Sá-Pinto, X., Beniermann, A., Børsen, T., Georgiou, M., Jeffries, A., Pessoa, P., Sousa, B., & Zeidler, D.L. (Eds.). (2022). Learning Evolution Through Socioscientific Issues. Aveiro: UA Editora. http://hdl.handle.net/10773/35673

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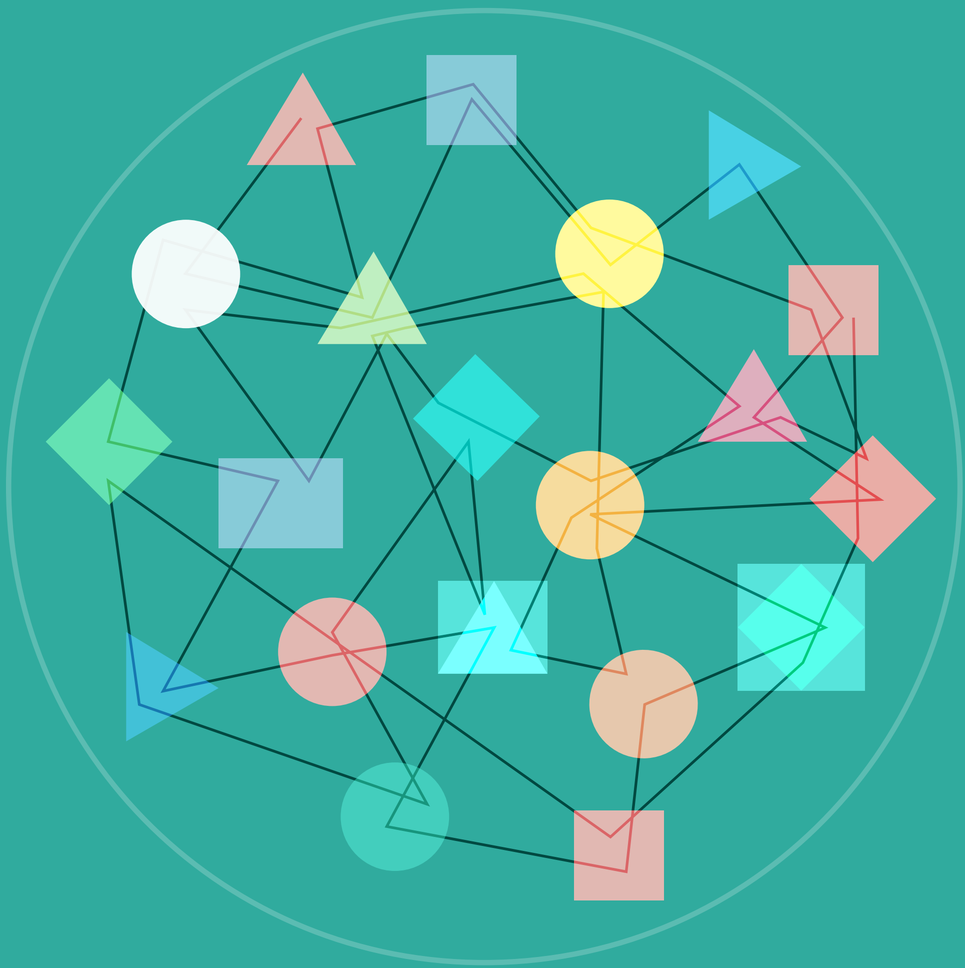
Open access learning materials from the chapter are available:
https://openevo.eva.mpg.de/teachingbase/evolution-cooperation-and-sustainability/

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).

