s, political scientist Elinor Ostrom explored a diversity of real-world case studies of common-pool resources (CPRs), such as pastures, irrigation and groundwater systems, and fisheries, to understand whether—and under what conditions—humans can cooperate and sustainably manage their shared resources (Ostrom, 1990).

Contrary to Hardin, she found that human communities can indeed cooperate and self-organise for the sustainable management of their shared resources; however, this only tends to be observed when certain conditions are met. Through this work, she derived her framework for the analysis of social-ecological systems (Ostrom, 2007, 2009; Fig. 1) and her Core Design Principles (CDPs) for the effective management of CPRs (Ostrom, 1990; Table 1).

Using her framework, Ostrom (2007) concluded that Hardin's scenario of the ToC emerges only under certain specific assumptions, including when there is no governance system at all, when resource users do not communicate at all and make their decisions independently and anonymously, and when users focus primarily on their immediate short-term benefits. In reality, humans often communicate, make rules, base their decisions on what others do and care about more than just immediate short-term benefits to themselves. Diverse methods and insights from evolutionary and behavioural sciences—including lab and real-world experiments and agent-based modelling—have provided further added insights into the conditions and proximate mechanisms that appear to enable humans to cooperate towards the common good.

In this chapter, we argue that these insights and associated scientific concepts and methods can serve as foundations for developing student understandings of scientific ideas as well as socioscientific reasoning skills. As indicated by Ostrom's CDPs (Table 1), ethical, moral and political dimensions are inherent in analysing and evaluating solutions to the sustainability of social-ecological systems.

The CDPs highlight the importance of shared identity, fairness, inclusion and autonomy of the stakeholders in a social-ecological system. The role of (scientific as well as local) knowledge and ongoing inquiry around a shared resource and its use is also salient in Ostrom's frameworks.

Furthermore, the CDPs are not exhaustive and do not prescribe specific policies or behaviours to be implemented. Rather, they only offer general guidance for a community, which needs to negotiate, experiment and test specific mechanisms that might be suitable in their context, thus highlighting the limits of science —or at least the need for an applied and participatory science approach.

Figure 1
Factors in a framework for analysing social-ecological systems. Adapted from Ostrom (2009).

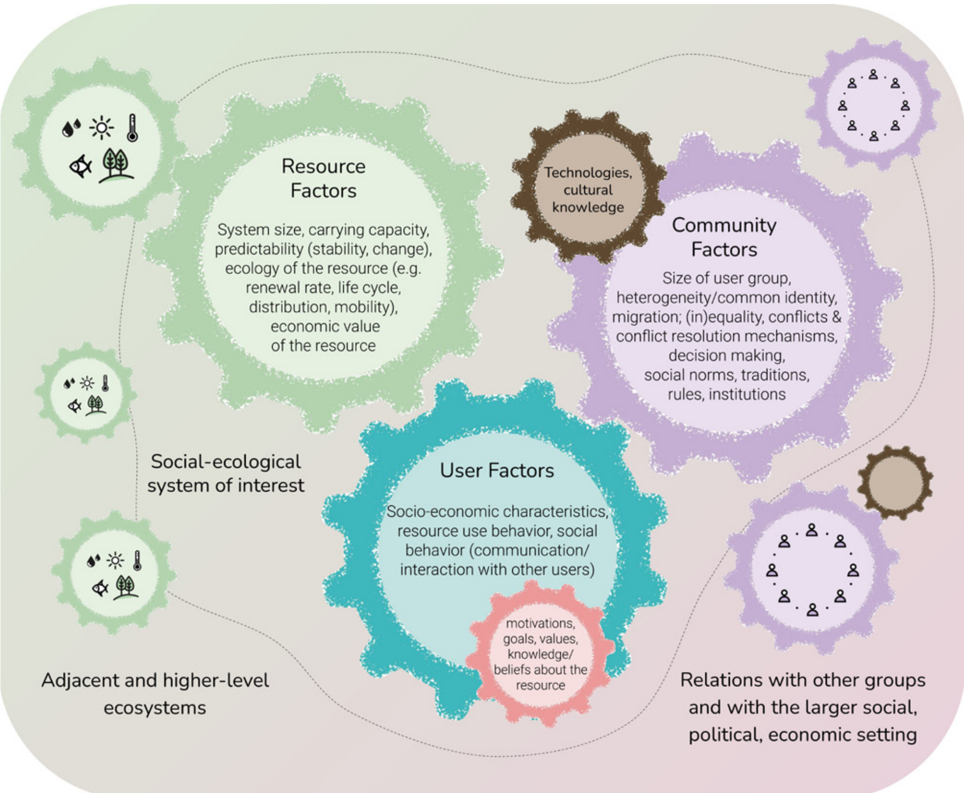


Table 1
Core Design Principles for the successful management of common-pool resources and successful cooperation, with analogous examples in biology (see Section 1.2).

Core Design Principle	Description	Analogous biological examples
1. Clearly defined boundaries	It is clear who belongs to a group, and all members have a shared sense of common goals and identity. Fates are intertwined.	Skin and cell membranes; fitness interdependence through factors such as physical proximity and low levels of migration, positive assortment and genetic relatedness.
2. Fair distribution of costs and benefits	The costs incurred by members for cooperation are distributed in proportion to their benefits from cooperation.	Need-based transfer of resources (e.g., vampire bats, trophallaxis in social insects, nutrient distribution in multicellular organisms).
3. Fair and inclusive decision making	Most individuals in the group can participate in decisions that affect them and set or change the rules of the game.	Quorum sensing in bacteria, decision making for nesting sites in honeybee swarms.
4. Transparency and monitoring	The community observes and monitors whether everyone behaves according to the rules, the condition of the resource and whether common goals are achieved.	Policing in insect societies; the immune systems in animal bodies.
5. Graduated responses to helpful and unhelpful behaviours	Rewards for valued behaviours and punishments for misbehaviours start at a low level (e.g., friendly discussion) and are increased in proportion to how helpful or unhelpful the behaviour is.	
6. Fast and fair conflict resolution	There are mechanisms for resolving conflicts among members in ways that are fast (efficient) and perceived as fair by those involved.	
7. Autonomy to self-govern	The group has a minimum of rights and the freedom to set its own rules without interference.	Becomes relevant when higher levels of selection emerge (e.g., endosymbiosis, multicellular organisms, symbiosis and major transitions in evolution).
8. Cooperative relations with other groups	The group has collaborative relations (according to CDPs 1–7) with other groups and across scales of social organisation.	

Sources: Aktipis (2016); Aktipis et al. (2018); Ostrom (1990); Rankin et al. (2007); Ratnieks and Wenseleers (2005); Seeley (2010); Wilson et al. (2013).

1.2 The Tragedy of the Commons in evolutionary biology

The ToC and other social dilemmas do not only present a challenge to our species but across life. In their article, *'The Tragedy of the Commons in Evolutionary Biology'*, Rankin et al. (2007) offer a summary of a diversity of contexts in which the ToC has been applied by evolutionary biologists to analyse how social interactions influence the evolution of traits, from intra-genomic conflict to virus-host relationships (e.g., Kerr et al., 2006), microbial communities (e.g., MacLean & Gudelj, 2006), plant competition for light and water (Zea-Cabrera et al., 2006), to sexual conflict (e.g., Rankin et al., 2011).

Similar to the early views of Hardin regarding the inevitability of the ToC in the human domain, evolutionary biologists since Darwin have been pondering how and under what conditions cooperation around shared resources could evolve. If we start from the premises that competition among individuals in a population is a core driver of evolutionary processes, that individual-level fitness differences are what matters for selection and that cooperative behaviour involves fitness costs, how can cooperative behaviour possibly evolve in a population?

However, Darwin (1871) already offered explanations for how this might be possible by considering a population that is structured into multiple sub-groups with various trait compositions within groups. A variety of mechanisms and concepts regarding the evolution of cooperative groups have since been formally developed and empirically studied by evolutionary biologists. Thus, important in the study of the evolution of cooperation and competition around shared resources is the search for conditions and mechanisms that may prevent selfish individual behaviour and an ensuing ToC (similar to what Ostrom has done for the human domain). Notably, Rankin et al. (2007) highlighted the following: *'One of the main advantages of using the tragedy of the commons as an analogy in evolutionary biology is that it forces us to ask the question why a tragedy of the commons is not observed in a particular scenario'* (p. 648).

Some of the mechanisms that can be found across the biological world include fitness interdependence (e.g., kin selection), the need-based and efficient distribution of resources among group members (e.g., among vampire bats), monitoring and sanctioning mechanisms (e.g., in social insects) and distributed collective decision-making mechanisms such as in honeybee swarms (Aktipis, 2016; Aktipis et al., 2018; Ratnieks & Wenseleers, 2005; Sachs et al., 2004; Seeley, 2010). In a more generalised fashion, these can be related to some of Ostrom's design principles (Table 1).

Rankin et al. (2007, p. 649) summarised how these evolutionary conceptions of the ToC across the living world can relate to socioscientific issues (SSIs) of sustainable resource use: *'In the light of ever-growing environmental concerns, thinking about the tragedy of the commons in evolutionary biology is of interest not only because of these evolutionary implications but also because of the applied analogy to human societies dealing with environmental and other public goods problems'.*

Today, the ecology and evolution of group behaviour and cooperation are often themes in curriculum standards (e.g., within the Life Sciences disciplinary core ideas in the Next Generation Science Standards of the US; NGSS Lead States, 2013). We propose that exploring contexts across biology in which evolution has favoured cooperative traits around shared resources can serve as fruitful lessons to help students gain a deeper understanding of the conditions and mechanisms that foster cooperation and sustainable resource use whilst critically transferring these to a variety of SSIs. Teachers that have already engaged students in the concept of biomimicry may see further opportunities for developing an understanding of deeper principles of living systems through comparative perspectives.

1.3 Understanding the cultural evolution of behaviours, norms and institutions in CPR dilemmas

Generally, the field of cultural evolution science proposes that cultural traits —including technologies, norms, traditions, rules, beliefs and knowledge—can be said to evolve by evolutionary processes such as variation, (multilevel) selection and transmission (Mesoudi, 2011). Cultural evolution scientists often use methods borrowed from evolutionary biology to study the evolution of cultural phenomena, such as population genetics, agent-based computer simulations and phylogenetic analyses.

Some sustainability scientists similarly apply such methods and concepts to the emergence and spread of human behaviours and institutions to gain an understanding of how the successful management of CPRs is achieved—or eroded—in social-ecological systems (e.g., Ghorbani & Bravo, 2016; Ostrom, 2013; Waring et al., 2015).

Whilst such a transfer of evolutionary concepts and methods to the domain of culture has not yet found its way into most curricula and learning standards (Hanisch & Eirdosh, 2020b), we propose that such explorations can serve as valuable lessons that can enhance both the understanding of scientific evolutionary concepts (e.g., Pugh et al., 2014) and the understanding and evaluation of SSI. After all, the causes of and solutions to SSIs often involve changes in the frequencies of behaviours and other cultural traits.

In this regard, exploring the scientific method of computational modelling, which abstracts real-world phenomena into mathematical terms and is used by biological as well as cultural evolutionary scientists, can help students understand the nature of evolutionary processes and critically transfer evolutionary concepts across domains.

2. PRACTICE DESCRIPTION

Sadler et al. (2017) proposed starting a unit on SSIs with an introduction to a focal SSI, followed by engagement with three-dimensional learning that integrates cross-cutting concepts, disciplinary core ideas, scientific practices and socioscientific reasoning, end ending with synthesis of ideas and practices via a culminating activity.

Sadler et al. (2019) also advanced a more flexible approach around six features of SSIs and model-based learning (SIMBL): 1) explore underlying scientific phenomena; 2) engage in scientific modelling; 3) consider issue system dynamics; 4) employ information and media literacy strategies; 5) compare and contrast multiple perspectives; 6) elucidate one's own position/solution with flexibility regarding the order and length of any of these features.

As highlighted in Section 1.1, we can encounter the challenges of CPR use and other social dilemmas in many different real-world contexts and sustainability problems. Thus, the focal SSI of the proposed unit (see Appendix) can include one or several examples that students might be familiar with or interested in.

Such SSIs could include a shared natural or social resource in their local area, a new policy in their school, community or country that is costly for individuals but benefits the community, or global problems such as climate change, fighting a pandemic or plastic pollution. Furthermore, the evolution of cooperation and sustainability around CPR use has been explored by scientists through a variety of methods, including experiments, observations of real-world case studies and computer simulations. Students can engage in scientific modelling and associated scientific practices by exploring a range of these methods and data.

Thus, in line with Sadler et al. (2019), we also propose that the selection and sequencing of lessons presented in this chapter can be approached flexibly depending on the teaching context, including curriculum goals and students' prior knowledge and interests. Although we propose a sequence below, all lessons can serve as starting points for introducing students to the core concepts and applying them critically to a focal SSI whilst introducing a range of scientific methods (Fig. 2).

In this unit, students will engage in cross-cutting concepts (i.e., systems and system models; cause and effect; stability and change), disciplinary core ideas from the NGSS Life Sciences (LS2: Ecosystems: Interactions, Energy, and Dynamics; LS4: Biological Evolution: Unity and Diversity) and Earth and Systems Sciences (ESS3: Earth and Human Activity), as well as scientific practices (e.g., by using and constructing models, analysing data and designing solutions). Through the exploration of cross-species comparisons, real-world human and non-human case studies, and agent-based computer simulations, students can develop scientifically adequate conceptual understandings of the challenges and solutions to CPR dilemmas across diverse contexts. Finally, students can use their understanding of concepts and methods to analyse a focal SSI and devise proposals for its improvement by practising socioscientific reasoning skills.

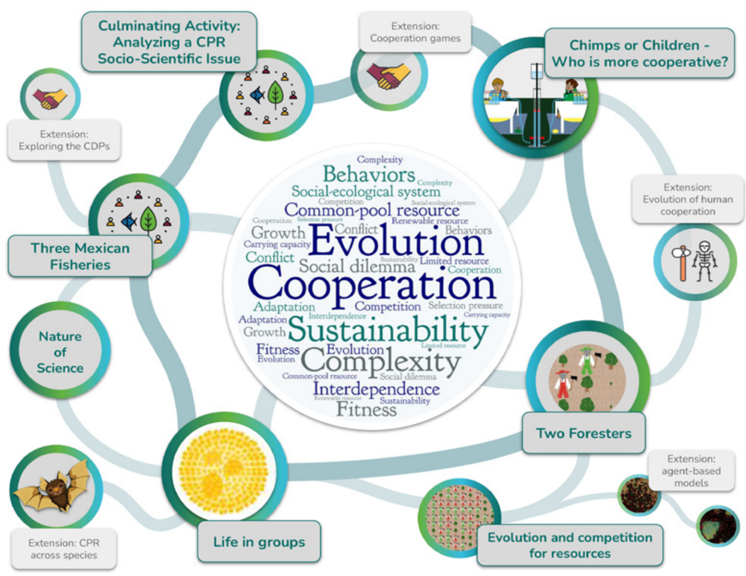


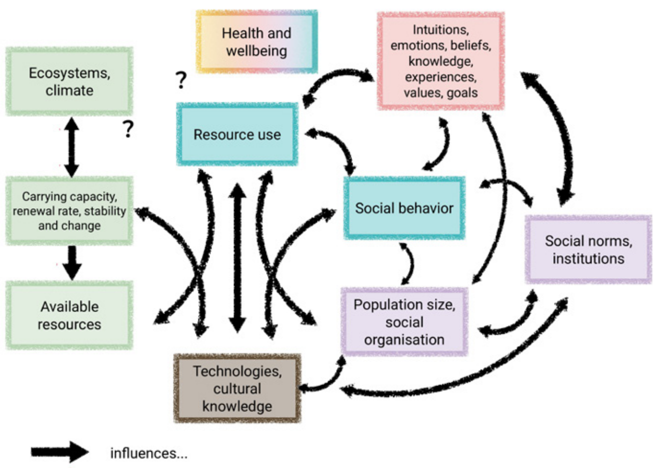
Figure 2
Overview of the unit with suggested core lessons as well as opportunities for additional lesson extensions to reinforce transfer and deeper understanding.

The lessons also include the use of a set of teaching tools informed by science, which helps to analyse and visualise concepts and relationships in social-ecological systems and develop systems thinking and socioscientific reasoning skills. These may be introduced within the lessons or used in various scaffolded ways, depending on the available time, age of students and specific learning goals:

- **Causal maps or causal diagrams:** These help students visualise the interrelationships between factors in social-ecological systems. The construction of causal maps can be scaffolded in a variety of ways, such as by completing nodes or relationships in partially completed causal maps, constructing maps from a list of given items and finally to constructing causal maps from scratch (Cox et al., 2018; Novak & Cañas, 2006, 2004). Group work and peer reviews of causal maps are also recommended to deepen reflection and understanding (Novak & Cañas, 2006; Schwendimann & Linn, 2016). Fig. 3 provides an example of a causal map of factors that impact the development of a (human) social-ecological system (with some elements that are transferable to other species). Notably, in such causal maps of (human) social-ecological systems, the boundary between a scientific model and a socioscientific model with social, ethical and political dimensions—as has been conceptualised in the SSI literature (Ke et al., 2021)—becomes blurred or disappears due to the interdisciplinary nature of this field of science.
- **Analogy maps:** These help students compare phenomena using overarching concepts and principles and transfer these concepts and principles to analyse novel contexts (e.g., Glynn, 2008).
- **Payoff matrix:** This is a tool used by evolutionary biologists, economists and sustainability scientists to understand the degree to which a social situation presents a dilemma between individual and group outcomes—and thus the degree to which selection on different levels favours cooperation or competition (Bowles & Gintis, 2011; Diekert, 2012). It can also be used to understand the motivations behind people's behaviour, thus fostering perspective-taking skills (Powers, 1986).

An introduction for teachers to the concepts and teaching tools of this chapter can also be found in Hanisch and Eirdosh (2020a).

Figure 3
Example of a general causal map of a social-ecological system.



2.1 Materials

Here, we present a detailed sequence of selected lessons that can help students understand and apply concepts across contexts and introduce them to a variety of scientific methods. Suggested extensions (see Section 2.6) are also listed here.

Lesson 1:
Chimps or children - Who is more cooperative?
- Extension: Evolution of human cooperation

Lesson 2:
Agent-based computer simulations of social-ecological systems
- Two foresters
- Evolution and competition for forest resources
- Extension: Further models that integrate further processes

Lesson 3:
How does life evolve solutions to CPR dilemmas?
- Reading text Life in groups
- Extension: Further biological case studies

Lesson 4:
Analysing real-world case studies of CPRs
- Three Mexican fisheries
- Extension: Further case studies of CPRs

Lesson 5:
Culminating activity: Analysing a focal SSI and deriving solutions
- Extension: Exploring and implementing the design principles for cooperation

2.2 Time

The proposed unit spans a minimum of 9 hours. We also encourage educators to engage students in some of the proposed extension lessons to deepen their understanding.

Lesson 1:
20–45 minutes

Lesson 2:
60–120+ minutes

Lesson 3:
45–120+ minutes

Lesson 4:
90 minutes

Lesson 5:
5: 3+ hours

Total:
~9+ hours

2.3 Target audience

This unit is most suitable for participants from the 9th to 12th grade (15- to 18-year-olds). Most of the lessons are suitable without students' prior understanding of relevant concepts (including evolutionary concepts). The lessons can be used to introduce these concepts.

