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From individuals to populations to cyclic interactions: investigating secondary students' descriptions of food web interactions

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ABSTRACT

Secondary-level students need a profound understanding of food relationships to assess the impact of human interventions on ecosystems. Food relationships are often introduced via food webs in early secondary education; however, current research shows that describing changes in food webs is challenging for students and that they tend to focus on individual organisms rather than populations. This study with German 6th graders ($N = 28$) investigated how an age-appropriate population concept, introduced through two consecutive text stimuli, can serve as a stepping stone to more sophisticated descriptions of (in-)direct effects and population dynamics in food webs. The students were interviewed before, in between and after reading the stimuli. Qualitative content analysis and frequency analyses were employed to examine the development of their descriptions of food web interactions during the interview. Our results indicate that shifting students' perspectives from individual organisms to populations, especially regarding carnivore predators, was crucial in fostering more scientifically adequate descriptions of indirect effects and fluctuating predator-and-prey populations in food webs; consequently, we recommend employing an agent-based perspective that conceptualises individuals as members of groups.

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Introduction

According to both the Next Generation Science Standards (NGSS Lead States 2013), a multi-state collaboration in the United States of America, and Saxony's Ministry of Education and Cultural Affairs (the Staatsministerium für Kultus des Freistaates Sachsen; SMK 2019), as one example from the Federal Republic of Germany, biology education should facilitate students' comprehension of complex ecological phenomena and enable them to participate in discussions about significant changes in ecosystems on a global scale. However, this comprehension is challenging, as the acquisition of food resources is a complex process involving various interspecific interactions, such as predation and

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herbivory (Smith and Smith 2015), which result in fluctuations in population densities (Campbell et al. 2019). Understanding how populations impact each other's densities, referred to as *food web interactions*, is seen as a crucial step towards assessing and reflecting on the impacts of human interventions on ecosystem dynamics and stability (see AAAS 2009; NGSS Lead States 2013).

A first step in this education process can be made in early secondary school during lessons about interdependent food relationships (NGSS Lead States 2013). For this, food webs serve as models that demonstrate the transfer of matter and energy across populations within a habitat (Begon, Townsend, and Harper 2006). In numerous curricula, the dynamics of interacting populations and food webs have been examined with educational intent and structured as learning objectives.

Unfortunately, a number of studies concerning the comprehension of food relationships have indicated that students encounter difficulties in describing changes in food webs (see Grotzer and Bell Basca 2003) and that they overlook indirect effects of population dynamics (see Hogan 2000), even after early secondary education (Barman, Griffiths, and Okebukola 1995; Eilam 2012; Griffith and Grant 1985; Hovardas 2016; Webb and Boltt 1990) and directly after teaching interventions (Demetriou, Korfiatis, and Constantinou 2009; Grotzer and Bell Basca 2003; Hogan 2000). A few studies suggest that students frequently describe interactions between individual organisms rather than dynamics between populations (see Mambrey, Schreiber, and Schmiemann 2022) and yet others have identified a tendency to use agent-based explanations at the individual level rather than reasoning at the population level (see Cuzzolino et al. 2019).

However, this previous research on food relationships has not clarified how a population concept is intertwined with scientifically more adequate descriptions of (in-)direct effects and/or population dynamics. Therefore, this study aims to bridge these two research areas and to describe how students shift from individual-level to population-level reasoning. This shift may serve as a stepping stone for more elaborate descriptions of food web interactions overall. By determining how and when to introduce the population concept in biology classes, the objective is to facilitate students in developing a more scientific understanding of ecosystem dynamics.

The present study does this by investigating how students describe food web interactions between (a) individuals or populations while also examining whether they describe these interactions (b) in linear, mutual or cyclic ways, and how they account for (c) direct and indirect effects within food webs. We refer to these three informational elements as components of students' oral descriptions. During the semi-structured individual interviews, 6th graders were asked to describe various food web interactions; that is, how populations influence each other's densities. The participants were engaged with two text-based learning materials specifically designed to facilitate a change of perspective: from reasoning about individuals to considering interactions between populations.