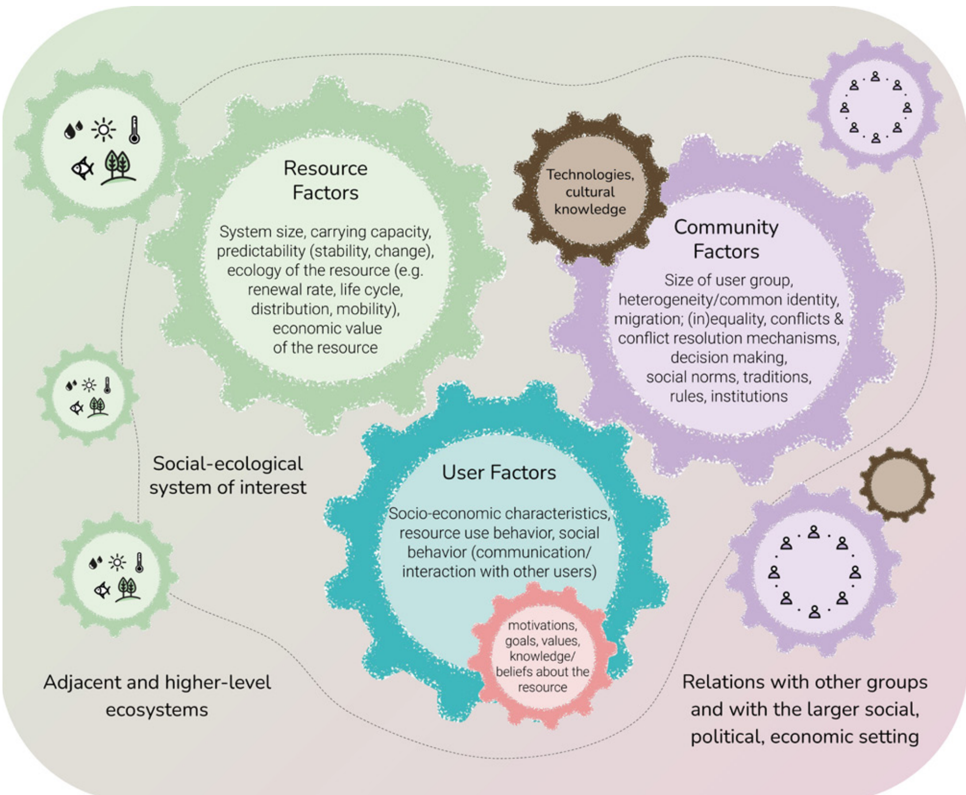


Table 1
Core Design Principles for the successful management of common-pool resources and successful cooperation, with analogous examples in biology (see Section 1.2).

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.

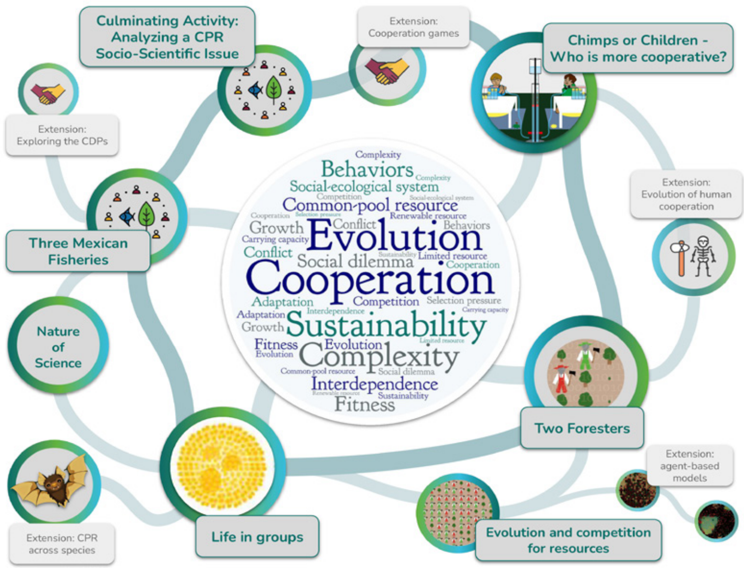


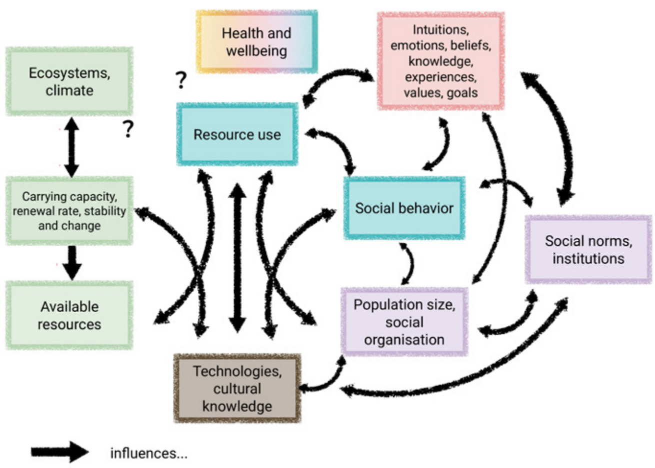
Figure 2
Overview of the unit with suggested core lessons as well as opportunities for additional lesson extensions to reinforce transfer and deeper understanding.