The unit contains lessons using agent-based computer simulations. For these, access to computers or tablets is necessary and students should be familiar with the basics of using such devices. The computer simulations can also be discussed with the entire class using just one computer and a projector or an interactive smartboard. The lessons using computer simulations can also be omitted; however, in this case, learning goals related to scientific practices (Section 2.4.2) cannot be targeted in the same manner.

Selected lessons can also be engaged by younger students, particularly Lesson 1 and the two foresters model, since the latter is very simple (for older students, this model might be introduced in a short interactive presentation, followed by moving on to more complex models). In Section 2.5 and the individual lesson documents, we highlight specific suitability and adaptations for different grade levels. Curriculum designers and teachers across grade levels are encouraged to think strategically about how to weave in lessons iteratively over grade levels.

2.4 Learning objectives

2.4.1 *Learning objectives related to awareness of the SSI*

Students are able to:
- Describe and explain the conditions and mechanisms that hinder and foster (the evolution of) cooperation around CPRs.
- Analyse case examples of CPR dilemmas in evolutionary biology and human ecology for dynamics that induce or prevent the ToC and develop solutions.

2.4.2 *Learning objectives related to evolution*

Students are able to:
- Describe the role of multiple mechanisms in the evolution of cooperation and sustainable use of shared resources.
- Evaluate evidence of the role of group behaviour on individuals' and species' probability of survival and reproduction.

2.4.3 *Learning objectives related to scientific practices*

Students are able to:
- Use and criticise models.
- Analyse and interpret data.
- Construct explanations and design solutions.

2.4.4 *Learning objectives related to the Nature of Science*

Students are able to:
- Understand that scientific investigations use a variety of methods, tools and techniques to revise and produce new knowledge.
- Understand that many decisions are not made using science alone but rely on social and cultural contexts to resolve issues.

2.4.5 *Learning objectives related to transversal skills*

Students are able to:
- Engage in socioscientific reasoning (Sadler et al., 2007):
  - (i) Recognise the inherent complexity of SSI.
  - (ii) Examine issues from multiple perspectives.
  - (iii) Appreciate that SSIs are subject to ongoing inquiry.
  - (iv) Examine potentially biased information with scepticism.

2.5 Description of the educational practice

The lessons presented here have been developed by building on instructional strategies of teaching for conceptual understanding and the transfer of learning by Stern et al. (2017, 2021).

As such, they focus on a core set of concepts and conceptual questions that are revisited across contexts. Student understanding is assessed by prompting them to reflect on their understanding of the concepts and conceptual questions, and/or to revise their causal models by integrating evidence from the lessons.

Core conceptual questions are:

- ? What problems can arise when a group of individuals has to share a common resource?
- ? What conditions and behaviours foster and hinder (the evolution of) cooperation and sustainability around shared resources?

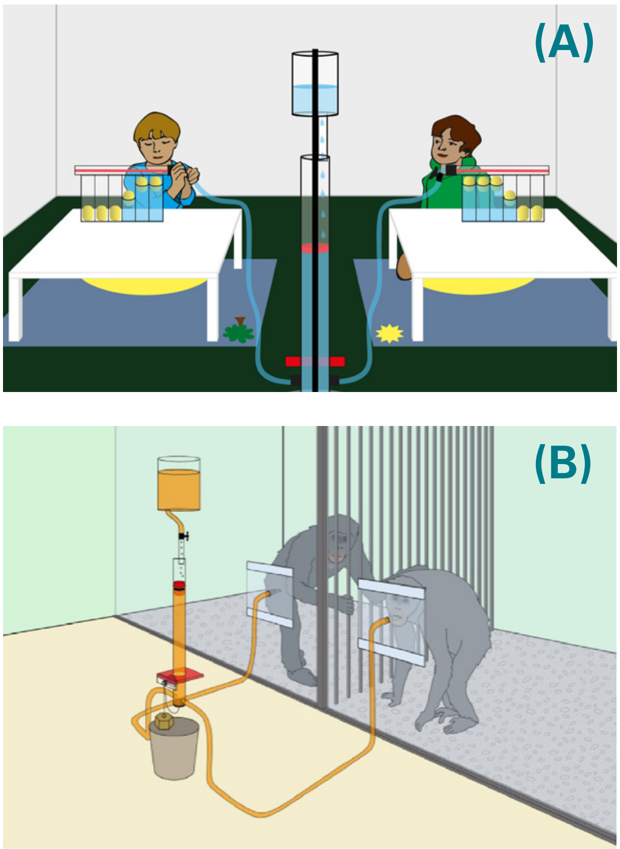
The following descriptions of lessons and recommendations for implementation draw on the authors' experiences in implementing lessons in secondary and teacher education contexts.

2.5.1 *Lesson 1: Chimps or children - Who is better at sharing resources?*

This lesson introduces a comparative series of experiments with chimpanzees and human children (Koomen & Herrmann, 2018a, 2018b; Fig. 4) and asks students to make predictions about the outcomes. The experimental setup models the situation of CPR use. The lesson elicits students' conceptions about the social behaviour of humans and our closest primate relatives. Thus, the lesson is suitable for introducing a number of basic concepts regarding sustainability science, cooperation and evolution in an engaging manner.

We recommend implementing this lesson with students as early as the 7th grade (12 to 13 years and above).

Figure 4
Experimental setup of the experiments with (A) children and (B) chimpanzees. Images sources: Koomen and Herrmann (2018a, 2018b).



Students are introduced to the experimental setup with the help of a short presentation, reading text or video. After this, they are asked to predict which of the two species (human children or chimpanzees) will be more successful at cooperating and sustaining a shared resource.

Students can be given the opportunity to ask clarifying questions about the experiment before they think about their prediction. Common questions concern the age of the chimpanzees, whether the chimpanzees or children knew each other, whether the partners were of the same sex and whether the children can communicate. In our experience (Hanisch & Eirdosh, 2021), many students and teachers tend to predict that chimpanzees would be more cooperative than children in this experiment, tending to give reasons such as, *'Chimpanzees need to live in harmony with nature', 'Chimpanzees live in groups and depend on each other'* or *'They need to share resources in their group', while children 'are greedy and selfish' or 'don't understand the situation'*. This may highlight possible misconceptions of students (and educators) about the causes of human sustainability issues.

In fact, humans are a much more cooperative species when compared to chimpanzees and other primates. Moreover, they can coordinate, communicate and share resources much more easily and fairly among their group than chimpanzees. Thus, the modern challenges of sustainability in our globalised world can be conceptualised as challenges of (cultural) adaptation, which involves devising and testing new mechanisms and technologies to ensure the sustainable use of shared resources.

Explanations for student predictions also often contain a range of causes that are explored by behavioural biologists, including the evolutionary, developmental and proximate causes and functions of traits (Tinbergen, 1963). Thus, the lesson can serve as an introduction to exploring the causes of organisms' (behavioural) traits.

After the minimal presentation of the experiment and discussion of the results (ca. 20–30 min), the lesson can be extended to explore how the experiments model real-world situations of shared resource use (e.g., using analogy maps) and how certain conditions could make it easier or more difficult to cooperate in such situations. For example, real-world cases included in the lesson materials include the shrinking of Aral Lake and Amazon rainforest deforestation; however, any focal issue involving (un)sustainable shared resource use can be used for this transfer.

Students can begin to create a causal map of the CPR situation by integrating factors of the resource and the behaviour of the resource users. In a unit on human evolution, the lesson can serve as an entry discussion about the evolutionary causes of our human social behaviours, as well as our similarities and differences to chimpanzees. The lesson plan lists a range of possible materials and ways to drive further reflection around this experiment.

At the end of this lesson, students could reflect on the question *'What conditions and behaviours allow humans to cooperate and share resources sustainably?'* and explain their answers by integrating evidence and insights from the lesson or providing a real-world example.

2.5.2 *Lesson 2: Agent-based models of social-ecological systems*

Evolutionary and sustainability scientists use agent-based models to understand the complex interactions among organisms and between organisms and their environments, as well as how such interactions impact the evolution of populations and ecosystems.

Agent-based computer simulations can also be used in the classroom to help students investigate and understand these processes. NetLogo (Wilensky, 1999) is a free software for agent-based models used in science (e.g., Aktipis et al., 2011; Ghorbani & Bravo, 2016; Waring et al., 2017) and education (e.g., Dickes et al., 2016; Wilensky & Reisman, 2006). We have developed a range of models of social-ecological systems to help students understand the mechanisms that influence the evolution of cooperation around CPR use.

A simple agent-based model that is conceptually similar to the previous lesson and allows the transfer and further abstraction of the dynamics of CPR use is the *'Two Foresters'* model. This is a model of a simple social-ecological system consisting of only two individuals and a renewable resource (trees). Through this model, students can observe how outcomes such as the accumulated harvest for each forester and the state of the forest are influenced by the parameters of harvest level, resource regrowth rate and carrying capacity (i.e., maximum tree height), and whether the resource is a common-pool or private resource.

Students can create a causal map of the factors and relationships represented in the model (or amend previously created causal maps), critically evaluate the model by comparing it to the real world with the help of an analogy table, and make predictions about how human traits and other factors might change these outcomes in the real world.

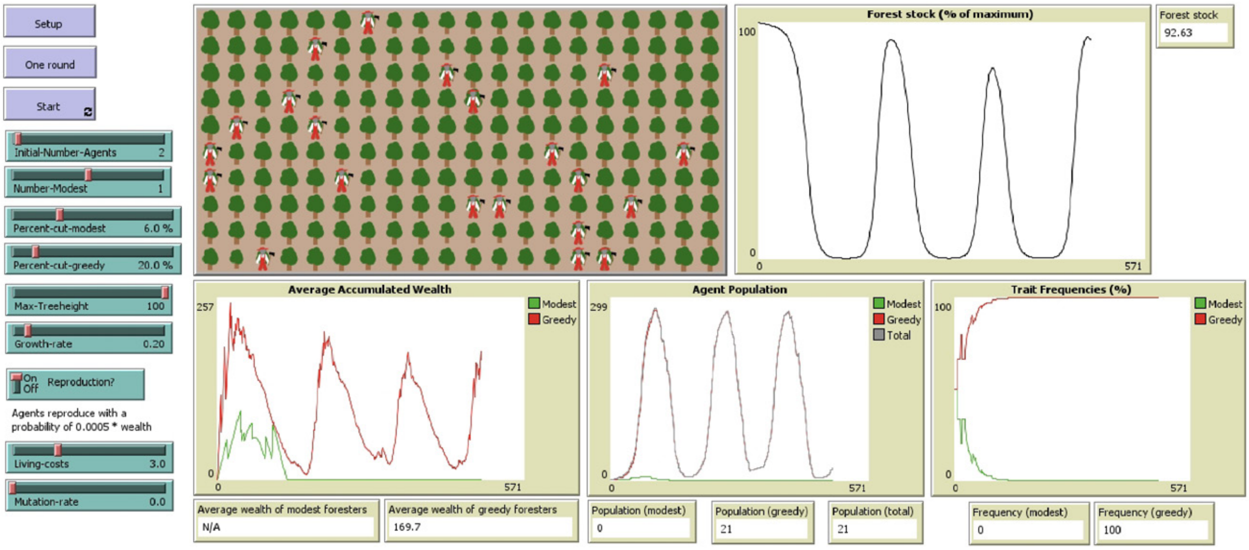
The lesson material contains a discussion guide to introduce the model and the NetLogo platform to students. In younger grades (5th to 8th grade; 11- to 14-year-olds), students can use the model to run and document experiments and reflect on results individually or in groups with the help of worksheets. In older grades (9th to 12th grade; 15- to 18-year-olds), the model might rather be used to introduce basic concepts and the use of the NetLogo platform, after which students can move on to explore more advanced models individually or in groups.

To follow up on the *'Two Foresters'* model, students can explore the model *'Evolution and competition for forest resources'* (Fig. 5). This model also simulates a population of foresters who harvest trees. It introduces further dynamics from the real world, including evolutionary processes of random variation, reproduction, inheritance, selection and predator-prey relationships. Due to the addition of evolutionary dynamics, students observe that, given the conditions and processes represented in the model, competition for resources leads to the depletion of the resource and the extinction of the forester population (i.e., the ToC) or boom-and-bust-cycles of population decline and growth (i.e., *'component tragedies'* according to Rankin et al., 2007, and predator-prey dynamics).

With the help of worksheets, students run experiments, make predictions, and describe and explain the observed outcomes. A payoff matrix can be used to document outcomes under different parameter settings and develop an understanding of social dilemmas.

Once again, students can create or extend their causal maps of the modelled social-ecological system, critically evaluate the model by comparing it to the real world with the help of an analogy table and think of other factors that might help stabilise or sustain the forester and tree populations in this social-ecological system. The extended resources presented in Section 2.6 propose further models that integrate mechanisms that can prevent the ToC.

Figure 5
User interface of the 'Evolution and competition for forest resources' model.



2.5.3 *Lesson 3: Understanding the evolution of cooperation around shared resources*

The previous lessons establish the basic challenge of cooperation around shared limited resources and pose the question of how cooperation evolves across life (including in humans).This lesson introduces the evolution of cooperation across examples of life with the help of a reading text.

After some reflections on the possible challenges of group life, the text introduces examples of multicellular organisms and honeybees as contexts to explore some of the mechanisms that have evolved to enable cooperation.

The lesson can optionally be expanded by a further reading text (contained in the lesson material) that explores the evolution of cooperation in human evolutionary history by looking at the social organisation of hunter-gatherer groups.

Further examples of the evolution of cooperation in biology can also be explored (see Section 2.6). Overall, this lesson reinforces the notion that certain behaviours and mechanisms must be in place to enable long-term cooperation and sustainability. These include the distribution of resources to where they are needed, as well as monitoring and sanctioning mechanisms to prevent selfish or harmful individuals from gaining fitness benefits (Table 1).

2.5.4 *Lesson 4: Analysing case studies of CPR use*

This lesson applies the previous learnings to an example of a real-world SSI and integrates another set of scientific methods for the study of social-ecological systems —namely, the analysis of real-world case studies to understand the conditions that tend to favour cooperation and sustainable resource use.

The lesson *'Three Mexican fisheries'* was developed based on the research of Basurto and Ostrom (2009), who investigated and compared three fishing villages in the Gulf of California with the help of the framework presented in Fig. 1.

In this lesson, students first explore findings about the ecology of one marine species and derive management recommendations for the sustainable harvesting of this species. Thereafter, they explore the historic, social, economic and political dimensions of each village via reading texts and use an analogy table integrating the factors of Fig. 1 to compare the villages and identify the factors that enabled or hindered villages in using their resources sustainably.

To prepare for the culminating activity and practice transfer, the lesson could end with a critical transfer of the analysis tool to a different real-world case. The lesson materials include climate change as an issue to be analysed.

2.5.5 *Lesson 5: Applying insights to a focal SSI*

The unit ends with a culminating project activity in which students use their understandings of the complexity of social-ecological systems and the analysis framework to analyse a focal SSI of the unit.

For this activity, the class could be divided into separate groups of experts. The lesson material contains a worksheet to guide students through the activity. Materials on the SSI can either be provided by the teacher or students can search for information in the media (thereby practising their media literacy skills as part of socioscientific reasoning). Expert groups then come together to integrate their findings into a causal map. Finally, the class decides on recommendations regarding the sustainability of the social-ecological system. For example, this can include recommendations for improving the knowledge base through the further inquiry of certain factors, recommendations for certain policies and practices that target the CDPs—or for the use or disuse of certain technologies.

Finally, students develop a way to communicate the results of their analysis to stakeholders whilst considering the motivations, goals, values, costs and benefits to stakeholder groups and communicating in a manner that empathises with them and speaks to their goals and values.

2.6 Further perspectives on how to use the activity in other contexts or with participants of other ages

As indicated in Fig. 1, the lesson sequence presented here can be extended in numerous ways.

Here, we highlight some of these possible extension lessons, which can also be found in the linked materials in the Appendix.

2.6.1 *Cooperation games*

One experiential method that can be used to introduce the challenge of cooperation in the classroom is cooperation games. An important aspect of using games in the classroom is the reflection phase.

We have developed a range of lesson materials for games that model the cooperation challenge around sustaining shared resources together with reflections on the concepts of the unit, including social dilemmas, cooperation, conditions that foster and hinder cooperation, and the functions of evolved human social behaviours.

For example, the *'Stone age hunting game'* simulates one of the cooperation challenges faced by our ancestors 2 mya in the African savanna and can serve to help students understand the early origins of human social behaviour. Moreover, the *'Climate change game'* models the cooperation challenges around global climate change. Whilst games can be used across different age groups, the rewards, level of reflection and introduced concepts should be adapted to suit the context.

2.6.2 *Additional agent-based models*

Agent-based models can introduce more and more processes and thus represent more and more real-world aspects. However, they will also become more complex in the process.

One set of factors that can limit the degree to which a situation of CPR use is prone to the ToC include diminishing returns of resource use and competitive behaviour (Foster, 2004; Rankin et al., 2007). For example, many organisms may not be able to fully exploit available resources due to limits on resource use efficiency, such that depletion does not occur. To transfer this to the human domain, the problems of sustainable resource use became more prevalent throughout human history with the advent of increasingly efficient technologies for resource extraction. This aspect is also apparent in the '*Three Mexican fisheries'* lesson.

This factor is simulated in the model *'Evolution of harvest rate'*, where students do not set the parameters for agents' harvest rate but the harvest rate itself evolves in the model. Instead, the parameter that the user sets is a factor for the fraction of energy costs that agents have to pay for harvesting. Students can create or extend their causal maps of the modelled social -ecological system, critically evaluate the model by comparing it to the real world with the help of an analogy table and think of other factors that might help stabilise (or sustain) the forester and resource populations in this social-ecological system in which foresters become increasingly efficient at extracting resources.

The model *'Evolution of social behaviour'* introduces one set of mechanisms that can help resolve the ToC —the monitoring of others in the social group and responding to them in such a way that selfish behaviour is curtailed (or has no more fitness benefits, or lower fitness benefits when compared to cooperative behaviour). This represents several of Ostrom's design principles for successful cooperation (Table 1). Notably, such mechanisms can be found in many species and symbiotic relationships (as described in Section 1.2 and the lesson on *'Life in groups'*).

Finally, the model *'Evolution of resource use through behaviour imitation'* simulates some cultural evolutionary dynamics of resource use behaviour by modelling a range of imitation biases that have been observed in humans (Mesoudi, 2016). This allows students to reflect on the similarities and differences between biological and cultural evolutionary dynamics and the role that imitation biases might play as causes and solutions to SSIs.

If computer programming and computational thinking are learning goals, then students can also modify and create their own models (Sengupta et al., 2013).

2.6.3 *Analysing further case studies of cooperation in biology*

To further transfer conditions and mechanisms that foster cooperation around shared resources (Table 1), students can more deeply explore examples of species that have evolved such mechanisms.

The extended resources contain a lesson on decision making in honeybee swarms based on Seeley (2010), with a critical transfer of principles to decision making in human groups.

2.6.4 *Evolution of human cooperation and social behaviour*

Understanding the role of human social behaviours in modern sustainability issues can be enhanced by exploring their evolution (e.g., within a unit on human evolution). A diversity of teaching materials for this can be found at:
http://human-evolution.globalesd.org.

2.6.5 *Understanding design principles for cooperation and finding solutions to real-world cooperation problems*

The lessons above introduce a variety of conditions and behaviours that foster or hinder cooperation across species and in humans. They implicitly relate to Ostrom's design principles for cooperation (Table 1).

These design principles can be explored in greater detail and used to analyse and improve cooperation dynamics that are relevant to students' lives, such as in a student project team, their classroom or their school community. The teaching material *'exploring the design principles for cooperation'* can be used for this extension.