Qualitative content analysis (following Saldana 2021) was employed to analyse the responses, utilising a deductive coding scheme adapted from previous studies (Grotzer and Bell Basca 2003; Hogan 2000). The coding scheme is comprised of three primary categories, each representing a distinct component of describing interactions in ecosystems: (a) use of grammatical number (UGN), (b) type of relation (ToR) and (c) type of connection (ToC). The first encompasses students' reasoning at both the individual and population levels; the second examines the increasing complexity of population dynamics described by students; and the third identifies whether students describe direct or indirect effects in food webs. Quantitative analyses were conducted to compare code distribution before, between and after the participants engaged with both learning materials. Additionally, the correlations between the three main categories were analysed to gain insight into the interplay between different components in students' descriptions.

In short, the present study aims to bridge the research areas of understanding food relationships and understanding causality. We examine how students shift their reasoning from the individual to the population level while describing population dynamics and its indirect effects. By focusing on this perspective shift, the study explores how perceiving individuals as members of groups could serve as a stepping stone to more sophisticated descriptions of food web interactions. Moreover, the study demonstrates that explicitly introducing the population concept in biology class can enhance students' ability to describe food web interactions in a more elaborate way and can thereby support a deeper understanding of ecosystem dynamics.

Food webs illustrate food relationships within a community

Organisms require energy and matter for survival, growth and reproduction (Smith and Smith 2015); for heterotrophic organisms, this means feeding on other organisms. Interspecific interactions – such as competition for food, predation, parasitism and herbivory – affect the survival and reproduction of the populations involved, leading to changes in population densities and resulting in characteristic energy and matter flows in ecosystems (Campbell et al. 2019). Although these interactions are confined to populations at the same or adjacent trophic levels, their non-dissipating consequences propagate across multiple trophic levels within an ecosystem, indirectly influencing the dynamics of other populations as well as further ecosystem processes like resulting nutrient flux (Begon, Townsend, and Harper 2006; Smith and Smith 2015). While the specific types of interspecific interactions may vary, all trophic levels are ultimately connected through food relationships.

To represent these food relationships, food webs are employed as a conceptual, abstract tool consisting of interconnected food chains. Each food chain is defined as 'a series of arrows, each pointing from one species to another, representing the flow of food energy and material from prey (the consumed) to predator (the consumer)' (Smith and Smith 2015, 360). Food webs thereby illustrate food relationships within a community and reveal the dynamics of energy and matter transfer in an ecosystem (Hui 2012). In doing so, they provide a logical approach to studying ecosystems and the impacts of anthropogenic interference (Begon, Townsend, and Harper 2006).

Food web interactions in curricula for biology education

In the context of school biology curricula, students are expected to progressively expand their comprehension of food relationships and the transfer of energy and matter within ecosystems. In the United States, the NGSS recommends that elementary students (starting from 1st grade) begin to learn about organisms as part of groups of varying sizes (NGSS Lead States 2013). The objective is to transition from a focus on individual organisms to populations, which can be defined as groups of individuals of a species within a specific habitat. In Germany, from the 5th grade, biology classes emphasise the dynamics of eating and being eaten (SMK 2019), thereby introducing an *age-appropriate conception of population*, describing groups of homogeneous individuals of a species within a habitat (AAAS 2009; NGSS Lead States 2013). Throughout the paper, the term ‘population’ is defined in this way, which emphasises the number of individuals of a species while disregarding more complex aspects of the concept, such as variability within a population (see Smith and Smith 2015). This reduction is necessary to facilitate the comprehension of population dynamics within ecosystems. In other learning contexts, such as evolutionary biology, the population concept would need to be expanded.

In the United States, once students understand individuals as members of groups, the American Association for the Advancement of Science (AAAS 2009) recommends that, between the 3rd and 5th grade, students are introduced to various interactions among organisms beyond providing food; this is in accordance with the initial understanding of inter- and intraspecific interactions (NGSS Lead States 2013; SMK 2019). By the 5th and 6th grade (ages 10–12), here referred to as early secondary education, students should understand that organisms are interconnected through their need for food within food webs (AAAS (2009); NGSS Lead States 2013). From 6th grade onwards, students should also understand that organism and population growth is limited by available resources and influenced by predation (NGSS Lead States 2013), thus introducing them to population dynamics. However, the introduction of fluctuating predator–prey relationships occurs in late middle school or early high school, starting from the 7th grade (NGSS Lead States 2013; SMK 2019). By the end of the 8th grade, students are expected to comprehend food webs as models for the transfer of energy and matter among producers, consumers and decomposers within ecosystems, thereby grasping a fundamental scientific conception of food relationships.