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?

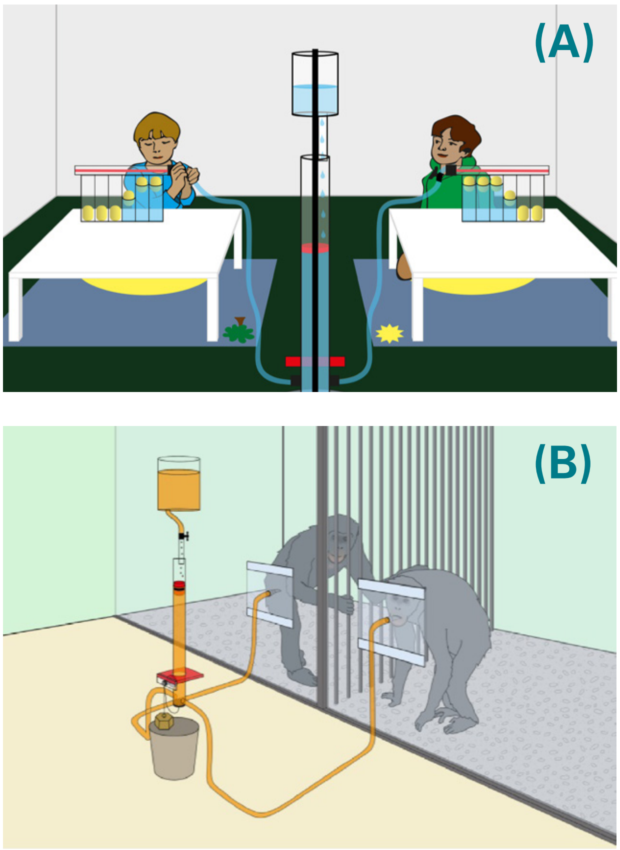
The following descriptions of lessons and recommendations for implementation draw on the authors' experiences in implementing lessons in secondary and teacher education contexts.

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.

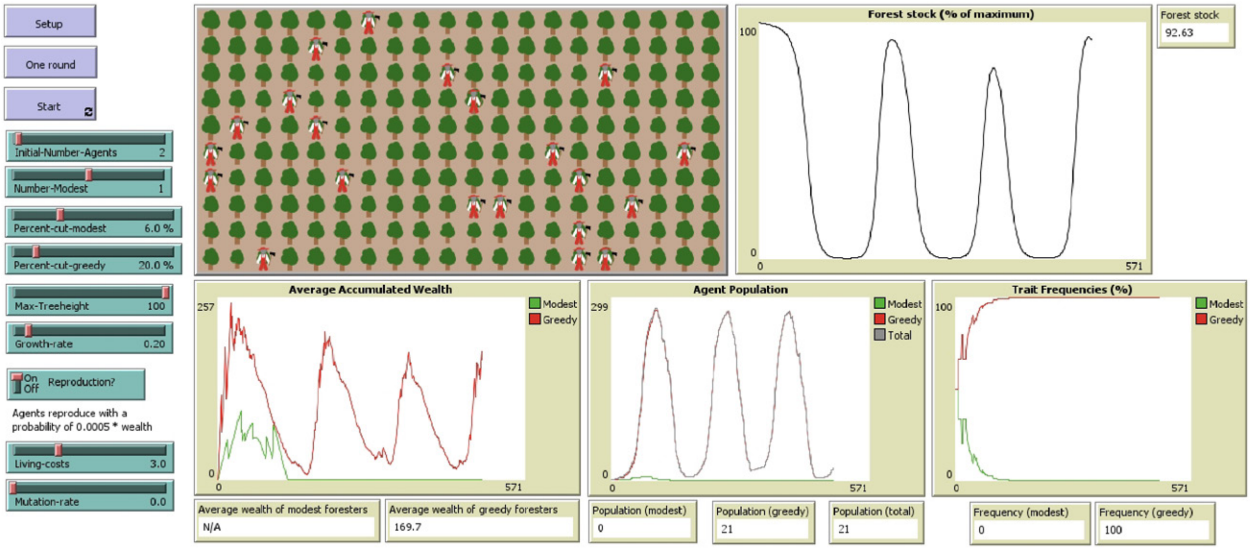
The lesson material contains a discussion guide to introduce the model and the NetLogo platform to students. In younger grades (5th to 8th grade; 11- to 14-year-olds), students can use the model to run and document experiments and reflect on results individually or in groups with the help of worksheets. 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.