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4. APPENDIX

All lesson materials can be accessed freely under the following link:

https://openevo.eva.mpg.de/teachingbase/evolution-cooperation-and-sustainability/

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Chapter 9

Considering evolution as a socioscientific issue: an activity for higher education

CHAPTER 9

Considering evolution as a socioscientific issue: an activity for higher education

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Abstract:

This activity aims to enhance participants' understanding of natural selection—which is a major mechanism in evolution—within the antibiotic resistance context. The activity starts by eliciting questions to explore participants' existing ideas about evolution and natural selection. Then, a scenario for discovering participants' ideas about antibiotic resistance is presented along with a series of questions, which is followed by a classroom discussion. The instructor explains the role of natural selection in antibiotic resistance and the three mechanisms of natural selection. In the last session, the teacher challenges participants' initial ideas with a whole-class discussion. At the end of the activity, participants are expected to understand that natural selection is one of the mechanisms of natural selection. Besides understanding natural selection concepts and the connections between these concepts, participants are expected to develop their decision-making skills whilst realising and respecting different perspectives. They should also learn how to develop arguments, justifications for their arguments, and counter-arguments (i.e., opposing arguments including different perspectives) for their justifications. This activity has been developed for senior students (aged 15–17 years old) and university students. Whilst the activity can be used for determining participants' existing knowledge and misconceptions about natural selection, natural selection concepts and evolution, it can also be used for assessment purposes—for example, determining students' argument construction quality and consideration of different perspectives (i.e., counter-arguments)—as explained at the end of the activity.

KEYWORDS

antibiotic resistance, argumentation, higher education, natural selection

1. INTRODUCTION TO THE SOCIOSCIENTIFIC PROBLEM

Socioscientific issues (SSIs) have been an interdisciplinary subject including non-scientific aspects (Fensham, 2012). SSI can be best described as social issues that are directly linked to science. However, these issues are poorly structured and controversial in nature. They include ethical and moral dilemmas, with scientific reasoning alone being insufficient for dealing with these issues due to their complex and ambiguous nature (Sadler, 2011).

Moreover, they require multiple perspectives—including ethical, moral, political and economic viewpoints—when making decisions (Fowler & Zeidler, 2016; Sadler & Zeidler, 2005; Zeidler & Sadler, 2008, 2011).

Making informed decisions related to SSIs requires the negotiation of students' own decisions (Fowler & Zeidler, 2016). Whilst negotiating and resolving complex SSIs, students often employ informal reasoning by considering the causes of different propositions and the effects of different choices, which eventually results in making informed decisions (Zohar & Nemet, 2002). Examples of SSIs present a wide range of issues, including climate change, genetic engineering issues, abortion and evolution (Cebesoy & Chang Rundgren, 2021; Fowler & Zeidler, 2016; Sadler & Zeidler, 2004, 2005).

SSIs represent a strong pedagogical tool that can be used to enhance students' argumentation skills (Garrecht et al., 2021; Guilfoyle & Erduran, 2021), decision-making skills (Cebesoy & Chang Rundgren, 2021; Eggert & Bögeholz, 2009; Fowler & Zeidler, 2010), reflective judgement skills (Karışan et al., 2018; Zeidler et al., 2009) as well as their informal reasoning (Sadler, 2005) and moral reasoning (Lee et al., 2012), understanding of the nature of science (Abd-El-Khalick, 2003) and the quality of their argumentation skills (Kolstø, 2006; Zohar & Nemet, 2002).

1.1 Socioscientific issues and evolution

SSIs are considered an important venue for improving students' scientific literacy through school curriculums (Chen & Xiao, 2021; Fowler & Zeidler, 2016; Zeidler et al., 2019; Zeidler & Sadler, 2008). In terms of biology related content knowledge, a scientifically literate individual must have a fundamental comprehension of biological principles and processes to make sense of situations in daily life. In this respect, the theory of evolution can be considered one of the most important topics in biology (Fowler & Zeidler, 2010, 2016; Sadler, 2005). According to Hermann (2013), the theory of evolution provides *'the best explanation for the diversity and interrelatedness of species on Earth'* (p. 598).

The term *'evolution'* has long been used in astronomy, geology, anthropology, biology and other scientific disciplines to describe many types of cumulative changes over time. However, biological evolution—which refers to the changes in living organisms over the long history of life on Earth—is the subject of this chapter (National Academy of Sciences, 1998).

1.2 Considering evolution as a socioscientific issue

Evolution can be described as 'the biological change in populations of organisms over time and is explained by the scientific theory of natural selection' (Fowler & Zeidler, 2010, p. 2). The topic of evolution includes the concepts of adaptation, reproduction, genetic variation, DNA and protein sequences, common ancestry, fossils and plant and/or animal diversity (Fowler & Zeidler, 2016, p.4). Among these concepts, the present educational activity focuses on the concept of natural selection.

The biological change in populations over time is explained by natural selection and it is one of the fundamental mechanisms of evolutionary change (Fowler & Sadler, 2016; Gregory, 2009). It can be difficult to comprehend why living things have such diversity without a solid understanding of natural selection (Gregory, 2009). As a consequence, the main focus of this activity is to enhance students' understanding of natural selection and how natural selection facilitates diversity in living organisms.

Fowler and Zeidler (2010) argued that evolution itself is not an SSI because it lacks basic characteristics such as being poorly structured or a controversial issue. Since evolution is universally accepted by the scientific community, it is not solely an SSI. However, these authors insisted that it is an SSI negotiation where SSI and evolution overlap. In support of this claim, studies have reported that undergraduate students' understanding of evolution has had a significant effect on their decisions when dealing with SSIs (Sadler, 2005; Sadler & Zeidler, 2004; 2005).

Therefore, Fowler and Zeidler (2010) insisted on the need for additional research on the connection between knowledge of and acceptance of evolution. They also noted that biology-based SSIs would be beneficial for SSI teaching. In contrast, Hermann (2008) considered evolution an SSI because it meets the four criteria for a controversial issue: (1) there are at least two opposing groups (i.e., evolutionists vs. creationists); (2) there needs to be a heated debate between supporters of opposing groups; (3) the answer of the heated debate is not evident for supporters of each side; (4) there is accepted uncertainty and disagreement about evolution for supporters of each side.

Supporting Fowler and Zeidler's (2010) claims, existing studies have revealed that evolution is one of the major factors exposed during SSI negotiations (Basel et al., 2013; Brehm et al., 2003; Fowler & Zeidler, 2016; Sadler, 2005). By exploring college students' informal reasoning in genetic engineering issues, Sadler (2005) revealed that students' decisions were influenced by evolutionary concepts such as genetic diversity and reproduction, which were stressed as building blocks of evolution. Still, some students adopted teleological (i.e., having a purpose or directive principle) and deterministic views of evolution in their decisions. In another study, Fowler and Zeidler (2016) explored how evolution acceptance influenced undergraduate biology and non-biology majors' decisions related to biology-based SSIs. They revealed that evolution acceptance is a mitigating factor in how science content knowledge is linked to evolution, which was elicited during SSI negotiation.

The students generally used evolutionary concepts such as population diversity, the inheritance of traits, differential success and change over time in their negotiations. As evident in the aforementioned studies, evolution and the concepts of evolution can be revealed as a consequence or influencing factor during SSI negotiations. Evolution could also be used as an SSI topic if it is carefully designed and includes Hermann's (2008) four criteria. Here, argumentation is proposed as a tool for dealing with evolution as an SSI. In the following subsection, brief descriptions of the components of argumentation and how argumentation could be used as a context are presented.

1.3 Argumentation as a tool for dealing with evolution as an SSI

Over the past few decades, argumentation has emerged as a significant field of research in science education (Lin et al., 2014). It can be defined as the process of a group of people proposing, supporting and analysing evidence—in addition to its connection with different theories—to convince the scientific community (Kuhn, 1993). Whilst the claim/argument refers to *'conjecture, conclusion, explanation, descriptive statement, or an answer to a research question',* the evidence refers to *'the reasons used by scientists including measurements, observations or even findings from other studies'* (Sampson & Gerbino, 2010, p. 428).

Evidence can be formed in multiple formats: (a) accepted theories; (b) laws; (c) models in science; (d) the findings of other research. Individuals use this evidence to support their claims. Notably, this is commonly used as data. There should be a third component *'rationale'* in scientific argumentation referring to why the evidence should be considered evidence and how it supports a claim (Sampson & Gerbino, 2010). The backing provides additional support for an argument. Lastly, a qualifier identifies the limits of an argument to be true by using words such as *'always', 'sometimes'* or *'usually',* among others (von Aufschnaiter et al., 2008). Since argumentation is frequently used in the SSI literature (Garrecht et al., 2021; Kolstø, 2006; Zohar & Nemet, 2002), it can be used as a useful tool for revealing students' reasoning and decision-making skills in SSIs. Moreover, argumentation is also used in the context of evolution (Basel et al., 2013; Guilfoyle & Erduran, 2021). For instance, Basel et al. (2013) explored students' argumentation skills in the context of evolution.

They revealed that students tended to generate single claims with single evidence including either data or warrants, thus showing a low level of complexity. The number of students using multiple types of evidence, qualifiers/backing or rebuttals (counter-arguments) was quite low. In another study by Guilfoyle and Erduran (2021), argumentation was used when discussing the evolution versus creationism debate. Thus, argumentation can serve as a useful tool for dealing with evolution in science courses.

2. PRACTICE DESCRIPTION

This activity has been planned and implemented in formal contexts (i.e., classrooms, etc.).

2.1 Materials

For this activity, three major reading materials are used by participants. The links for these are:

1. https://www.bbc.com/turkce/haberler-dunya-54109247
2. https://sagligim.gov.tr/akilci-antibiyotik-kullanimi/940-antibiyotik-direnci-nedir.html
3. https://bilimgenc.tubitak.gov.tr/makale/bakteriler-antibiyotiklere-karsi

2.2 Time

The estimated time for completing this activity is 6 class hours (i.e., 6 x 50 minutes = 5 hours). If possible, after 2 class hours (i.e., 100 minutes), a break could be provided or the activity could be implemented on different days (i.e., 2 class hours x 3 days) to improve students' comprehension.

The activity could also be implemented on consecutive days.

2.3 Target audience

This activity can be performed with university students (aged 18–22 years old). It can also be performed with senior students (aged 15–17 years old) without changing the structure of the original activity. Whilst the activity is appropriate for the older group audience, it can also be adapted for high school students (aged 12–14 years).

For high school students, teachers/educators can choose one of the reading materials. Notably, Reading Material 3 can be used for this purpose since it is informative and includes more graphics and less text.

2.4 Learning objectives

At the end of this activity, the participants are expected to achieve the following.

2.4.1 *Learning objectives related to awareness of the SSI*

- To develop their understanding of SSI;
- To develop their decision-making skills;
- To realise the existence of different perspectives;
- To make informed decisions related to natural selection.

2.4.2 *Learning objectives related to evolution*

- To realise natural selection as one of the mechanisms of evolution;
- To identify variation, heritability/inheritance and reproductive advantage/differential reproduction as the three main concepts of natural selection;
- To discuss the role of variation, heritability/inheritance and reproductive advantage/differential reproduction in understanding natural selection;
- To recognise the role of mutations as significant sources of genetic variation.

2.4.3 *Learning objectives related to scientific practices*

- To construct explanations;
- To engage in argumentation and seek evidence;
- To obtain, evaluate and communicate information

2.4.4 *Learning objectives related to scientific practices*

- To realise that science is based on empirical evidence.

2.4.4 *Learning objectives related to transversal skills*

- To analyse issues from multiple perspectives.

2.5 Description of the educational practice

The primary aim of this activity is to have participants engage in the topic of natural selection within the context of antibiotic-resistant bacteria.

Session 1 (2 x 50 minutes)

The instructor provides a written form consisting of the questions provided below. Students are asked to answer the questions individually before the activity begins (30 minutes for this pre-activity). Students are asked to write their answers. These questions will be discussed at the end of the activity as a whole-class discussion to determine whether they changed their initial perspectives.

A1) What do you know about the theory of evolution?

A2) Do you personally accept the theory of evolution?

A3) Choose one of the statements below by ticking (e.g.,)

( ) I think the theory of evolution is valid.
( ) I think the theory of evolution is invalid.
( ) I think the theory of evolution is partially valid.

A4) Why do you think the theory of evolution is a valid/invalid/partially valid theory? Can you provide reasons for your position?

A5) If someone holds an opposing position to yours on this issue, what arguments might he/she have?

A6) If you want to convince your friend about your position, what arguments would you propose?

The activity begins with a scenario about Mrs Jones (a fictitious character), who was using chemotherapy drugs and had a comprised immune system. Then, six questions to explore participants' knowledge and prior experience with antibiotic resistance were asked on an activity sheet, which is shown below:

Scenario

Mrs Jones (a fictitious character) has a comprised immune system due to the chemotherapy drugs she used once in a while. Since her cancer treatment, she often gets sick due to infections. Her doctor prescribes her some antibiotics as a treatment.

B1) Do you know why the doctor might be prescribing antibiotics to Mrs Jones?

B2) How do antibiotics affect bacteria?

B3) What happens if Mrs Jones wants to use the same antibiotics for her flu as well?

B4) Should the doctor prescribe antibiotics for her flu? Why or why not

B5) What happens if Mrs Jones is really feeling bad and insists on taking antibiotics for her flu?

B6) What do you know about antibiotic resistance?

Students are then asked to write down their answers on the activity sheet individually (30 minutes). Then, the instructor organises a whole-class discussion about participants' individual answers to reveal their existing knowledge about antibiotics and antibiotic resistance (40 minutes). If possible, the instructor can use digital tools like Mentimeter

(https://www.mentimeter.com/plans), slido (https://www.slido.com/product) or padlet (https://padlet.com/features). These digital tools are appropriate for engaging all students when participating in a whole-class discussion.

After Session 1, a break should be provided. If possible, the next session could be held on another day. In the interim, the instructor should check the answers. This information can be used to determine participants' existing ideas about antibiotic resistance, natural selection and evolution.

Session 2 (2 x 50 minutes)

The instructor divides the students into groups of four to five and the activity continues with group work. The instructor hands out three reading texts (see the Appendix) along with new questions and provides an appropriate amount of time for reading (ideally, the three reading texts are given in order). After reading the texts, the participants are asked to work in groups to answer the questions provided below. The groups are first asked to discuss and then write down their collective answers on the activity sheet (20 minutes for reading and 30 minutes for answering):

C1) How do antibiotics work against bacteria?

C2) How do the bacteria become resistant to antibiotics?

C3) What do you think about the relationship between natural selection and antibiotic-resistant bacteria?

C4) How does natural selection explain bacteria becoming resistant to antibiotics?

Next, the instructor explains the mechanisms of bacteria becoming resistant to antibiotics and the definitions of natural selection concepts (Table 1).

There are three essential components of natural selection: (a) The trait must vary in the population; (b) it must be heritable; (c) individuals with a particular type of variation must have a reproductive advantage over those who do not (30 minutes).

Table 1
Natural selection concepts.

Concept	Description
Variation	A trait variation becomes more or less common in a population over time as a result of natural selection. Notably, the variations should act randomly and must be passed from parent to offspring.
Heritability/ inheritance	Some traits are consistently passed on from parent to offspring. Such traits are heritable, whereas other traits are strongly influenced by environmental conditions and show weak heritability.
Reproductive advantage/ differential reproduction	This is an evolutionary mechanism that works by altering the heritable traits of a population. For instance, if an individual has an advantageous trait, then it is more likely to reproduce. Therefore, this trait becomes more common in a population over time.

Along with these three essential mechanisms, the instructor should also explain the role of mutations in natural selection because variation can arise as a result of mutations (University of Michigan, nd). Mutations are structural alterations to DNA molecules and represent significant sources of genetic variation. The mutations can be neutral, harmful or helpful. The instructor must note that mutations occur randomly without considering the advantages or disadvantages of the mutations (i.e., mutations do not arise because they are needed) (National Geographic, nd).

Session 3 (2 x 50 minutes)

In the final part of the activity, the instructor explains how natural selection plays a crucial role in the theory of evolution and asks the following questions, which students should write their answers to individually (20 minutes):

D1) What is the role of natural selection in evolution?

D2) Did you change your initial answers about evolution in Questions A2 and A3? Please explain why or why not.

D3) If your classmate disagrees with you, what might be possible reasons for her/his position?

D4) How would you convince your classmate about your position? Please explain.

Whole-class discussion (2 x 50 minutes)

The questions (D1–D4) were designed to navigate a whole-class discussion from an argumentative perspective. The participants are expected to make explicit connections between the theory of evolution and natural selection and how natural selection plays a crucial role in evolution.

By using the questions (D1–D4), the instructor challenges the initial answers participants provided in Session 1. They can revise their answers in light of the new information provided (i.e., the reading texts and the instructor's teaching material). A whole-class discussion at the end of the activity will facilitate participants' understanding of different perspectives about evolution.

Proposing counter-arguments (rebuttals) and providing justifications (evidence) for opposing ideas in evolution will also facilitate participants' understanding of the SSI. Even if the theory of evolution itself is not scientifically debatable, acceptance of evolution among participants provides an excellent opportunity to discuss different perspectives regarding the theory of evolution since it is related to cultural and social background.

The instructor can complete the activity by explaining how the acceptance of evolution can be regarded as an SSI requiring multiple perspectives whilst dealing with and making decisions about it. If possible, the instructor can use digital tools such as Mentimeter (https://www.mentimeter.com/plans), slido (https://www.slido.com/product) or padlet (https://padlet.com/features). These digital tools are appropriate for engaging all students when participating in a whole-class discussion. The instructor could use participants' written responses for assessment purposes. The written responses could be analysed to determine existing misconceptions about evolution and natural selection. Additionally, the quality of participants' written argumentation can be analysed using Zohar and Nemet's (2002) evaluation criteria. For instance:

A1) Why do you think the theory of evolution is a valid/invalid/partially valid theory? Provide reasons for your position.

This question is asked to identify participants' positions (arguments) and for them to support their arguments with justifications (reasons). It can be scored as 0 points for no justification, 1 point for one justification and 2 points for two or more justifications.

D2) Did you change your initial answers about evolution in Questions A2 and A3? Please explain why or why not.

This question is asked to make participants think about revising their arguments with justifications, backings and—if possible—qualifiers (this time, we expect them to use knowledge about natural selection and antibiotic resistance in their justifications). The same criteria presented above are used for the analysis.

A5) If someone holds an opposing position to yours on this issue, what arguments might he/she have?

D3) If your classmate disagrees with you, what might be possible reasons for her/his position?

These questions are asked to reveal whether participants could propose opposing argument(s) and support these with justifications.

Opposing arguments should be analysed using the same criteria used to analyse the original argument. Whilst question A5 was designed to determine participants' ability to produce counter-arguments before the activity, D3 is asked to determine their ability to do so after the activity. The instructor can also compare participants' pre- and post-activity answers.

A6) If you want to convince your friend about your position, what arguments would you propose?

D4) How would you convince your friend about your position? Please explain.

These questions are asked to determine whether participants could refute an opposing argument and support it with evidence before (Question A6) and after the activity (Question D4). The same analysis pattern is used.

TIP 1

If possible, and if the resources are available, the activity can be expanded by including a laboratory investigation of the development of antibiotic resistance in a bacterial population over time (see Williams et al., 2018). Through this, participants can set up an experimental procedure for observing antibiotic resistance. First, they can set up control and antibiotic (experimental) plates under the supervision of the instructor. Then, they take samples from a bacterial culture and place them on the control and antibiotic plates. They can then add an appropriate antibiotic to the antibiotic plate. After a while, they observe an increase in the bacterial colonies on the antibiotic plate due to mutations. Lastly, they can have a whole-class discussion about their observations at the end of the activity. Details on this type of activity can be found in Williams et al.'s (2018) study. This step can be useful for developing NOS aspects of how scientific knowledge accumulates based on evidence and observations.

TIP 2

It can be useful to provide the activity to the participants with the questions in a written format. Collecting participants' written responses will be useful in terms of analysing participants' written arguments and possible misconceptions.

2.6 Further perspectives on how to use this activity in other contexts or with participants of other ages

This activity was planned and implemented in formal education contexts.

For this reason, there is an informative part (natural selection concepts; see Table 1) that will enhance the argumentation portion. In informal contexts, the informative part could be summarised.

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4. APPENDIX

The three reading materials used in this activity are presented as follows:

Reading Material 1
Superbug: Antibiotic-resistant bacteria may be riskier than the coronavirus*

After 3 years of work in Fiji, Researcher Paul De Barro concluded that antibiotic-resistant bacteria—also referred to as 'superbugs'—are *'the greatest threat to human health, without exception'.*
According to The Guardian, Australian scientist Dr Paul De Barro argued that antibiotic-resistant bacteria could be a very serious health threat that could return modern medicine to *'the Middle Ages'.* Dr De Barro said, *'If you think COVID is bad, then you do not ever want to encounter antibiotic-resistant bacteria'.* He added, *'I don't think I'm exaggerating when I say this is the biggest health threat without any hesitation. COVID can't even come close to the effects of antimicrobial resistance'.*
Although drug-resistant bacteria threaten public health around the world, the effects are more apparent in the Pacific, where the risk has become even more apparent. This situation could push the region's fragile healthcare systems to a breaking point.
*The original article is in Turkish and was translated into English by the author.

Link:
https://www.bbc.com/turkce/haberler-dunya-54109247

Reading Material 2
What is antibiotic resistance? *

Antibiotics are medicines that are used to kill bacteria. Some bacteria can naturally resist these antibiotics. Over time, some bacteria may adapt to certain antibiotics. Antibiotic resistance is an example of this adaptation process: Resistance to a particular antibiotic means that the antibiotic cannot kill or prevent the reproductionof resistant bacteria at the therapeutic dose. Antibiotic-resistant bacteria gain an advantage over non-resistant bacteria in the presence of antibiotics. As a result, most of the bacteria in the environment become resistant to those antibiotics after a certain period. Additionally, bacteria can transfer the genetic material that causes resistance to different bacteria, which significantly contributes to the spread of antibiotic resistance among bacteria. Diseases caused by resistant bacteria pose a serious health threat—especially in intensive care settings and in patients with compromised immune systems. The diseases caused by resistant bacteria are resistant to treatment and cause prolonged hospitalisation, the development of related complications and an increase in mortality and disease rates. If antibiotic resistance is not prevented, the danger that awaits us in the future is much greater than this. Soon, antibiotics may become completely ineffective in the treatment of infectious diseases, resulting in even simple wound infections potentially resulting in death.

Antibiotic resistance as a global problem:

Antibiotics are clinically important drugs used in the treatment and prophylaxis of infectious diseases caused by microorganisms. The discovery of antibiotics has been an important turning point in terms of human health, with mortality and morbidity rates due to infectious diseases having decreased dramatically since the clinical use of these drugs. However, with the discovery of antibiotics, it was almost simultaneously predicted that microorganisms may acquire resistance to these drugs. Thus, if the necessary precautions are not taken, existing antibiotics will lose their effectiveness in the treatment of infectious diseases, resulting in humanity potentially encountering the pre-antibiotic era once again. The importance of global initiatives to prevent antibiotic resistance is not new. In 1998, the General Assembly of the World Health Organization (WHO) concluded that member countries should take action against antibiotic resistance. In 2001, the WHO Global Strategy for Limiting Antibiotic Resistance was published. The 2005 decision of the General Assembly of the WHO drew attention to the slow progress on limiting antibiotic resistance and called on providers and consumers to use antibiotics rationally. To draw attention to the importance of the threat to public health, the WHO determined the theme of World Health Day 2011 as antibiotic resistance and called on the whole world to think about this issue and take action and responsibility to stop the development of resistance. Antibiotic resistance is a very serious health problem that concerns the entire world both today and in the future. Currently, antibiotic resistance mechanisms are accepted as a part of the evolutionary processes of bacteria. Accordingly, it is foreseen that antibiotic resistance will always exist as it always has and that there is not and will not be an antibiotic that is not resistant to its effect. Moreover, it is accepted that the plan to combat antibiotic resistance should be based on this assumption. Additionally, it is thought that clinically important resistance mechanisms and resistant bacterial species may change over time. For these reasons, the production of new antibiotics at regular intervals suggests that these antibiotics should be specific to certain resistance mechanisms and that their use should be limited to these conditions.
*The original article is in Turkish and was translated into English by the author.

Link: https://sagligim.gov.tr/akilci-antibiyotik-kullanimi/940-antibiyotik-direnci-nedir.html

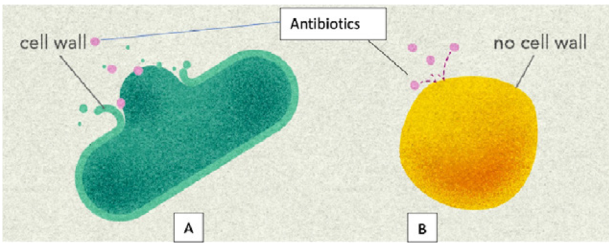
Reading Material 3
Bacteria vs. antibiotics*

If you have visited a doctor recently, you may have encountered a warning on the walls of the hospital: *'Do not insist on your doctor prescribing antibiotics'.* Why is this warning made? Why do we use antibiotics? Are antibiotics dangerous? Let's look at the answers to these questions together. Although there are many bacteria in our bodies, not all of these are harmful. For example, beneficial bacteria living in the gut help our metabolism function. On the other hand, harmful bacteria can cause various infections in the body. Antibiotics are used to fight infections caused by these bacteria. Antibiotics fight infections by killing bacteria or preventing them from growing and reproducing.
On the other hand, antibiotics do not affect viruses. Since the sources of diseases such as colds, flu, pharyngitis (throat infection) and bronchitis are mostly viruses, antibiotics are useless against these infections. Bacteria gain resistance In some cases, antibiotics cannot effectively destroy bacteria. This condition is called *'antibiotic resistance'.* It occurs when bacteria develop the ability to survive against antibiotics. This process can occur in a variety of ways.

Natural (intrinsic) resistance

Sometimes bacteria continue to live and grow despite antibiotic treatment. For example, whilst many bacteria have a cell wall made up of amino acids and sugars that surround them (Figure 1, A), some bacteria do not have a cell wall (Figure 1, B). Penicillin, the world's first antibiotic (discovered in 1927) prevents cell wall formation in bacteria. Therefore, penicillin or an antibiotic with a similar effect mechanism cannot harm bacteria that already have no cell wall (Figure 1, B). As a result, while Bacteria A will be affected by penicillin, Bacteria B will continue to grow in the presence of the antibiotic. In Figure 1, Bacteria B is naturally resistant to penicillin.

Figure 1
Figure showing Bacteria A (with a cell wall) and Bacteria B (with no cell wall) and how penicillin affects both bacteria (retrieved and adapted from https://microbeonline.com/lists-bacterial-pathogens-intrinsic-antibiotic-resistance/)



Acquired resistance

Bacteria can also become resistant to antibiotics over time. This occurs when a type of bacteria changes the way it protects itself from antibiotics. Bacteria can acquire resistance in two ways: by undergoing a new genetic change (spontaneous mutation) that helps the bacteria survive, or by acquiring a resistance gene from another antibiotic-resistant bacteria (horizontal gene transfer). Whilst spontaneous mutations can result in antibiotic resistance by altering the target of the antibiotic, its expression level, or the regulation of resistant genes, the horizontal gene transfer mechanism is another way to acquire resistant genes. Horizontal gene transfer enables bacteria to share their genetic material—including antibiotic resistance genes. Whether acquired by horizontal gene transfer or mutation, resistant bacteria can continue to grow in the presence of antibiotics, whilst sensitive bacteria are eventually halted. Thus, resistant bacteria can swiftly outnumber more sensitive bacteria and spread throughout a population.

Why is antibiotic resistance important?

Antibiotic resistance is one of the most important threats to human health because diseases that cause dangerous infections but can be easily treated with antibiotics become incurable over time due to antibiotic resistance. Diseases caused by antibiotic-resistant bacteria are very difficult to treat since it is much more difficult to destroy resistant bacteria. As a result, new antibiotics need to be developed for antibiotic-resistant bacteria. Therefore, antibiotic resistance both jeopardises the lives of patients and makes the treatment of diseases more costly. Antibiotics are not only used for treatment but also for preventing diseases. For example, patients undergoing chemotherapy treatment have weakened immune systems and an increased risk of infection. Therefore, doctors may recommend the use of antibiotics to prevent illnesses in these patients. Also, after open surgeries (e.g., heart surgery or organ transplantation), patients can be given antibiotics to prevent infections from the environment. Thus, infections caused by bacteria can be prevented or their effects can be reduced. This helps to reduce deaths from infection.

*The original article is in Turkish and was translated into English by the author.

Link: https://bilimgenc.tubitak.gov.tr/makale/bakteriler-antibiyotiklere-karsi

Additional sources used in reading material 3:
Figure 1 was adapted from:
https://microbeonline.com/lists-bacterial-pathogens-intrinsic-antibiotic-resistance/

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https://doi.org/10.1146/annurev-micro-090817-062148

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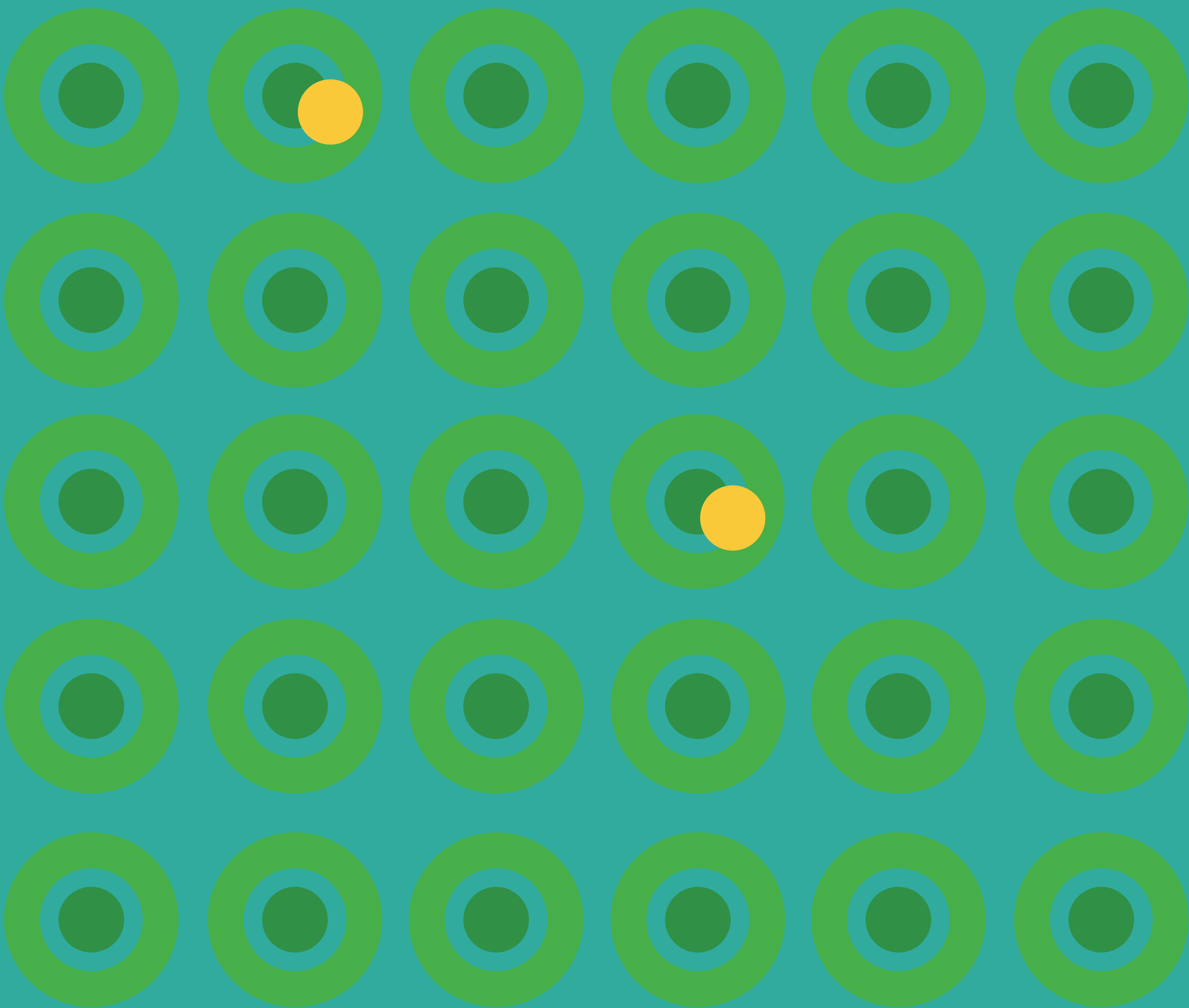
https://doi.org/10.1126/science.aad3292

Chapter 10

Why are pollinators declining?



CHAPTER 10

Why are pollinators declining? Balancing pollinator health and stakeholder assets

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Abstract:

Insects form the largest group of animals on the planet, with 1 million described species and an estimated 5 million or more that remain unidentified (Stork, 2017). They provide a wide range of ecosystem services, including pollination. Due to anthropogenic activities causing habitat loss and fragmentation, pesticide impacts and climate change, pollinators are in decline, which can result in reduced agricultural yield and impacts on ecosystem function. This activity aims to illustrate that the decisions made by farmers can influence the rate and severity of pollinator decline whilst also highlighting the difficulties that farmers face in running farms in the most optimal, eco-friendly manner and still making a living in the present socio-economic context. In this activity, students will play the role of a farmer trying to balance money and pollinator health whilst riding the storm of unexpected events that can affect their success. This activity is aimed at young teenage students aged 11–14.

KEYWORDS

farming, diversity, insect, climate change, agriculture

1. INTRODUCTION TO THE SOCIO-SCIENTIFIC PROBLEM

Insects are found worldwide and have adapted to live in many environments, from hot arid deserts to tropical forests and mountain alpine meadows.

The insects that live in these different habitats have several morphological and behavioural adaptations that allow them to successfully survive and reproduce within their environment.

1.1 Plants and pollinators

Plant-pollinator relationships are an essential part of the ecosystem. Without plants, pollinators would have less food and decline in number, which would have a knock-on effect on other animal species. Also, many plants would not be able to sexually reproduce without pollinators. Wildflowers and other native taxa are declining in abundance due to habitat loss, which places even greater importance on the animals that play a role in their life cycles (Cane, 2008).

Many different types of pollinators exist, including birds, bats, moths, butterflies, beetles and bees (Halder et al., 2019). The process of animal pollination occurs when a pollinator visits a flower to search for food (i.e., nectar or pollen). When the animal approaches the flower, it brushes against the male parts (anthers), which produce thousands of pollen grains. The pollen grains get stuck to the animal's body so that when the next flower is visited, the pollen comes into contact with the female part (the stigma), resulting in fertilisation. Notably, not all flowering plants are pollinated by animals; for example, some rely on wind to carry pollen from one flower to another (Culley et al., 2002).

Since an estimated 87.5% of flowering plant species depend on animals to transfer pollen from one flower to another, they have evolved various strategies for attracting pollinators (Ollerton et al., 2011). The shape, colour and odour of flowers act as signals to attract different groups of pollinators. For example, bat- and moth-pollinated flowers are usually white and heavily fragrant because these animals are most active at night and would not be able to identify brightly coloured petals, thus relying on scent signals instead (Halder et al., 2019).

Once fertilised, flowers complete their reproductive cycle and produce seeds, which may grow into mature plants under the correct conditions. Humans have cultivated plants for many thousands of years to harvest their fruit or seeds. Foods such as chocolate, coffee, nuts, tomatoes and berries all originate from plants that have been pollinated by insects. In fact, approximately one-third of the food we eat originates from an insect-pollinated plant, which highlights the high economic value of insect pollinators worldwide (Klein et al., 2007).

Fruit set is the proportion of a plant's flower that develops into fruit or seeds, which is influenced by pollination. Farms with high pollinator diversity have been shown to produce larger yields and higher quality fruit when compared to those with a low diversity of insect pollinators. In a study of 41 animal-pollinated crops, wild insect visitation enhanced fruit sets in all crops (Garibaldi et al., 2013), which highlights the importance of wild pollinator conservation.

1.2 Specialism and generalism

As Darwin noted in 1876, bees tend to *'visit the flowers of the same species as long as they can before going to another species'* (Darwin, 1876). This tendency to temporarily specialise is beneficial to plants that require conspecific pollen for fertilisation to occur; however, this is also beneficial for bees since floral fidelity can improve foraging efficiency (Chittka et al., 1999). Despite this, specialism comes at a cost to species since high levels of specialism in an ecosystem can lead to fragility in times of environmental change. A plant that can only be pollinated by a single pollinator species ties its fate to that of its pollinator. Therefore, there is a crucial balance between levels of specialism to preserve robustness in ecosystems (Brosi, 2016).

An example of a specialist pollinator is Peponapis pruinosa, the squash bee, which can pollinate squash more quickly and efficiently than introduced honey bees (Tepedino, 1981). However, agricultural activities such as using pesticides and tillage can damage squash bee populations. Thus, it is important to conserve specialist pollinator species since they are often more effective pollinators (Larsson, 2005).

Furthermore, there is evidence suggesting that levels of specialisation can change since climate change, habitat fragmentation and range shifting leads to decreased fitness among more specialised species. In Colorado, bee tongue length appears to be rapidly evolving from long tongues specialised for collecting nectar from deep flowers to shorter tongues adapted for effective nectar collection from a broader range of flowers (Miller-Struttman et al., 2015).

This leaves the deep, tubular flowers at risk of extinction if there are no pollinators specialised to pollinate them.

1.3 Causes of pollinator decline

Domesticated bumble bee and honey bee species are commonly used to subsidise the pollination services performed by wild pollinators. Bumble bees and honey bees are ideal to manage on farms because they are social, live in hives consisting of thousands of individuals, and are low cost and convenient to use. However, these species are not as effective at pollinating certain crop flowers when compared to other species of wild pollinators. In a study of 41 crops, researchers discovered that honey bees (*Apis mellifera L.*) produced a lower fruit set and were less consistent for fruit production than wild bees (Garibaldi et al., 2013).

There are several ways in which domesticated bees may negatively affect wild pollinator populations, including competition for resources such as nectar, pollen or nesting habitats. In the presence of imported honey bees, wild bees may be forced to forage on plants with lower nutritional quality or spend more time—and therefore energy—foraging on flowers that are a greater distance from their nest (Mallinger et al., 2017). Managed bees are often stocked at high densities, which makes them more likely to harbour pathogens than solitary wild bees. The transmission of pathogens from managed bees can occur via contaminated pollen, faeces or contact with shared floral resources (Graystock et al., 2016).