3. BIBLIOGRAPHY

Aktipis, C. A. (2016). Principles of cooperation across systems: From human sharing to multicellularity and cancer. *Evolutionary Applications, 9*(1), 17–36. https://doi.org/10.1111/eva.12303

Aktipis, C. A., Cronk, L., Alcock, J., Ayers, J. D., Baciu, C., Balliet, D., Boddy, A. M., Curry, O. S., Krems, J. A., Muñoz, A., Sullivan, D., Sznycer, D., Wilkinson, G. S., & Winfrey, P. (2018). Understanding cooperation through fitness interdependence. *Nature Human Behaviour, 2*(7), 429–431. https://doi.org/10.1038/s41562-018-0378-4

Aktipis, C. A., Cronk, L., & de Aguiar, R. (2011). Risk-pooling and herd survival: An agent-based model of a Maasai gift-giving system. *Human Ecology, 39*(2), 131–140. https://doi.org/10.1038/s41562-018-0378-4

Basurto, X., & Ostrom, E. (2009). Beyond the tragedy of the commons. *Economia Delle Fonti Di Energia e Dell'ambiente,* 35–60. https://doi.org/10.3280/EFE2009-001004

Bowles, S., & Gintis, H. (2011). *A cooperative species. Human reciprocity and its evolution.* Princeton University Press.

Cox, M., Steegen, A., & Elen, J. (2018). Using causal diagrams to foster systems thinking in geography education. I*nternational Journal of Designs for Learning, 9*(1), 34–48. https://doi.org/10.14434/ijdl.v9i1.22756

Darwin, C. (1871). *The descent of man, and selection in relation to sex.* John Murray.

Dickes, A. C., Sengupta, P., Farris, A. V., & Basu, S. (2016). Development of mechanistic reasoning and multilevel explanations of ecology in third grade using agent-based models. *Science Education, 100*(4), 734–776. https://doi.org/10.1002/sce.21217

Dickinson, J. L., Crain, R. L., Reeve, H. K., & Schuldt, J. P. (2013). Can evolutionary design of social networks make it easier to be "green"? *Trends in Ecology and Evolution, 28*(9), 561–569. https://doi.org/10.1016/j.tree.2013.05.011

Diekert, F. K. (2012). The tragedy of the commons from a game-theoretic perspective. *Sustainability, 4*(8), 1776–1786. https://doi.org/10.3390/su4081776

Foster, K. R. (2004). Diminishing returns in social evolution: The not-so-tragic commons. *Journal of Evolutionary Biology, 17*(5), 1058–1072. https://doi.org/10.1111/j.1420-9101.2004.00747.x

Ghorbani, A., & Bravo, G. (2016). Managing the commons: A simple model of the emergence of institutions through collective action. *International Journal of the Commons, 10*(1), 200–219. https://doi.org/10.18352/ijc.606

Glynn, S. M. (2008). Making science concepts meaningful to students: Teaching with analogies. In S. Mikelskis-Seifert, U. Ringelband, & M. Brückmann (Eds.), *Four decades of research in science education: From curriculum development to quality improvement* (pp. 113–125). Waxmann.