The extent to which disease spread affects wild pollinator health would depend on the density of managed pollinators and the type of pathogen. As human populations have grown, increased pressure has been placed on the land, thereby causing a decline in insect abundance. Land use change is a key driver of pollinator decline that has been documented for many groups, including bees, butterflies and hoverflies (IPBES, 2016; Powney et al., 2019).

The increased urbanisation of land has led to the removal and fragmentation of natural habitats to make room for housing, infrastructure, farms and other man-made structures. Furthermore, farming has changed dramatically over the last century. Historically, farmland was a mosaic of habitats including flower-rich meadows, hedgerows and flowering weeds. More recently, farms have expanded into large areas of monoculture that use pesticides and fertilisers. Also, many have removed semi-natural habitats, thus creating environments that are inhospitable for wild insect communities.

As climate change brings extreme weather and a warming planet, there is evidence of the impact of increased temperatures on insect populations. The ranges of some insects have begun to shift, with some North American and European species moving away from the southern edges of their ranges and occupying the higher elevations of mountainous regions (Pyke et al., 2016). There is also some evidence of phenological mismatch, whereby the flowering times of plants and the emergence of insects have become uncoupled (Kudo & Cooper, 2019).

For example, there is evidence suggesting that some plants are coming into flower earlier than when bees emerge from winter hibernation, which results in fewer resources for early queen bees (Kudo & Cooper, 2019; Kudo & Ida, 2013). The long-term impacts of rising temperatures on insects are not yet fully understood because they are difficult to uncouple from other factors such as habitat loss and agricultural intensification.

In Puerto Rico, the forests have increased in temperature by 2°C over the last 50 years, which has coincided with a dramatic decline in insect biomass (Lister & Garcia, 2018). There has been little disturbance to the forests in this region during this time, which suggests that climate change has been a major driver in the recorded insect declines.

1.4 Pollinator-friendly farming

With 75% of crops requiring insect pollination to some degree, the ecosystem services that pollinators provide are estimated to be worth $235 to $577 billion per year worldwide (IPBES, 2016). Insects contribute to the agricultural production that feeds millions of people around the world; therefore, a decline in their population affects food production for local consumption and global trade.

Notably, certain strategies and policies have been proposed to combat insect decline. First, land can be managed in such a way as to aid the conservation of pollinators. For example, sowing field margins around crops, providing nesting resources, diversifying the farming system and providing financial incentives to farmers for practices that support pollinators are all actions that could increase and maintain pollinator abundance and diversity in agriculture (IPBES, 2016).

Europe, Australia and the USA use agri-environment schemes (AESs) to offer farmers short-term payments for implementing certain management practices, such as the creation and restoration of semi-natural habitats, reductions in chemical use on their land and establishing flower margins. Financial schemes are costly to implement in less economically developed countries, where community-led conservation could be an alternative measure (Khadse & Rosset, 2019). Pesticide reduction has also been a focal point of pollinator conservation. Increased awareness of responsible pesticide use, as well as raising global standards, regulations and risk assessments related to pesticides, are important factors in changing how chemicals are used on farms. Research on pesticides (e.g., neonicotinoids) found they cause a wide range of problems for bee health (Blacquiè et al., 2012).

In the presence of neonicotinoids, bee learning, memory, foraging behaviour and pollination ability were negatively impacted. Furthermore, the neonicotinoid residues on wildflowers in field margins have been found to contain a high enough concentration of chemicals to affect the pollinators foraging on the nectar and pollen of these flowers (Botías et al., 2015), which suggests that the exposure of pollinators to chemicals is widespread and goes beyond farm boundaries.

In the European Union, this family of chemicals was banned from being sprayed on farms in 2018, which was an important step towards recognising the importance of pollinator health in agricultural systems (Butler, 2018).

However, although there is substantial evidence of the negative effects that these chemicals have on the environment, many governing bodies have refused to ban them, which further highlights the challenges of pollinator-friendly farming (Sonne & Altrup, 2019).

2. PRACTICE DESCRIPTION

2.1 Materials

- Pollinator-friendly farming (PowerPoint presentation).
- A six-sided die.
  Tokens to represent currency (enough for each participant/group to have up to 35 x $1 tokens).
- Tokens to represent pollinator points (enough for each participant/group to have up to 30 tokens).

2.2 Time

- Introduction to the issue and explanation of the game (30 minutes).
- Gameplay (30 minutes).
- Post-game discussions (30 minutes).

2.3 Target audience

This activity can be adjusted to work with nearly any age group. However, at present, the recommended age group is 11+.

Younger participants may play with suitably sized tokens (to avoid choking hazards) but may not fully comprehend some of the nuances of the exercise.

2.4 Learning objectives

2.4.1 *Learning objectives related to awareness of the SSI*

- To understand the issue of pollinator decline and that pollinator diversity is as important as absolute pollinator abundance.
- To appreciate the importance and difficulty of balancing a healthy, pollinator-rich ecosystem with acceptable profit margins for stakeholders (i.e., farmers).
- To appreciate that improvements to ecosystem services (e.g., pollinators) often come at the cost of yield (i.e., profits) to stakeholders (i.e., farmers).
- To appreciate the impact of larger-scale environmental or societal changes such as drought or government incentives on both ecosystem services (in this case pollinators) and crop yields (and thus stakeholder profits).

2.4.2 *Learning objectives related to evolution*

- To recognise that humans directly impact biodiversity and that this may impact future evolutionary potential.
- To recognise the roles of specialists and generalists in ecosystems.

2.4.3 *Learning objectives related to scientific practices*

- Recognise the benefits and limitations of using conceptual models to communicate and examine complex principles.

2.4.4 *Learning objectives related to the nature of science*

- To develop an understanding of how science can inform policy, which can then impact stakeholder land management and lead to valuable changes that benefit ecosystems whilst creating a more sustainable way of living.

2.4.5 *Learning objectives related to transversal skills*

- To appreciate the complex interplay between different perspectives, such as those of governing bodies, stakeholders and champions of ecosystem services.
- To develop problem-solving skills as part of a team.

2.5 Description of the educational practice

We recommend that session leaders begin with a brief overview of the importance of pollinators as an essential ecosystem service and not just as a means of maintaining a healthy, diverse environment or improving crop yield (Hoehn et al., 2008). We also suggest some discussion surrounding the importance of pollinator diversity since it is a common misconception that the pollinator crisis can be averted by increasing the abundance of domestic honey bees.

The session leader may then wish to introduce some aspects of conventional farming and the impacts it has on pollinator abundance and diversity. These discussions will then be further illustrated and reinforced by the main activity, which takes the form of a strategy-based engine-building game. Since this game is a simple model of a very complex issue, it has important limitations. After playing the game, we encourage educators to examine this model with the students.

Students could be guided to identify simplifications in this game and discuss what these may be like in real life. Another suggestion is to explore what complexity could be added to this model and how it would affect the way the game is played. We also encourage the discussion of models as tools more generally.

Can students suggest the reasons why scientists might use models? Similarly to the use of a model here, students could be involved in discussions on how models can be used to understand complex issues or make predictions/estimates.

(i) Game setup and main aims

The pollinator game aims to illustrate the interplay between stakeholders (represented here by farmers), ecosystem services (pollination) and governance. In the game scenario, the local government has declared that the country is undergoing a pollinator crisis and that they will fine any farm $20 if it has a pollinator health score of less than 3 pollinator points.

Each player has a farm with a starting value of $10. Thus, the government fine represents a significant penalty that could remove the player from the game. Additionally, each farm comes with a starting pollinator health score of 5 pollinator points. Players should all be allocated appropriate currency and pollinator point tokens. The game aims to increase the profits of your farm whilst also increasing its pollinator health score, with the pollinator health score feeding directly into the overall value of the farm at the end of the game.

(ii) Gameplay

A complete game takes place over seven rounds (representing 7 years of farming). Each round is composed of two decision-making steps and an event (either randomly chosen or selected by the session leader).

Table 1
The cost, profits and impacts on pollinator health scores when growing one to three crops on a farm. The return is subject to a dice roll in order to represent the annual variability in farmers' yields.

Number of crops	Cost	Return	Number of pollinator points
1 – Oilseed rape	$3	$4 or $6	-2
2 – Tomato and oilseed rape	$4	$4 or $6	No change
3 – Strawberries, tomato and oilseed rape	$5	$4 or $6	+1

Step 1: ▲

Players choose how many crops they wish to grow on their land. This choice influences the farms' profits and pollinator points (Table 1). Session leaders should note that the farmers' returns from this step are irrespective of the number of crops planted but are rather dependent on fluctuations in the local economy as defined by a dice roll. Dice rolls of 1 or 2 indicate a struggling economy or a year with poor yield, in which the return on all crops would be $4, whilst dice rolls of 3 to 6 equate to a healthy, booming economy and high yields for which the return of all crops would be $6. This adds an unpredictable element to the game, which reflects some of the difficulties faced by farmers when undergoing this decision-making process. Since the cost of planting more than one crop increases incrementally, the profits will be smaller and come with a higher risk of losses during a year in which one chooses to grow more than one crop.

Whilst the potential profits are higher and financial risks smaller in the years in which a single crop is grown, the pollinator health of the farm will suffer. Moreover, single-crop farms will lose 2 pollinator points, a reflection of the negative impact that monocultures have on the health of ecosystem services. Meanwhile, farms that choose to plant three crops will gain pollinator points, thereby indicating improved pollinator health on their farm—but at a financial cost. Once players have chosen how many crops they wish to plant, they should take note of their decisions and make appropriate payments from their currency and pollinator point tokens. The session leader should then roll the die to define the economic climate for the year. A roll of 1 or 2 gives a smaller return, whilst a roll of 3, 4, 5 or 6 gives a larger return.

TIP 1

Rather than trying to work with net loss/profit (which is most often peoples' instinct), we have found that it is most effective for players to pay in the required currency and pollinator points at the start of a 'round' after Step 1 and then receive their returns at the end. This also more closely mirrors the actual experiences of farmers, who pay out for seed and chemicals and do not see a return until the harvest.

Table 2
Optional additional measures with their respective impacts on profits and pollinator health scores.

Additional measures	Effect on return	Pollinator points
Dedicate some land to pollinators	-$1	+2
Introduce field margins	-$1	+1
Chemical-free farming	-$2	+3
Using pesticides	+$1	-2

Step 2: ▲

Although Step 1 involves the basic planting decisions being made, in Step 2, players decide whether or not they wish to bring in any further measures to improve either their pollinator health score or profits (Table 2). These additional measures are based on real practices employed by the farming industry and are weighted accordingly. Session leaders should note that the costs or benefits of these additional measures affect the return that each farm receives and do not require a pay-in at the beginning of the round. Players may choose to implement multiple additional measures if they wish, with one exception: players cannot choose to introduce chemical-free farming whilst also choosing to use pesticides since these two measures are contradictory. Also, players cannot obtain a negative return, so any additional measures resulting in a return <$0 will result in no return. Once they have decided on additional measures, players should take note of the choices they made and the respective potential costs and benefits of those decisions. Whilst groups familiarise themselves with the format of the game during the first two rounds, we recommend that these rounds are limited to performing Steps 1 and 2.

Tip 2

Session leaders can select events to occur randomly or strategically, depending on how the players have been responding to the game. For example, if players have been repeatedly monopolising on growing a single crop (e.g., oilseed rape) then it may be instructional to introduce the "Oilseed rape has grown extremely well this year" event.

Step 3 (events): ▼

From round 3 onwards, session leaders will introduce an event (Table 3) after Step 2. These events represent the impacts of local environmental changes (e.g., flooding, pests or disease), changes in government policy (e.g., the introduction of financial incentives), economic changes (e.g., impacts of supply and demand and public perception) and changes introduced by local competitors (e.g., neighbouring farms). Players should take note of the impacts of these events in terms of their costs or benefits to their farms, which will often depend on the decisions they made in Steps 1 or 2 of the round.

Table 3
A selection of events and their weighted impacts that may be introduced by the session leader after Step 2 of the game.

Event	Event impact
Your farm has flooded.	Everyone only salvages a maximum return of $2, minus any deductions from additional measures introduced in Step 2.
A disease has emerged that kills oilseed rape.	If you planted one crop, you gain a $0 return. If you planted two crops, your return is $2. If you planted three crops, your return is $4.
The government awards a subsidy to farms with land dedicated to pollinators.	If you chose to dedicate some land to pollinators this year, you gain an extra $2.
Tomato plants have been attacked by beetles.	If you used pesticides this year, your crops are safe and your return is $7. If you planted only one crop (e.g., oilseed rape), your return is $7. If you planted two crops, your return is $3. If you planted three crops, your return is $4.
Breaking news: Pollinator decline is headline news! The public is choosing to buy pollinator -friendly produce.	If you have 4 or fewer pollinator points, you lose $2 from your return. If you have nine or more pollinator points, you gain an extra $2 in return. If you have 5–8 pollinator points, your return remains the same.
There has been a heatwave.	Everyone loses 2 pollinator points.
The government offers grants for eco-farming.	If you have over 7 pollinator points, you get a $3 payout.
A celebrity has (incorrectly) tweeted that strawberries are unhealthy. Nobody wants to buy them anymore.	If you planted one or two crops, this does not affect you. If you planted three crops, you lose $1 of your return.
Oilseed rape has grown extremely well this year. Supply has outweighed demand and it is less valuable than usual.	If you planted one crop, your return is reduced by $2. If you planted two crops, your return is reduced by $1. If you planted three crops, your return is unaffected.
A neighbouring farmer has brought in honey bees to improve pollination. They are out-competing local pollinators.	Everybody loses 2 pollinator points.
The winter was very cold, causing a decline in the number of bumble bees. Bumble bees are needed to buzz-pollinate tomato plants.	Everybody loses 1 pollinator point. Those who planted tomatoes also lose $2 of their return.

Tip 3 ***We strongly encourage session leaders to incorporate their own ideas for events that may be more relevant to pop culture, real-world events or local conditions. We would be thrilled to hear your ideas! Finishing a round: After the impacts of the event have been established, players should calculate the returns their farm is due in terms of both monetary returns and pollinator points. Players should take currency and pollinator point tokens accordingly and establish the new value of their farm. Finishing the game: At the end of seven rounds, players should add up their currency tokens and pollinator points. The pollinator health of the farm adds back to the final overall value of the farm. Thus, for every 3 pollinator points obtained by the player, they obtain an additional $1 onto their farm value. The player/team with the highest final farm value wins.***

Final thoughts and discussion:

This game has been designed to be sympathetic to the difficulties facing farming communities and to demonstrate—in a simplified manner—how difficult it can be to balance profits and pollinator health with fluctuating economies in farming. It also aims to draw attention to the impacts that government policies can have on farming practices as well as the unpredictable impacts of environmental and socio-economic factors on profits and pollinator health. Session leaders are encouraged to draw their sessions to a close with some discussions around these points. Some suggested discussion points and key conclusions are provided in Table 4.

It would also be beneficial to discuss why each event students encountered in the game had effects on profits/pollinator points. This could either occur during gameplay when an event takes place or afterwards as part of the summary discussion. We encourage sessions leaders to link back to evolution and ecology where possible (e.g., honey bees were brought up in an event) and note the effects that societal changes can have on the natural world to show students how far-reaching the effects of their decisions can be (e.g., the celebrity tweet event).

Some discussion prompts have been suggested below and in Table 4. We anticipate some complaints from students about *'fairness'* when they do not receive the returns that they may have anticipated. We believe that this would provide an excellent opportunity to discuss with students how nature is not fair since natural events leave farmers at a disadvantage, with them needing to do what they must to remain afloat—even if it is at the expense of pollinator health.

(iii) Linking the game to evolutionary biology

Many of the 'events' in this game have results that may seem counterintuitive. However, in these scenarios, the outcomes are rooted in evolutionary biology concepts (primarily specialism, generalism and coevolution). Therefore, these would make excellent discussion or further exploration points.

For example, since a neighbouring farmer bringing in honey bees would increase the number of pollinators around their farms, students may expect that their pollinator points would increase. However, this results in a reduction in pollinator points. You may wish to explore this with the students. Swamping the environment with imported generalist bees can lead to them outcompeting specialist native species (Ings et al., 2006) and dominating the environment (Garibaldi et al., 2021). If the specialist pollinators become endangered or extinct, it can have consequences for specialist plants since generalist invaders may not pollinate them or may pollinate them inefficiently (Larsson, 2005).

An example of pollinator specialism is buzz pollination. Some plants, such as tomatoes, can be much better pollinated when buzz pollination is employed (https://www.youtube.com/watch?v=J7q9Kn1rhRc) (Cooley & Vajello-Marín, 2021). This also links to another event in the game (a cold winter leading to a decline in bumble bees). Notably, another game offers the

Tip 4

Session leaders may wish to construct a leader board to update every couple of rounds to raise the enthusiasm and competitive attitudes of students. Please allow additional time if you wish to include this.

opportunity to explore other specialisms in plants and pollinators and uses this to match up specialist plants with their pollinators (see: http://www.pbs.org/wgbh/nova/nature/pollination-game.html).

Such specialisms arise through a process of coevolution, where the plants and pollinators evolve in response to one another (Johnson & Anderson, 2010). Coevolution is a fascinating topic to explore with students since they often respond well to the exciting traits selected for by this process. The following papers suggest a variety of ways to guide students towards understanding coevolution: Brockhurst (2010), Gibson et al. (2015), Thanukos (2010).

Another aspect for discussion that you might wish to explore with your students is the idea of differential disease resistance between species. This is relevant to many of the events (imported bees may carry disease; tomato plants and beetles; oilseed rape and disease). Consider a thought experiment with your students that involves modelling the process of adaptation to a new disease by wild species.

Ask your students to imagine a large population of a wild pollinator species (if necessary, draw the individuals of that population on a board and use this to depict change across generations). Most individuals from that species are not resistant to a certain disease, whilst a few of them carry alleles conveying resistance to this disease (you may depict these individuals in a different colour, for example) due to natural variation within the population.

Ask your students what they think will happen to this population during the generations following the introduction of the disease. In the first generation, we expect most of the individuals who do not carry the resistance allele to die. Those carrying the resistance allele will survive and produce offspring, most of which are expected to carry the resistance alleles. However, not all of these offspring will necessarily carry the resistance allele; therefore, the non-resistant offspring will die. Overall, the frequency of resistance is likely to increase.

Repeat these steps through some generations and discuss the impact of this process with your students: i) the number of individual wild pollinators over the years following the introduction as well as the impact of this in terms of fruit production; ii) the frequency of resistant individuals in the population. Also, discuss what would occur if there were no intraspecific diversity in the initial wild pollinator population. This activity explores the process of natural selection, which is explained in the following video: https://www.youtube.com/watch?v=7VM9YxmULuo.

Although this video uses predation as a selective pressure, it is clear how predation acts as a selective pressure in the same way that a disease would. In this video, the dark colour phenotype is fitter, just like the resistance allele in our example.

Table 4
Suggested post-game discussion points and 'steering' prompts to facilitate understanding of why this SSI is so complex from a societal perspective. A selection of events and their weighted impacts that may be introduced by the session leader after Step 2 of the game.

Discussion points	Key considerations
Do celebrities really have such an impact on society? (include a link to celebrity tweet event).	To discuss this point, you could find some real-world national case studies of celebrities not supporting science and discuss those with your students. You could even give your students the task of finding some examples. For example, see alternative medicine businesses (for an example, see Arnocky et al., 2018).
Why would the government or policymakers provide bursaries or subsidies to pollinator-friendly farms?	Here, you could encourage a discussion of who chooses those in power. Consider the commitments that governments make to preserving the environment. How important is public opinion to governments?
Other than the crop yield, is there anything else that might affect farmers' profits?	At this point, you can discuss the upfront financial costs of the additional measures. Your students may have additional valid ideas. Examples include: • Pesticides have an upfront cost associated with them. • Land dedicated to pollinators: How effective would it be in real life if you did this for just 1 year? Does it need several years to 'rewild'? • Do you need to pay to plant wildflowers on field markings/land dedicated to pollinators? There is a cost for wildflower seeds AND a reduction in profit due to not growing crops on this land.
In this game, you grew one to three crops and had a choice of four possible special measures to increase either yield or pollinator points. In real life, do you think farming is like this? Is there anything else that farmers need to think about that has not been represented in this game (i.e., limitations of this model)?	Your students may have many valid ideas for this. Some examples of aspects of farming that are not represented by this model include: • It is simpler and more efficient for a farmer to grow only one type of crop; however, this strategy also has a higher level of risk (e.g., due to disease or drought susceptibility; Balough, 2021). When growing multiple types of crops, farmers must consider the timings of harvests, required equipment, environmental impacts and saleability (Navarette et al., 2015). • Some special measures cost money at the outset, with farmers having to be able to afford them. • Different crops are worth different amounts of money.

2.6 Further perspectives on how to use this activity in other contexts or with participants of other ages

This activity could be modified to suit a range of issues that encompass other ecological crises, stakeholders and governing bodies (e.g., fishery decline, fishermen and a national government, respectively). Modification would require work from session leaders to research the respective ecological crisis and edit the events section accordingly.

It would be very interesting to play this game with students that have different focuses/disciplines. We suggest two alternative ways in which to manage this: i) by playing this game with older, more specialised students to prompt multi-disciplinary discussions; ii) older students who have specialised could act as expert mentors and guide teams by discussing the impacts of events with their teams.

Any aspect of this game can be edited to suit current affairs or different age groups. For instance, new events can be incorporated, more options can be added for extra measures and the crops used as examples can be changed.

We strongly encourage educators to make these changes to maximise the relevance of the scenarios to their country/locality.

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4. APPENDIX

At https://doi.org/10.5281/zenodo.7323863 you can find a PowerPoint file that we created to help you to run the game with your class. It contains simple instructions and several *'event'* pages.

Please spend some time familiarising yourself with this since you may wish to exclude certain events or edit/remove the competitive element on the *'leader board'* slide at the end.

Chapter 11

The impacts of solar radiation on our health

CHAPTER 11

The impacts of solar radiation on our health

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Abstract:

The correlation between the geographic distribution of human skin colour and the intensity of solar radiation is one of the most remarkable examples of how natural selection has shaped the evolution of our species and the divergence between human populations. The selective pressures shaping this distribution are still acting today, resulting in health problems for individuals whose skin colour is not adapted to the environment in which they live. Healthy sun exposure habits depend on both the individual's skin colour and the environment in which they live. Thus, health communication strategies should recognise and reflect this diversity. However, although it is an important feature, skin colour is sometimes not mentioned — possibly due to a historical association with racism.Herein, we propose an activity aimed at 9th to 12th-grade students in which they are invited to plan and implement a dissemination campaign to inform their school community about the health impacts of solar radiation. During this process, students will learn about natural selection, how it causes population divergence and how such divergence is related to evolutionary processes. Additionally, students will explore the concepts of subspecies and races (and how the latter does not have a true biological meaning). They will also debate the ethical and medical consequences of using ethnic information to diagnose and communicate health issues whilst learning about the nature of science. Additionally, students will develop scientific practices such as asking questions and obtaining, evaluating and communicating information.

KEYWORDS

health education, human evolution, racism, skin colour, sunlight exposure

1. WHAT DO WE KNOW ABOUT THIS SOCIOSCIENTIFIC ISSUE AND HOW IT CAN BE INFORMED BY AN EVOLUTIONARY PERSPECTIVE?

On the first day of June 1858, Charles Darwin and Alfred Russell Wallace's theory of evolution by natural selection was presented at the Linnean Society of London. This idea would revolutionise not only biology but also society. Currently, evolution is one of the central concepts of biology, being essential to understanding the world around us and our origins, with additional implications for our health and well-being. One important contribution of evolutionary biology has been enabling us to understand the origin and implications of human skin colour. Body colour is an important feature in the animal kingdom that serves many roles, from sexual selection to adaption to the environment.

Skin colour is one of the characteristics that shows the greatest variation among human populations, with a significant correlation being observed between the degree of skin pigmentation of native populations in a region and the intensity of ultraviolet (UV) radiation. Current evidence suggests that this distribution is due to the occurrence of different selective pressures that acted on ancestral human populations due to latitudinal variation in the intensity and seasonality of UV radiation (Crawford et al., 2017; Jablonski & Chaplin, 2000).

When it reaches our skin, part of the energy from UV radiation (especially UVB) is used to produce vitamin D. Vitamin D is an essential nutrient for human development and has important effects on human health. However, intense exposure to UV radiation can cause cell damage, including damage to DNA and the destruction of nutrients (e.g., folate) that are essential for the survival and reproduction of individuals.

The outermost layers of the skin serve as a barrier against the harmful effects of solar radiation, thereby decreasing the intensity of UV radiation reaching the innermost layers of the skin and body. Melanocytes, which are cells located in the basal layer of the epidermis, produce a natural sunscreen known as melanin, which is capable of absorbing and dissipating between 50 and 75% of incident UV radiation (Brenne & Hearing, 2007; Solano, 2020).

In humans, two types of melanin are produced within the melanocytes: a) brown/black eumelanin, which has a greater capacity to absorb and protect against UV radiation; b) lighter red/yellow pheomelanin, which has a lower capacity to absorb and protect against UV radiation. In addition to protecting against UV radiation, melanin is also responsible for skin pigmentation, which depends on the location, total amount and proportion of the two types of melanin produced. Notably, the global distribution of skin colour results from this dual function of melanin (i.e., pigmentation and protection) (Schlessinger et al., 2021).

The human species originated near the equator in Africa, where the intensity of UV radiation (both UVA and UVB) is high throughout the year. Without clothes or sunscreen, the main barrier against the harmful effects of UV radiation on the skin was melanin (particularly eumelanin). Thus, the individuals who had it in greater quantity survived longer and, more importantly, left more offspring who would also carry their parents' genes coding for higher melanin content. Thus, in each generation, individuals with darker skin colour benefited. Over time, due to natural selection, the number of individuals with darker skin increased in equatorial populations. Although a higher amount of melanin in the skin reduces the amount of UVB radiation available to produce vitamin D, the high intensity of this type of radiation throughout the year in this area of the globe would still allow the necessary amount of this molecule to be synthesised.

However, when humans began dispersing throughout the world, they started living in areas where UV radiation (especially UVB) is less intense and has important seasonal variations. In fact, in some areas of Asia, Europe and America, the incident UVB radiation is not sufficient to produce the necessary amount of vitamin D during most months of the year. Notably, this production is much lower in individuals with a darker skin tone. Under these circumstances, the lighter the skin tone of the individuals, the greater the probability of producing enough vitamin D for their healthy development and reproduction. Thus, over the generations, individuals with lighter skin colour left more offspring that inherited their lighter skin tone—an effect that led to the depigmentation of populations further north. This depigmentation occurred independently in European and Asian populations, with different genes being involved in the two cases (Crawford et al., 2017; Jablonski & Chaplin, 2017).

However, beyond historical curiosity, what is the relevance of knowing the evolutionary processes involved in the current distribution of skin colour? The relevance is that the factors that acted in the past to cause selective mortality and fertility in humans are still acting today, causing health and fertility problems for individuals worldwide. Understanding that the propensity to suffer from these problems depends—among other factors—on one's skin colour and the environment in which they live allows individuals to make informed decisions to prevent them. Notably, this is also important for health professionals when communicating information on these topics.

However, human skin colour is a feature that has been historically associated with complex social problems such as racism and discrimination (Jones, 2001; Pew Research Center, 2021). The discussion about whether and how to use features such as skin colour or ethnic group to support diagnoses and communicate health information remains a hotly debated issue in scientific and medical communities (Klonoff & Landrine, 2000; Landley et al., 2019). The purposes, ethics and values that should inform how to use skin colour to prevent or diagnose a health problem and communicate with the public is an important debate in society. It is also important to understand the most appropriate ways of doing this to avoid people feeling harmed, ashamed or insulted by the way such information is communicated.

In this activity, we explore the relationships between health and skin, particularly solar exposure and skin colour. One of the factors affecting the consequences of sun exposure is the individual's skin colour. Therefore, the use and sharing of ethnic information (e.g., skin colour) in diagnosing diseases could be important to the agenda of the medical and scientific communities. However, this is not a simple decision or an easy debate. It could be said that accessing and sharing such information could offer opportunities such as taking preventive health measures, the early diagnosis of diseases, identifying and applying treatment methods specific to certain ethnic groups and even working in a suitable job. However, it can also be argued that this implies classifying certain groups as stronger or weaker regarding a certain health issue, which may also lead to possible undesirable consequences, such as discrimination in hiring or health insurance conditions based on shared genetic information. Therefore, *'stop using skin colour to determine health tendency'* and *'early diagnosis saves lives'* are two common and opposing perspectives.

2. PRACTICE DESCRIPTION

2.1 Materials

A projector, a blackboard and computers with internet access (for students to perform online research).

The editable scripts for the students can be found here:
https://doi.org/10.5281/zenodo.7323921

2.2 Time

This activity can be implemented in four 90-minute sessions, which coincide with the four stages of the activity.

However, depending on your setting, the length of time can be extended (as described in the tips).

2.3 Target audience

Suggested target audience:
9th to 12th-grade students.

9th to 12th ***grade students.***

2.4 Learning objectives

2.4.1 *Learning objectives related to awareness of the Socioscientific issue (SSI)*

- Understand dynamic relationships between science, technology and society.
- Many decisions are not made using science alone but rely on social and cultural contexts to resolve issues.
- Argue, criticise and make informed decisions on the effects of science and technology on society.
- Recognise the complex, scientific inquiry-based, sceptical and multiple-perspective nature of SSIs.
- Discuss the epistemological, ethical and moral dimensions of science-related social issues in the context of daily life.

2.4.3 *Learning objectives related to scientific practices*

- Asking questions.
- Obtaining, evaluating and communicating information.
- Analysing and interpreting data.
- Scientific inquiry-based practices.

2.4.2 *Learning objectives related to evolution*

- Recognise the existence of heritable intraspecific diversity.
- Describe the process of natural selection by explicitly mentioning how the environment impacts the survival and reproduction of organisms with distinct features.
- Describe how differences in environmental features may lead to population divergence.
- Discuss the concepts of species and subspecies as biological concepts, their relationship with evolutionary processes and the concept of race as a non-biological concept.

2.4.4 *Learning objectives related to the nature of science*

- Science is based on empirical evidence.
- Scientific knowledge is open to revision in light of new evidence.
- Science models laws, mechanisms and theories to explain natural phenomena.
- The following objectives are in the interphase between the nature of science and SSIs:
- Science and engineering are influenced by society, whilst society is influenced by science and engineering.
- Not all questions can be answered by science.
- Scientific knowledge can predict what can happen in natural systems but does not indicate what should happen. The latter involves ethics, values and human decisions related to the use of knowledge.

2.4.4 *Learning objectives related to transversal skills*

- Analyse issues from multiple perspectives.
- Identify aspects of issues that are subject to ongoing inquiry.
- Explore how science can contribute to addressing current health problems in humans and understand the limitations of science.
- Perspective taking.
- Collaborative problem-solving skills.

2.5 Description of the educational practice

A. **Before the sessions:**

If possible and desirable, articulate with the arts and humanities subjects courses since connections may be found with these curricula. Our experience has shown us that in addition to these courses, effective articulations can be fostered with geography, history, philosophy, biology, arts, history of science and religious education courses.
Ask your school board if they agree with the letter from page 2 of your students' script (see Figure 1). If they agree, ask them to sign it.

Figure 1
Presentation letter.

Dear students:

We hereby request your help to carry out a dissemimination project related to the impacts of solar radiation on health, almed at your school's community. With this project we aim to alert people about the consequences of sun exposure and inform them about the care they should take in their daily lives to avoid health problems. With this aim, we would like to ask you to investigate the impacts of sun exposure on people's health and discuss what information you think is pertinent to disclose, given the characteristics of students, teachers and school staff, as well as their lifestyle habits. We would also like to ask you to think about how to disseminate this information. After gathering information and discussion, we would like you to develop a dissemination project aimed at promoting healthy habits in your school community. We thank you in advance for your collaboration, which we are certain will contribute to changing lifestyles and thus preventing disease and/or saving lives.

Best regards,

On behalf of the school board,

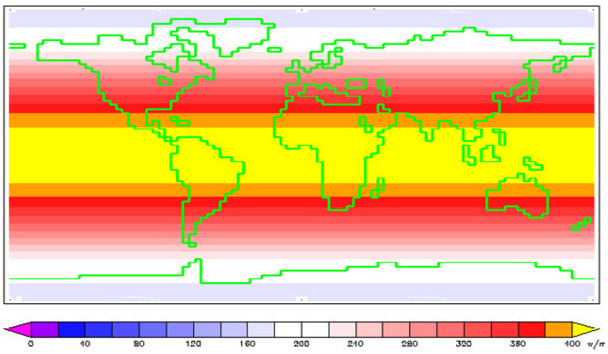
Location, date

(Signature)

2.5 Description of the educational practice

B. In the first session (or first stage) — Introduction:

Present the letter from page 2 of the student's learning script (Figure 1) to introduce the project and the problem to be addressed.
Present the UV and skin colour distribution maps (Figures 2 and 3, below) from page 3 of the student script to your students.



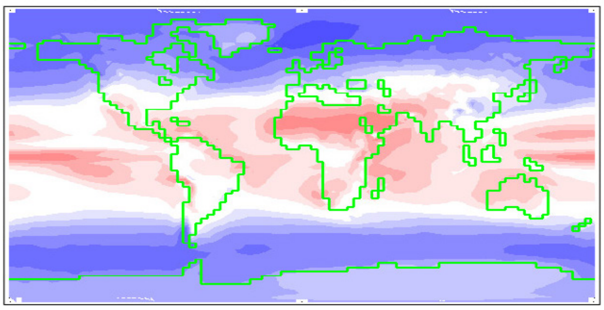
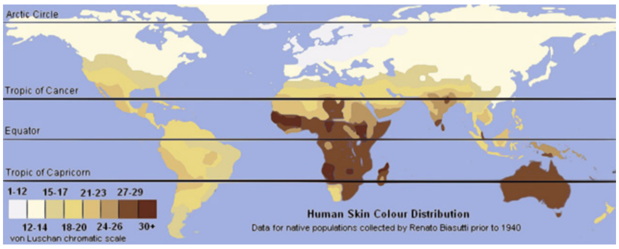


Figure 2
Annual insolation reaching the Earth's surface after passing through the atmosphere. Credits: This image was produced by William M. Connolley using HadCM3 data and is available at. https://commons.wikimedia.org/wiki/File:Insolation.png.

Figure 3
Distribution of skin colour in Indigenous populations before colonisation processes based on the chromatic scale of Von Luschan (data from Biasutti, 1940; disputed). Credits: This image was first uploaded to Wikipedia by The Ogre and was reshaped and coloured by Crisco 1492. Data from: Jablonski & Chaplin (2000).



To foster a discussion, ask students the following questions:

- What is the relationship between skin pigmentation and UV radiation?
- What do you think can be the causes of the global distribution of skin colour?

In small groups, ask the students to first think about these questions themselves. Then, ask them to share and discuss their thoughts within the group and register the group's ideas in the sections '*Your idea' and 'Other ideas in the group'* (see Table 1) from their script.

This may take 5 to 10 minutes. Ask the groups to share their ideas with the classroom, which may take 5 minutes.

Table 1
Hypothesis for skin colour distribution.

Skin colour distribution
What is the relationship between skin pigmentation and UV radiation? Your idea: Other ideas in the group: After wacthing the video:
What do you think can be the causes of the worldwide distribution of skin tones? Your idea: Other ideas in the group: After wacthing the video:
Questions or observations

With your students, watch the TED Talk from Nina Jablonski (https://www.ted.com/talks/nina_jablonski_skin_color_is_an_illusion#t-865407; 15 minutes).
In this video, researcher Nina Jablonski reflects upon the evolution of skin colour and how skin colours are an adaptation to different levels of UV exposure.

In small groups, ask students to compare their initial ideas with what was described in the video. Then, ask them to discuss these differences within their groups, register their new ideas and answer the questions in Table 1 from their script. Ask the groups to then share their ideas with the classroom and promote a classroom discussion (this may take 15 to 20 minutes).

At this stage, make sure that the students understand that natural selection does not offer individuals what they need to survive, but instead acts by causing mortality and reduced fertility to individuals with less adapted features. Skin colour is a consequence of melanin presence, which can have two important roles: protecting from the damaging effects of UV light and influencing vitamin D production. Also, make sure they notice that this is related to health problems that are still affecting people today.

In a class discussion, ask students to state what they know about the impact of solar radiation on human health, what information they feel is still missing for them to prepare for the dissemination campaign and how they will look for this information. Register this information on the blackboard and ask each group to register it in Table 2 of their script. They can then be prompted to decide what information will they be looking for until the next class.

Table 2
Collecting additional information.

The impacts of solar radiation in our health
What do you we know?
What do you we need to know?
How will we look for this information?
What information did you collect?
Is this information reliable? (Check if your information source is reliable. The more boxes you tick the more reliable the information is expected to be. Check the CRAP test of reliability at https://ccconline.libguides.com/c.php?g=242130&p=2185475 **)** The information is coming from a scientific paper or book. The source I found cites the sources of the information and provides a reference list. The source is a well-known and credible organistation. I interviewed an expert in the field (in this case tell us who and ask her/him to check what you wrote) ______________________________ The information I collected is supported by more than one reliable source of information. The information I collected seems impartial, objective, and unbiased. It is credible because____________________________

Autonomous work: Each group will look for the required information and prepare a 5- to 10-minute presentation (depending on the number of groups in the class) to share their information with the other groups.

C. In the second session (or second stage) — Reflection:

Ask each group to present the information they collected with the other groups.
After the presentations, in a class discussion, ask students what key messages should be part of the dissemination campaign that they will prepare for their school community to promote healthy lifestyles, as well as who their target audience will be (students can then complete Table 3).

Table 3
Key messages and target audience.

The impacts of solar radiation in our health
What key messages are important to disseminate in our community?
What should be our target group(s)?

After the key messages are chosen, ask them to discuss how they will communicate these to the school community. During these discussions, introduce the following questions (see Table 4):
Questions related to medical and ethical issues:

- ? Should we use information about ethnic groups to inform people about health issues?
- ? What ethical and medical problems are associated with the position held by the authors of the articles?
- ? What good practices are mentioned by the authors of the articles for communicating human health issues that are different for individuals with distinct features?

Questions that invite students to rethink the misinterpretation of the association of skin colour with race:

- ? What is the difference between a ‘race’, a ‘subspecies’ and a ‘species’? Why aren’t there races in humans?
- ? How are these concepts related to evolution?

Table 4
How to comunicate about health problema related with skin color.

The impacts of solar radiation in our health
What is the difference between a "race", a "subspecies" and a "species"? And why aren't there races in humans?
How are these concepts related to evolution?
Should we use the ethnic information to inform about health issues?
What ethical and medical problems are associated with the position held by the authors?
What good practices are mentioned by the authors for communicating human health issues that are different for individuals with distant features?
What decision did your group take about the best way to communicate the health issues? Why did you make such a decision? What are the possible ethical and medical problems arising from this decision?