Hanisch, S., & Eirdosh, D. (2020a). *A teacher's guide to evolution, behavior, and sustainability science,* (2nd edition). https://openevo.eva.mpg.de/teachingbase/a-teachers-guide-to-evolution-behavior-and-sustainability-science/

Hanisch, S., & Eirdosh, D. (2020b). Educational potential of teaching evolution as an interdisciplinary science. *Evolution: Education and Outreach, 13*(1), 25. h ttps://doi.org/10.1186/s12052-020-00138-4

Hanisch, S., & Eirdosh, D. (2021). Are humans a cooperative species? Challenges & opportunities for teaching the evolution of human prosociality. *The American Biology Teacher, 83*(6), 356–361. https://doi.org/10.1525/abt.2021.83.6.356

Hardin, G. (1968). The tragedy of the commons. *Science, 162*(3859), 1243–1248. https://doi.org/10.1126/science.162.3859.1243

Ke, L., Sadler, T. D., Zangori, L., & Friedrichsen, P. J. (2021). Developing and using multiple models to promote scientific literacy in the context of socioscientific issues. *Science and Education, 30*(3), 589–607. https://doi.org/10.1007/s11191-021-00206-1

Kerr, B., Neuhauser, C., Bohannan, B. J. M., & Dean, A. M. (2006). Local migration promotes competitive restraint in a host–pathogen "tragedy of the commons". *Nature, 442*(7098), 75–78. https://doi.org/10.1038/nature04864

Koomen, R., & Herrmann, E. (2018a). An investigation of children's strategies for overcoming the tragedy of the commons. *Nature Human Behaviour, 2,* 348–355. https://doi.org/10.1038/s41562-018-0327-2

Koomen, R., & Herrmann, E. (2018b). Chimpanzees overcome the tragedy of the commons with dominance. *Scientific Reports, 8*(10389). https://doi.org/10.1038/s41598-018-28416-8

MacLean, R. C., & Gudelj, I. (2006). Resource competition and social conflict in experimental populations of yeast. *Nature, 441*(7092), 498–501. https://doi.org/10.1038/nature04624

Meinzen-Dick, R., Janssen, M. A., Kandikuppa, S., Chaturvedi, R., Rao, K., & Theis, S. (2018). Playing games to save water: Collective action games for groundwater management in Andhra Pradesh, India. *World Development, 107*(July), 40–53. https://doi.org/10.1016/j.worlddev.2018.02.006

Mesoudi, A. (2011). *Cultural evolution: How Darwinian theory can explain human culture and synthesize the social sciences.* University of Chicago Press.

Mesoudi, A. (2016). Cultural evolution: Integrating psychology, evolution and culture. *Current Opinion in Psychology, 7*(February), 17–22. https://doi.org/10.1016/j.copsyc.2015.07.001

Messner, D., Guarín, A., & Haun, D. B. M. (2013). *The behavioural dimensions of international cooperation.* Global Cooperation Research Papers, 1. Käte Hamburger Kolleg / Centre for Global Cooperation Research. https://www.gcr21.org/de/publikationen/gcr/research-papers/the-behavioural-dimensions-of-international-cooperation/

NGSS Lead States. (2013). *Next Generation Science Standards: For States, by States*. Washington, DC: National Academies Press.

Novak, J. D., & Cañas, A. J. (2006). The origins of the concept mapping tool and the continuing evolution of the tool. *Information Visualization, 5*(3), 175–184. https://doi.org/10.1057/palgrave.ivs.9500126

Novak, J. D., & Cañas, A. J. (2004). Building on new constructivist ideas & CmapTools to create a new model for education. In A. J. Cañas, J. D. Novak, & F. M. González (Eds.), *Concept maps: Theory, methodology, technology. Proceedings of the First International Conference on Concept Mapping. Vol. 1* (pp. 469–476).

Ostrom, E. (1990). *Governing the commons. The evolution of institutions for collective action.* Cambridge University Press.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. P*roceedings of the National Academy of Sciences of the United States of America, 104*(39), 15181–15187. https://doi.org/10.1073/pnas.0702288104

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science, 325*(5939), 419–422. https://doi.org/10.1126/science.1172133

Ostrom, E. (2013). Do institutions for collective action evolve? *Journal of Bioeconomics, 16*(1), 3–30. https://doi.org/10.1007/s10818-013-9154-8

Powers, R. B. (1986). The commons game: Teaching students about social dilemmas. *Journal of Environmental Education, 17*(2), 4–10. https://doi.org/10.1080/00958964.1986.9941402

Pugh, K. J., Koskey, K. L. K., & Linnenbrink-Garcia, L. (2014). High school biology students' transfer of the concept of natural selection: A mixed-methods approach. *Journal of Biological Education, 48*(1), 23–33. https://doi.org/10.1080/00219266.2013.801873