For a deeper exploration of these issues, you may also want to introduce the following questions (adapted from Sadler & Zeidler, 2005).

These are suited for older students and/or when relating the activity to other subjects (e.g., philosophy).

- ? What do you think about using skin colour information for medical research, communication, diagnosis and treatment? What factors were influential in determining your position on this subject?
- ? If somebody agrees with your decision, what are the arguments he/she may have?
- ? If somebody disagrees with you, what arguments may he/she hold?
- ? Why do you agree/disagree with using skin colour to prevent or diagnose a health problem and/or communicate with the public? Explain your position.
- ? Do you think that using skin colour as described in this case is subject to any kind of moral rules or principles? If so, how did this affect your decision making?
- ? Did you immediately feel that using skin colour to prevent or diagnose a health problem and/or communicate with the public was the right/wrong course of action in this context? Did you know your position on the issue before you had to consciously reflect on it?

Is there anything else that I should know about your thinking process or decision making as you considered this issue?

Divide your students into groups and ask each group to look for information to answer the previous questions in the documents shared with them.

Ask your students to complete Table 4 with the information they collected. Based on that, ask the students to debate and decide whether and how they would use ethnic information in their proposal and the implications that this decision may have.

D. In the third session (or third stage) — Development of the dissemination campaign:

Based on their findings and previous debates, ask each group to develop a proposal and a product for the dissemination campaign for the school community by using Table 5 to describe it. Ask the students to prepare a 5-minute presentation of their proposal and present it to their classmates. When presenting, the students should ask for feedback from their classmates and consider incorporating it into their final product. Additionally, ask your students to plan the dissemination campaign and ensure that it gets high visibility.

Table 5
Table to plan your dissemination project proposal.

The impacts of solar radiation in our health
What will we do in our dissemination campaign? (describe here what will you do for your dissmination campign)
How will we communicate the key messages? (describe here ow your projet will be communicating the key messages you want to share)
Why do we think the format we propose will be effective to reach our target group(s)?
What do we need and how will we get this?
What was our colleagues' feedback and what did we change in our initial proposal to incorporate it?

E. In the fourth session (fourth stage) — Presentation of the dissemination campaign:

In the final session, the students should present their final product and plan for the dissemination campaign.

TIP 1

Skin colour is a trait that is frequently not thoroughly analysed in the school context. However, it seems important to explore the biology behind this very diverse trait, address health issues and promote a deconstruction of racist ideas associated with skin colour. From our experience, the natural course of an open discussion usually leads to a deconstruction of racist ideas. However, we wish to alert the leaders of the discussion that it may be important to consider that we are addressing skin colour as a physical trait and that race and other classifications are social constructs. As such, it might be good to be prepared to talk about the topic.

TIP 2

We have already implemented this activity in a formal education setting (i.e., classroom) and an informal education setting (i.e., science club) with 9th-grade students. However, we found this activity to be suitable for students from the 9th to 12th grade. Additionally, according to the settings, this activity can be extended to more than four sessions. In particular, this would be necessary if sessions are shorter (e.g., 50–60 minutes). If sessions are shorter, you may wish to explore one topic per session. When coordinating the activity with other courses—and when in a problem-based learning setting—more sessions may be required (we consider that it can be extended to up to 12 sessions of 60 minutes).

TIP 3

During the first session, when asking the students to think about the relationship between skin pigmentation and UV radiation and the causes of the global distribution of skin tones, students may answer that humans developed features to protect them from UV radiation because they needed them. This corresponds to a frequent misconception of evolution.

TIP 4

Please be aware that the way Nina Jablonski presents this topic in the TED Talk may reinforce the frequent misconception that natural selection provides individuals with what they need.

TIP 5

This activity may serve as the basis for interesting reflections when schools have students from diverse backgrounds by valuing the diversity of the group.

TIP 6

When articulating with art courses, we have complemented this activity with another TED Talk

(https://www.ted.com/talks/angelica_dass_the_beauty_of_human_skin_in_every_color?language=pt) and discussed the project Humanae (https://angelicadass.com/pt/foto/humanae/ ***).***

Additionally, students also attempted to use different painting techniques to reproduce their own skin colours.

TIP 7

In the student script we indicate four articles as suggested reading. Herein we provide a list of articles that may be considered as an alternative.

https://www.nytimes.com/2017/10/12/science/skin-color-race.html

https://www.newscientist.com/article/mg24132210-100-too-much-sunscreen-why-avoiding-the-sun-could-damage-your-health/

https://www.newscientist.com/article/dn13922-skin-tone-gene-could-predict-cancer-risk/

https://www.scientificamerican.com/article/how-skin-cancer-rates-vary-across-the-globe/

https://www.sciencedaily.com/releases/2021/02/210218142820.htm

http://douglasallchin.net/papers/Allchin-skin-color-and-NOS.pdf

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Solano, F. (2020). Photoprotection and skin pigmentation: Melanin-related molecules and some other new agents obtained from natural sources. Molecules, 25(7), 1537. https://doi.org/10.3390/molecules25071537

Laidley, T., Domingue, B., Sinsub, P., Harris, K. M.& Conley, D. (2019). New evidence of skin color bias and health outcomes using sibling difference models: A research note. Demography, 56 (2), 753–762. https://doi.org/10.1007/s13524-018-0756-6

4. APPENDIX

The editable scripts can be found here:
https://zenodo.org/record/7323921#.Y5IP--zP2Cc

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Chapter 12

Are we allowed to tinker with (human) DNA? Addressing socioscientific issues through philosophical dialogue - the case of genetic engineering

CHAPTER 12

Are we allowed to tinker with (human) DNA? Addressing socioscientific issues through philosophical dialogue - the case of genetic engineering

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Abstract:

Education about socioscientific issues (SSIs) can be challenging as underlying tensions can surface. When discussing the topic of genetic engineering, these tensions can be related to (1) the molecular biology of genetics and genetic engineering, (2) the evolutionary aspects of genetic engineering, (3) the nature of science and (4) the ethical understanding of this SSI. Such tensions may lead to confrontation, either between students or between students and teachers. The practice of 'philosophical inquiry' provides a pedagogical approach to help explore these tensions and engage in dialogues. Philosophical inquiry entails a dialogic approach in which a facilitator helps a group of students uncover hidden presuppositions and elicit an argumentative conversation. Stimuli such as pictures, cases or quotes provide a context to help students engage in dialogues about philosophical questions. Thus, students can reflect upon the relationship between science and evolution, the nature of science and the tensions between genetic engineering and society. In this chapter, we first explore different sensitivities related to genetic engineering. Then, we showcase learning material for secondary school students to cope with these issues. We focus on an approach to using big questions and stimulating dialogue to explore sensitivities. Ultimately, we provide tips to consider when addressing SSIs through philosophical dialogue.

KEYWORDS

philosophical inquiry, nature of science, questions, ethics

1. QUESTIONS ABOUT GENETIC ENGINEERING

For decades, the practice of genetic engineering (GE), which is the manipulation or modification of the genetic makeup of an organism, has resulted in new crops and therapies for people. In the medical field, millions of people with diabetes are treated with insulin produced by genetically modified bacteria. Genetic engineering sparks our imagination, but it can also lead to questionable practices.

For example, Schwarzenegger mice were genetically engineered to have increased muscle growth and researchers aim to protect us from HIV by genetically modifying human embryos. These and many other examples demonstrate how scientists might be tempted to genetically engineer humans to possess certain desired traits. However, is this what we want? Is this morally acceptable? Discussions about GE easily elicit hundreds of ethical questions.

The impact of GE cannot be understood without taking an evolutionary perspective. In this regard, GE can be considered an instrument to artificially select organisms that fit human needs; thus, it can be viewed as an instrument to 'steer' evolution. The introduction of new technologies to alter genetic codes and repair genes with deficiencies (CRISPR-Cas) makes such discussions ever more urgent. This raises the following questions: Are people allowed to fiddle with the gene pools? Are we allowed to tinker with human DNA and redirect the course of evolution?

GE is an archetypical socioscientific issue (SSI) in science education. This means it is a (potentially) controversial social issue related to science that is open-ended and has multiple solutions (Sadler 2004; Zeidler & Keefer, 2003). Addressing socially acute questions is one of the many ways to equip students to take part in discussions on SSIs. These kinds of questions are open-ended and involve poorly structured problems that integrate knowledge in the humanities and sciences (Morin et al., 2017).

GE allows the exploration of (socially acute) questions related to food production, identity, the direction of evolution, the interchange of science and technology, the ethics of research and the relationship between science and society. Furthermore, the topic of GE provides a myriad of opportunities to promote scientific literacy. Scientific literacy is relevant to questions that students may encounter as citizens and to the socio-ethical implications of scientific knowledge (i.e., literacy about the implications of science for society).

Thus, it provides an opportunity to not only help students understand the issues at stake and stimulate students' socioscientific reasoning skills but also contribute to citizenship education since it helps students make informed decisions and empowers them to participate in debates (Sadler et al., 2007; Simonneaux & Simonneaux, 2008).

Notably, GE can stir up emotions in a classroom. The number of (big) questions that might surface when discussing genetic modification seems endless: Are we allowed to genetically engineer humans? Are humans playing God when they do so? Can we improve nature? Do some people need to be 'fixed'? Does genetic modification only favour rich people? If we allow genetic modification, then what is next? Can we improve nature? Is it right to tinker with DNA? Are we sure that our cells function as we think they do? Do big pharma companies know what is best? Can we prohibit a technology even if it has a lot of potential? The broad variety of big questions that can be raised in the context of GE can be categorised into different domains (see Table 1).

Table 1
Types of big questions in the field of genetic engineering.

Scientific concepts	Evolution	Nature of science	Ethics
What is a gene?	Can evolution exist without genetic modification?	Are we sure that our cells function as we think they do?	Should we genetically engineer humans?
How does CRISPR-Cas function to change the genetic makeup of organisms?	Is it unnatural to tinker with DNA?	Do science and religion exclude each other?	Are humans playing God when they genetically engineer organisms?
How can genetic malfunctions lead to illnesses?	Can evolution be improved?	Do we have to know all the potential consequences of introducing a technology before it is introduced?	Are scientists allowed to improve nature?
What is the relationship between genotype and phenotype?	What is the difference between evolution, change and engineering?	How can we know genes' functions in evolutionary processes?	May we forbid a technology even if it has a lot of potential?

Whereas some of the questions focus on the scientific knowledge involved in GE, others focus on the relationship between evolution and GE, the epistemological aspects of science and the socio-ethical aspects of GE. In each of these domains, students can experience difficulties and challenges that hinder an understanding of the issues at stake. In this chapter, we explore how the practice of philosophical inquiry allows teachers to address these different aspects. First, we will zoom in on the challenges students face within each of these domains.

1.1 The molecular biology of genetic engineering

The GE of organisms is a broad domain. It covers the production of genetically modified crops, the use of genetic modification to *'improve'* organisms and discussions on the genetic modification of humans to cure diseases or promote more desirable characteristics. In any of these applications, an understanding of genetics is relevant.

This not only entails an understanding of cell biology, heredity, and genetics but further involves an understanding of the techniques of GE (e.g., the use of CRISPR -Cas to do so). It also entails a fundamental understanding of the relationships between organisms and their genes, which is the degree to which genes are simply blueprints or essences.

A broad range of misconceptions (alternative conceptions) about the biology of GE can surface in the classroom (Aldahmash et al., 2012; Briggs et al., 2016; Wisch et al., 2018). For instance, these can relate to the meaning of words such as *'recombinant DNA'*, the idea that one trait corresponds to one gene, that an allele is a subcomponent of a gene and that proteins store genetic information. Questions phrased in this domain are scientific questions that can be answered through study or research. Notably, our approach in this chapter focuses on philosophical dialogue and will not focus on these types of questions.

1.2 The evolutionary aspects of genetic engineering

Dobzhanski famously wrote, *'nothing makes sense in biology, except in the light of evolution'*. Indeed, since Darwin, the *'ever-evolving'* theory of evolution has had far-reaching implications on our understanding of biological diversity, our worldview and more specific issues such as drug resistance and pandemic outbreaks. Evolution also helps us understand sensitivities related to GE.

An important connection between evolution and GE is that we can think of GE as a new form of artificial selection. Artificial selection has been practised for centuries on both plants and animals, resulting in new varieties. Unawaringly, farmers and breeders thereby altered organisms' genetic makeup. In the case of GE, scientists are certainly aware that they are selecting genes and modifying genomes, with the process and results essentially being the same (i.e., organisms evolved by artificial selection). Darwin (1859) relied on the analogy of artificial selection to explain natural selection.

As Dawkins (2009) later clarified, this analogy makes sense because we can understand artificial selection as a special case of natural selection in which organisms adapt to an environment in which the needs and tastes of humans exert strong selective pressure. The organisms with the most desirable traits are the most reproductively successful. Hence, GE can be used to clarify the central evolutionary mechanism.

Students could still argue that the products of GE are artificial or unnatural in the sense that in contrast to natural selection, we intervene with nature to produce them. Such considerations provide the ideal opportunity to discuss two important dimensions of evolution. One is that evolution is a blind process that does not have our best interests at heart.

Therefore, what is natural is not necessarily good. Evolution produces traits that favour the reproductive success of its bearers, not our well-being. These adaptive traits often include defences or weapons targeted at other organisms, including us. For example, many plants produce toxins that are harmful and sometimes even lethal, which prevents them from being eaten.

Since nature does not provide, we must do it ourselves - which implies that we must alter our ecological surroundings. However, since species will continue to adapt to changes in the environment through natural selection in ways that favour them and not us, this is a continuous struggle. For instance, consider that insects can become resistant to pesticides.

Another dimension is that humans are not separate from, but rather part of nature. This means that, like any other organism, humans will make the most of their environment. Although humans might be exceptional in this regard, their differences from other organisms are not essential but gradual. As such, artificial selection can be regarded as a form of natural selection since our interests and tastes are part of the natural environment to which other species adapt. GE is different from traditional forms of breeding in the sense that the technology enables us to modify the genomes of organisms by introducing genes from different species.

This crossing of species barriers represents an important concern among the general public. However, this practice can help explain that horizontal gene transfer is quite common in nature and that the process plays an important role in evolution - a point that scientists are now becoming increasingly aware of. For instance, approximately 8% of human DNA is of viral origin. Furthermore, the technology of GE recruits a natural process by which bacteria introduce their genetic material into the cells of their hosts.

Certainly, horizontal gene transfer is only possible because the genetic code is universal. As such, GE also provides a context in which to discuss common descent.

1.3 The nature of science of genetic engineering

How is our current understanding of GE achieved? Is our understanding of GE biased? If so, how? What is the relationship between technology and science? These issues relate to the nature of science (NOS) and touch on metaphysics (i.e., what is real; genes, evolution, species), epistemology (i.e., how we know, including the question of what we can know about genes and evolutionary processes) and axiology (i.e., what is valued), among others. Logic and different forms of reasoning are required to answer questions of this nature.

It is important to consider philosophical (i.e., NOS) questions when it comes to GE in education for several reasons. In terms of knowledge, it is important for students to understand the basis upon which claims about GE and evolution are made. Through this, they may understand how science works and be able to approach social and ethical questions from an informed position. Since GE can be a divisive topic, there is a need to establish a good understanding of what is known, what the evidence is and what the limitations and uncertainties are. GE is a *'hot'* area of research, where governance and regulations are barely catching up at times. Thus, it is important for society to answer the question *'just because we can, does it mean we should?'*.

It is also important to open spaces where students can agree or disagree with the direction that science is taking. In dealing with questions that link science and society and creating space for dialogue, we empower students to handle science-based issues that will determine their future world. Finally, it is important to pay attention to good quality thinking about what is known and how we can help students gain a better understanding of how science works in the lab and beyond while avoiding arguments based on misinformation or logical fallacies in arguments.

Critics of school science have drawn attention to the focus on *'final form'* or *'readymade'* science, which emphasises the products rather than the processes of science. When considering science-in-the-making, such as at the frontiers of GE, it is important to understand not only what is known, but also how that knowledge has been gained and the status and certainty of scientific truths.

Teaching and learning NOS is one way of responding to this criticism because it draws attention to the knowledge creation process and science as a human practice. Clough (2020) argued that NOS should be framed and taught as questions rather than as declarative statements to (i) more accurately reflect the context, cultural embeddedness and nuance needed for understanding and (ii) foreground the investigative process. The use of questions to investigate NOS in relation to GE allows teachers and students to attend to contemporary conditions including politics, democracy, capitalism, subjectivity, agency and ethics.

For example: Are we sure that genetically modified organisms will not harm the planet? How should decisions about GE be made when there is uncertainty about its consequences? Do cells function as we think they do? What does it mean to *'own'* a gene? Can nature teach us about what is good? Should we consider the impact that the GE of crops has on the job quality of farmers? Who benefits from GE? In our description of practice below, we demonstrate how questions can be used in this way.

1.4 The ethics of genetic engineering

GE is a challenge in our contemporary society. It opens a sea of possibilities and just as many discussions. It has raised many concerns, especially in the domain of agriculture. Medical applications such as insulin tend to be less contentious amongst the public. Concerns related to GE include worries about the safety of the technology, its threats to the environment and its socio-economic consequences.

Since the matter is highly complex, when assessing environmental and socio-economic impacts, it is important to consider not only the safety of the technology itself but also how it is used and regulated, as well as the impact on different groups of stakeholders in society. GE is a popular tool used to develop crops that are more tolerant to extreme conditions, resistant to pesticides and viruses or able to fight malnutrition (e.g., the case of golden rice). However, such technology also often evokes questions about the involvement of multinationals, patents and the agro-industry.

However, in the future, GE might have other applications. The possibility of human enhancement raises different types of concerns. For example: Is GE safe? Is it good for everybody or just a selected group? Should GE be used to enhance humans? What is the difference between therapy and enhancement in the use of GE? What responsibility do people have towards future generations? Is GE different from other therapies and enhancements? Is human GE *'market-based eugenics'*? A broad range of ethical frameworks resonates in discussions on GE.

In a way, what is considered *'good'* and why it is considered so depends on the ethical framework that is embraced. Consequentialism provides a costs and benefits approach to the impact of GE. A deontological approach rather focuses on the principles underpinning the act of GE and what ought to be done.

Thinking about human enhancement also invokes questions about human nature, personal identity, autonomy, values and social inequality. Philosophers and ethicists bring various perspectives to these issues. Transhumanists argue that modes of human enhancement, including GE, should be seriously considered as a means to improve the quality of human life (e.g., Bostrom, 2003).

Others, such as the influential ethicist Hans Jonas, argue that in dealing with such technologies, one should 'act so that the effects of your action are compatible with the permanence of genuine human life' (Jonas, 1984, p. 11). Feminist bioethicists focus on power relationships and the impact of human enhancement on women and other marginalised groups (e.g., Simonstein, 2019).

2. PHILOSOPHICAL INQUIRY ABOUT QUESTIONS CONCERNING GENETIC ENGINEERING

The key idea of this educational practice is to help students reflect on the NOS as well as the ethics and evolutionary aspects of GE. Here, philosophical inquiry (and philosophical dialogues) are the means to realise this goal.

2.1 Materials

- Stimuli to start the dialogue (see below).
- Philosophical questions (see below).
- A classroom in which students sit in a circle.

2.2 Time

The philosophical inquiries can last from 10 to 30 minutes (or even longer if the students are well acquainted with this teaching method).

2.3 Target audience

The activities focus on 12- to 18-year-old students in the context of both formal science education (i.e., schools) and informal contexts (i.e., science museums, science centres, etc.).

2.4 Learning objectives

2.4.1 *Learning objectives related to awareness of the SSI*

1. The social, ethical and moral issues emerging from the context of GE and sensitive SSIs.

2.4.2 *Learning objectives related to evolution*

2. Evolution does not consist of progress in any particular direction.

2.4.3 *Learning objectives related to scientific practices*

3. Asking questions.

2.4.4 *Learning objectives related to the nature of science*

5. Scientific ideas can change over time.
6. Science is a human endeavour.

2.4.5 *Learning objectives related to transversal skills*

7. Analyse issues from multiple perspectives.
8. Explore how science can contribute to the issues and the limitations of science.

2.5 Description of the educational practice

In a philosophical inquiry, participants search for answers to challenging (philosophical) questions under the supervision of a facilitator. The facilitator structures the dialogue and stimulates a logical investigation without providing any answers. This helps create a space for students to inquire about the epistemological underpinnings of science and the relationship between science and human values.

The use of philosophical dialogues is inspired by the philosopher John Dewey. He argued for a form of education in which the emphasis is placed on the learners, with the latter taking responsibility for their own learning process (Dewey, 1997). It is on this track that the American philosopher Matthew Lipman developed the methodology of *'philosophy for children'* in the 1960s (Lipman, 1988).

Lipman regarded philosophy not only as an academic discipline for specialists but as a form of dialogical thinking (Lipman, 2003). Central to philosophical inquiries is the ambition to induce *'critical and creative thinking'* in students. Logic plays a central role in this process (e.g., by exploring how to distinguish arguments from fallacies). This process occurs in a social context (e.g., a class), which is called the *'community of inquiry'.* In this community of inquiry, a group of students can search for answers to philosophical questions under the guidance of a facilitator.

Students are questioned about the coherence and relevance of arguments and the (hidden) premises or consequences of statements. In recent decades, the impact of philosophical conversations on young people's behaviour has been investigated more systematically (Reznitskaya, 2005).

Philosophical dialogues not only stimulate young people's curiosity and capacity for analysis but also sharpen their social and discussion skills and reasoning ability (Lafortunate, 2003; Lipman, 2003). Philosophical dialogues allow students to explore the meanings of (philosophical) concepts and distinct perspectives in order to understand them.

The use of philosophical dialogues may be promising to help students critically reflect and develop an ecologically valid understanding of knowledge - especially because this process of developing knowledge is re-enacted during the dialogue itself. Thus, students can come to an understanding of ideas, the relationships between these ideas and reality, and the ways such understandings can differ for different people (Worley, 2016).

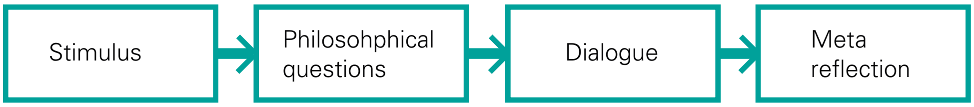
Studies on the implementation of philosophical inquiries in the context of science education show how these inquiries can be used to help students reflect on scientific concepts, ethical issues or NOS (De Schrijver et al., 2018; Dunlop & De Schrijver, 2020).

2.4.1 *Learning objectives related to awareness of the SSI*

During a philosophical inquiry, students sit in a circle and are guided by the questions of the teacher (facilitator) to explore different answers.

A philosophical inquiry entails different phases (figure 1): (i) stimulus; (ii) raising philosophical questions; (iii) dialogue; (iv) meta-reflection. Depending on your approach as a teacher, different phases will allow you to work on different learning objectives (e.g., whereas the stimulus phase provides excellent opportunities to create an awareness of the issue, the dialogue phase provides opportunities to analyse an issue from multiple perspectives).

Figure 1
Phases in a philosophical inquiry.



(i) Stimulus

A philosophical dialogue often begins after a philosophical problem is introduced with a stimulus that provokes reflection. Stimuli may include short videos, songs, cartoons, texts, strange experiments, cases, images or stories.

Typically, the stimulus material is shared with the group, with students being asked to reflect on what they have seen, read, heard or shared. This might include identifying troublesome concepts, responding to the stimulus using a limited number of words or asking students to identify ideas that they agreed or disagreed with. Also, a short case study or picture can function as a stimulus to start the dialogue. A picture (figure 2) can serve as a stimulus to begin a dialogue, as shown in the following dialogue:

Facilitator	**What do you think of when you see this image?**
Student 1	A finger, DNA.
Student 2	A person who thinks he is God.
Student 3	How dangerous it is to change DNA.
Facilitator	Is this what you think or what you see?
Student 1	It is what I think, I think
Facilitator	What are the themes of this image?
Student 2	Genetic modification, God, science.
Student 5	Danger, because I see dark clouds
Student 6	Opportunities… to make what we want.
Facilitator	What do the others think?

Figure 2
Example of a stimulus for a philosophical inquiry.

(ii) Philosophical questions

What is a philosophical question?

Philosophical questions can be described as those that are 'open to informed, rational and honest disagreement...' (Floridi, 2013 —i.e., to be open and to lend themselves to authentic exploration through reasoning. Using philosophical questions (e.g., Can scientific knowledge ever be proven?) as the focus for inquiry allows students to explore, discuss and develop their own ideas about NOS. These philosophical questions can originate from the students or the teacher. Interactions between the participants and facilitation by teachers enable students to reflect upon NOS and develop their own arguments.

As a teacher, you may describe these big philosophical questions as questions that are interesting to explore together, questions that are difficult to give a final answer to and/or questions that Google does not know the answer to.

How do you raise philosophical questions?

In creating the environment for philosophical dialogue, a range of approaches to generate questions exists. This includes (i) the development and/or selection of the question by the teacher/facilitator and (ii) the creation and/or selection of the question by the students.

The creation and/or selection of the question by the teacher/facilitator might be important when there is a specific question or issue that the teacher would like the class to explore; for example, what is the difference between science and technology? Are scientists playing God? What is the difference between science and religion? This may yield a philosophical dialogue that focuses tightly on what teachers want their students to learn.

However, students may lack ownership of and investment in questions that have been selected for them. The creation and/or selection of questions by students might be important when the teacher wants to engage students by making connections between science, themselves and the world. It can further give students ownership of the inquiry and ensure that the philosophical inquiry is relevant to them. Also, it can help them develop their ability to ask (philosophical) questions. Furthermore, it gives the teacher an idea of the (pre) concepts living within the students' minds.

As discussed above, a stimulus can be useful for raising a philosophical question. For example, after a short dialogue regarding an image, the teacher can ask students to phrase philosophical questions. It may be helpful to ask students to write all the questions that come to mind and then look for the most interesting ones. It could also be helpful to stress that philosophical questions are open, easy to understand and elicit a cognitive conflict.

Table 2
Examples of philosophical questions that (do not) work in a philosophical dialogue.

Examples of big questions	Is this a useful question for a philosophical dialogue?
Why is it good to genetically modify organisms?	This question is not open. It is manipulative since it already suggests that genetic modification is good. Thus, it does not allow students to explore all of the options.
What is genetic modification?	This is a factual question. However, it is not very useful as a philosophical question since there is only one clear answer (or scientific consensus).
Can nature improve itself?	This question is a useful philosophical question since it allows us to explore the meaning of 'improvement/progress' and 'nature'. It does not lead to one scientific explanation but invites one to explore different points of view.
Is genetically modifying a plant better than genetically modifying an ant?	This question makes students smile and stimulates wonder. It invites them to look for differences between the engineering of ants and plants. Using specific organisms helps students to be concrete.
Can evolution be improved?	This is a useful philosophical question. It focuses on the meaning of 'improvement' in the context of evolution. It elicits a cognitive conflict by mixing two kinds of thinking: scientific thinking (evolution) and ethical thinking (improving).
Are we allowed to tinker with the blueprints of human beings?	This is a useful philosophical (ethical) question that invites students to argue whether they agree or disagree and why. Having a yes-or-no question is helpful since it makes it easy for participants to react. After their initial reaction, students will have to elaborate on it.

(iii) Dialogue

Whilst facilitating a philosophical dialogue, the following rules usually apply (Rondhuis, 2005):

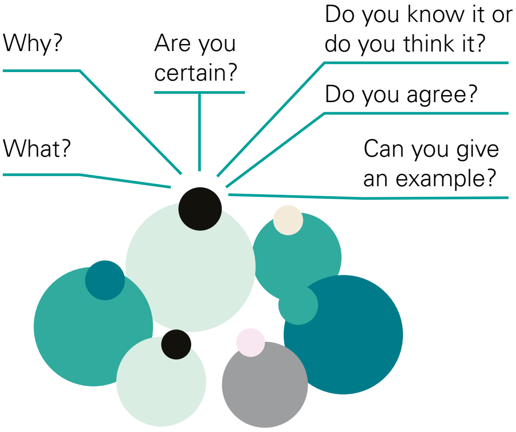
- Opinions are only allowed if they are supported by arguments.
- Participants may respond to each other's arguments, but not each other's opinions.
- Statements and arguments must be understandable and accessible to everyone.
- Dogmas, irrational certainties and arguments based on external authorities are not allowed.
- Reasoning must be structured consistently and systematically.
- Thus, the facilitator helps the learners structure and clarify their views, assumptions and concepts.

Philosophical questions can give rise to new (follow-up) questions that help to deepen the inquiry. In the table below, we show that one big question can give rise to extra questions that a facilitator may ask.

Table 3
Philosophical questions and follow-up questions.

Philosophical questions	Philosophical follow-up questions
Is genetically modifying a plant better than genetically modifying an ant?	• Who decides what is good and what is bad? • Are animals more important than plants? • May we modify everything? • Should we follow (ethical) rules for genetic modification? • Is modifying a sheep better than modifying a human
Can evolution be improved?	• Is a human better adapted to its environment than a bacterium? • Does evolution lead to progress? • Is improvement always the best option? • How do you know that something is better? • Can progress go backward? • Does evolution have end goals?
Is GE a form of evolution?	• Is life possible without change? • Is life possible without evolution? • Is GE possible without an engineer? • Is nature an engineer? • Can GE occur by coincidence?
Can you have evolution without genetically engineering organisms?	• Is there a difference between engineering, modification and change? • Which elements are necessary to be able to speak of evolution? • Can you have evolution without change?
Would the world be a better place if GE did not exist?	• Is GE a good technology? If yes, why? • Does GE have more advantages than disadvantages? • Is GE the same as playing God? • Can we interfere in nature?

Figure 3
Facilitator questions in a philosophical inquiry.



The role of the facilitator

The facilitator does not provide any answers but instead asks questions. These questions encourage students to explore various points of view.

The emphasis lies not on finding one final answer, but on collectively exploring a topic. The types of questions a facilitator may ask are presented as follows.

1. Facilitator questions asking for clarity

These questions stimulate participants to understand the words and concepts that are used.

- What do you mean with…?
- Can you give an example?
- Can you summarise what … is talking about?
- What is the main question in this discussion?
- Can you rephrase your/her/his answer?

2. Facilitator questions asking for arguments

We all make judgements all the time. However, we rarely stop to think about where these judgements come from and whether they are based on valid grounds. In a philosophical conversation, we look for the basis of our judgements and examine the hypotheses and assumptions upon which they are built.

- Why do you think so?
- Why is it so?
- How do we know this is true?
- What is it based on?
- What do we know for sure about this?
- How can we prove it?
- Is it a fact or an opinion?

3. Facilitator questions asking for alternative perspectives

These questions invite us to look at and question our own familiar perspectives. Our everyday experiences and views are usually self-evident. However, you can also experience and understand the same things differently if you look at them from a different angle. Questions about changing perspectives are also suitable for exposing unfounded arguments or opinions without explicitly acting as a content 'corrector' of the conversation.

- Can you imagine the opposite?
- Are there other options that could also be true?
- Can the opposite be true?
- Does anyone think otherwise?

4. Facilitator questions about implications and consequences

You can also test an assertion by making its consequences and implications explicit. For example, this type of question can be used to expose contradictions in a line of reasoning.

- What can we deduce from this?
- Is there a general rule for this?
- How does that fit in with what you just said?

(iv) Meta-reflection

The focus of philosophising is on learning to think critically together rather than on finding one correct answer. It rarely or never happens that a group comes to a consensus. The characteristic of this activity is that it raises more questions than answers. The main goal is to increase one's understanding of the complexity of the matter. You do not have to wait for an answer that everyone agrees with before you can conclude the discussion. However, it is useful to have a short meta-reflection after the research in which you discuss the conversation itself.

During a meta-reflection, the conversation is summarised, the most important insights are listed and a joint decision is made as to whether there should be a follow-up conversation. You can also conclude with a round of questions if there is sufficient time. The questions that remain after the discussion can be noted in a philosophy notebook and dealt with in a subsequent session.

It is also useful to determine how the students experienced this activity, what went well and what did not. Based on this feedback, you may want to revise the process of the discussion.

Facilitator questions for the meta-reflection

- What can we conclude?
- What insights remain?
- Do we understand the issue better?
- Was the conversation useful?
- Does everyone agree with the way
- the conversation went?
- What questions were not addressed?
- Is a follow-up discussion desirable?

2.5.2 *Dialogue examples*

Example 1: May we improve nature?

Stimulus

Students are asked to categorise objects into two groups: 'natural' and 'unnatural'. The facilitator asks students to explain why they made a choice. Other students can also respond.

Dialogue

Facilitator **May we improve nature?**

Student 1 No, we aren't God.

Facilitator **What do the others think? Do you agree?**

Student 2 No, we do it all the time—and that doesn't make us God.

Facilitator **Can you give an example?**

Student 2 My aunt has a new hip. She can walk again.

Facilitator **Student 1, what do you think about this example?**

Student 1 Yes, I agree with Student 2. But this is not what I wanted to say. I mean like cloning.

Facilitator **Can you try to put your argumentation into a rule?**

Student 1 If you don't play with our genetic material, it is OK.

Student 3 So a plastic hip is OK, but a cloned hip is wrong. Why?

Student 1 Because it will never stay with a hip. Once we have the technology, we will want more and more.

Facilitator **What do you mean by more and more?**

Student 4 Like perfect people?

Student 1 Yes.

Facilitator **Who disagrees?**

Student 5 I don't know if that is true. If we can improve hips, it does not mean that we 'will want more'.

Facilitator **What do the others think?**

Student 6 Maybe we need rules, like a boundary.

Example 2: May you doubt everything in a science lesson?

Stimulus

Quote: 'To doubt everything and to believe everything are two equally convenient solutions; each saves us from thinking' (Poincaré, 1902).

Students are asked to say what they think this quote means. Then, the students should answer why it means what they think it means. Based on their ideas, new philosophical questions can be phrased.

Dialogue

Facilitator **May you doubt everything in a science lesson?**

Student 1 Yes, because sometimes you find out something new and you have to change your original idea.

Facilitator **Does everyone agree?**

Student 2 Yes, a theory is never really finished. It is like a tree—it keeps growing.

Facilitator **Aren't there theories that never change?**

Student 3 The theory of evolution. That's a theory that cannot change.

Student 4 I disagree. Imagine that we discover a planet where all the organisms are identical to the organisms on Earth. That would show that evolution is different from what we understand… or imagine that we would find a skeleton of a human in an earth layer from the dinosaur age… Then we might have to adapt the theory of evolution, don't we? The theory of evolution can change. But thus far, we haven't needed to change it.

Student 5 Perhaps only facts can change.

Facilitator **Can you give an example of a fact that never changes?**

Student 3 The Earth is round.

Facilitator **What do the others think? Is 'the Earth is round' a fact that never changes?**

Student 3 We used to think that the earth was flat, so that has already changed.

Student 5 But then it wasn't a fact if it could change.

Facilitator **Let's go back to the beginning. Can you doubt everything in the science class?**

Student 4 Yes and no. In a way, you should doubt, because if you think something is true, it is much more like dogma—and science is no dogma.

Student 3 But if you doubt everything, you will never be able to know everything. Maybe you should doubt everything, but not the fact that science can give us knowledge.

Student 7 Ay, my head aches—but I'm inspired as well.

Example 3: Can you believe in science?

Stimulus: Case study

Students read a case study. Afterwards, they answer the questions below in small groups.

Case study. During the lesson on genetic modification, Paulo gets angry and walks out of the classroom, saying, 'We must not tamper with what God has given us! Scientists work for the devil!'

- What do you think of this statement?
- (How) Do religion and science differ?
- Can you talk about faith in science class?
- Can you believe in science?
- Can a scientist believe in God?
- Can scientists learn from religion?

Dialogue

Facilitator **Can you believe in science?**

Student 1 No, you can only believe in God. Science is not something you believe in, it is something you know.

Facilitator **Does everyone agree?**

Student 2 No, I think you can believe in science. You can believe that science gives you a better understanding of the world.

Student 3 You can believe that science is a good approach to knowing something.

Facilitator **What is the difference between knowing and believing?**

Student 4 If you know something, it is true. But if you believe it, you think it is true.

Student 2 I disagree. sometimes I say I know something. For example, I know that my brother is at home—but in the end, he is not.

Student 1 Sometimes a scientist says he knows something when he actually doesn't. He only believed that he knew it. You can never be absolutely sure.

Facilitator **Is it possible to be absolutely sure of something?**

Student 3 Hmm, perhaps not. But that makes it difficult because if we are not sure, how can we make choices?

Facilitator **Can you give an example?**

Student 3 Well, if we don't really know whether genetic engineering is dangerous, then what should we do? Should we wait with it or should we start nevertheless?

Student 4 I agree. If we cannot be really sure of anything, that's what makes science science. But at least I believe that science is one of the best instruments used to know what is true.

TIP 1: Take the Socratic stance

What teachers find most difficult is not to answer the questions themselves or to correct the students. However, most of the time, students will investigate each other's ideas on their own. As soon as you start correcting students, the dialogue evaporates and students mainly listen to your answers. Then, the thinking process has come to an end. If you start the dialogue, make it clear to the students that in a philosophical inquiry, you do not know the answers. Afterwards, in a different teaching phase, you can come back to ideas or misconceptions that surfaced in the dialogue.

TIP 2: Science education is more than dialogue alone

These philosophical dialogues should be part of a larger teaching approach. Of course, a science lesson is more than simply having dialogues and exploring student ideas. It also involves acquiring an understanding of biology and science. However, these dialogues can be useful instruments for stimulating active reflection about science and ethics.

TIP 3: Timing can vary

The dialogic exercises can vary over time. Sometimes it suffices to only ask the question for a whole dialogue to be sparked. Other times, it is more difficult. Sometimes it may suffice to simply ask a question and go on with the regular science activity. For example, the question 'Do you think this, or do you know it?' can be a useful question to elicit a brief moment of philosophical reflection.

TIP 4: Participation is not compulsory

Not everyone feels eager to participate in the dialogic process. For some students, it may be frightening that certainties are questioned. We often give students the chance to participate by actively addressing them as a facilitator. Yet, if they do not wish to respond, that is OK. Giving students time to discuss a certain question in a pair helps to involve the ideas of those who are shyer to participate.

2.6 Further perspectives on how to use the activity in other contexts or with participants of other ages

In this chapter we provided example questions, stimuli and dialogues to start a philosophical dialogue about GE in your classroom. The dialogic approach can function in many different contexts. The challenge is to find stimulating philosophical questions. Taking the Socratic stance and questioning the students' responses will create a community of inquiry that enhances a sense of wonder and motivates students to think and provide arguments.

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