Rankin, D. J., Bargum, K., & Kokko, H. (2007). The tragedy of the commons in evolutionary biology. *Trends in Ecology and Evolution, 22*(12), 643–651. https://doi.org/10.1016/j.tree.2007.07.009

Rankin, D. J., Dieckmann, U., & Kokko, H. (2011). Sexual conflict and the tragedy of the commons. *The American Naturalist, 177*(6), 780–791. https://doi.org/10.1086/659947

Ratnieks, F. L. W., & Wenseleers, T. (2005). Policing insect societies. *Science, 307*(5706), 54–56. https://doi.org/10.1126/science.1106934

Sachs, J. L., Mueller, U. G., Wilcox, T. P., & Bull, J. J. (2004). The evolution of cooperation. *The Quarterly Review of Biology, 79*(2), 135–160. https://doi.org/0033-5770/2004/7902-0001$15.00

Sadler, T. D., Barab, S. A., & Scott, B. (2007). What do students gain by engaging in socioscientific inquiry? *Research in Science Education, 37*(4), 371–391. https://doi.org/10.1007/s11165-006-9030-9

Sadler, T. D., Foulk, J. A., & Friedrichsen, P. J. (2017). Evolution of a model for socioscientific issue teaching and learning. I*nternational Journal of Education in Mathematics, Science and Technology, 5*(2), 75–87. https://doi.org/10.18404/ijemst.55999

Sadler, T. D., Friedrichsen, P., & Zangori, L. (2019). A framework for teaching for socioscientific issues and model based learning (SIMBL). *Revista Educação e Fronteiras On-Line, 9*(25), 8–26.

Schwendimann, B. A., & Linn, M. C. (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. J*ournal of Research in Science Teaching, 53*(1), 70–94. https://doi.org/10.1002/tea.21244

Seeley, T. D. (2010). *Honeybee democracy.* Princeton University Press.

Sengupta, P., Kinnebrew, J. S., Basu, S., Biswas, G., & Clark, D. (2013). Integrating computational thinking with K-12 science education using agent-based computation: A theoretical framework. *Education and Information Technologies, 18*(2), 351–380. https://doi.org/10.1007/s10639-012-9240-x

Stern, J., Ferraro, K., Duncan, K., & Aleo, T. (2021). *Learning that transfers: Designing curriculum for a changing world.* Corwin.

Stern, J., Ferraro, K., & Mohnkern, J. (2017). *Tools for teaching conceptual understanding, secondary. Designing lessons and assessments for deep learning.* Corwin.

Tinbergen, N. (1963). On aims and methods of ethology. *Zeitschrift Für Tierpsychologie, 20*(4), 410–433. https://doi.org/10.1111/j.1439-0310.1963.tb01161.x

Waring, T. M., Goff, S. H., & Smaldino, P. E. (2017). The coevolution of economic institutions and sustainable consumption via cultural group selection. *Ecological Economics, 131*(January), 524–532. https://doi.org/10.1016/j.ecolecon.2016.09.022

Waring, T. M., Kline, M. A., Brooks, J. S., Goff, S. H., Gowdy, J., Janssen, M. A., Smaldino, P. E., & Jacquet, J. (2015). A multilevel evolutionary framework for sustainability analysis. *Ecology and Society, 20*(2), 34. https://doi.org/10.5751/ES-07634-200234

Wilensky, U. (1999). *NetLogo*. Center for Connected Learning and Computer-Based Modeling, Northwestern University. http://ccl.northwestern.edu/netlogo

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories - An embodied modeling approach. *Cognition and Instruction, 24*(2), 37–41. https://doi.org/10.1207/s1532690xci2402

Wilson, D. S., Ostrom, E., & Cox, M. E. (2013). Generalizing the core design principles for the efficacy of groups. *Journal of Economic Behavior and Organization, 90*(Suppl.), S21–S32. https://doi.org/10.1016/j.jebo.2012.12.010

Zea-Cabrera, E., Iwasa, Y., Levin, S., & Rodríguez-Iturbe, I. (2006). Tragedy of the commons in plant water use. Water Resources Research, 42(Suppl.), 1–12. https://doi.org/10.1029/2005WR004514

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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