In Germany, national education standards for biology (KMK 2005, 2024) delineate general competence objectives, which are implemented in state-specific curricula. The educational objectives stated in various curricula across federal states are analogous to those outlined by the NGSS and AAAS (see SMK 2019).

Overall, various curricula encompass activities involving food webs and confront students with challenges, such as thinking about the outcomes of environmental contamination (see SMK 2019). Consequently, the description of both direct and indirect effects, along with population dynamics within food webs, emerges as a pivotal necessity for students and is thus the focal point of our study.

Understanding food web interactions

Taking the scientific and the curricular perspective into account, three levels of abstraction in understanding food relationships can be differentiated (Figure 1). The first is the ‘everyday conception’, which entails the observation of eating and being eaten between individual organisms in everyday life within forests or other environments. These observations can be generalised and abstracted into the second level as interspecific interactions at the population level. The resulting energy and matter flows can then be described by food relationships, which can be further extended to the third level and modelled as energy and matter flows within an ecosystem.

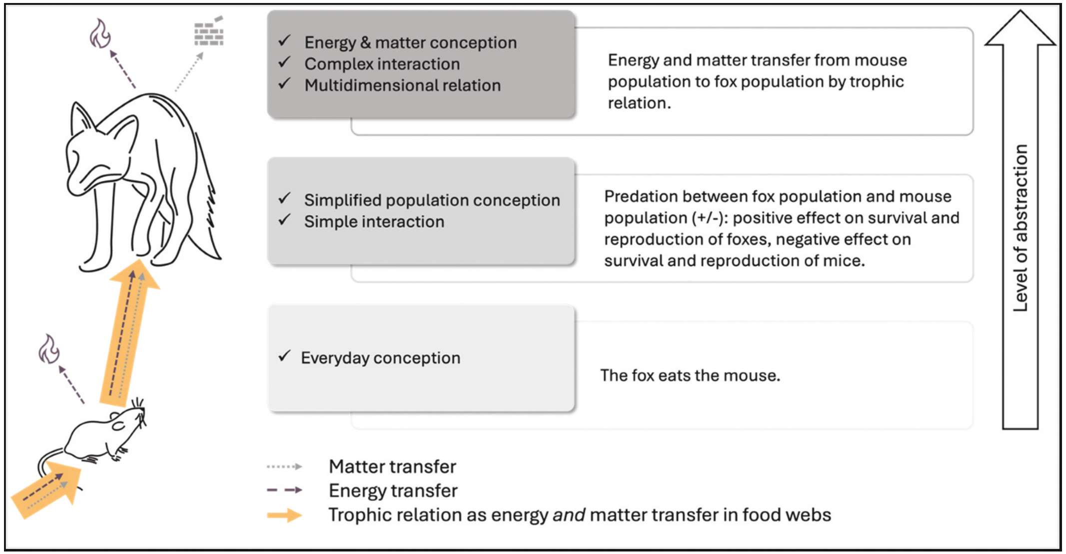

Figure 1. Food web snippet (European wood mouse, red fox), extended by energy and matter flow in the ecosystem.

Following Vosniadou (2013), we see understanding as a conceptual development in which students refine their initial conceptions and progressively acquire scientifically more sophisticated ones. This progression in conceptual understanding enables students to transition from direct observations of individual organisms to a more expansive comprehension of interacting populations within ecosystems. Consequently, we hypothesise that as students develop a more sophisticated understanding of food relationships, they progressively reconstruct scientifically more adequate conceptions of population, energy and matter, based on their prior everyday conceptions.

Current state of research on students' understanding of food web interactions

Early secondary students' understanding of (certain components of) food web interactions has been investigated in several studies, often in the light of systems thinking (Allen 2017; Cuzzolino et al. 2019; Demetriou, Korfiatis, and Constantinou 2009; Eilam 2012; Evagorou et al. 2009; Grotzer and Bell Basca 2003; Grotzer and Solis 2015; Grotzer, Derbiszewska, and Solis 2017; Hogan 2000; Hokayem 2012; Hokayem, Ma, and Jin 2015; Levy and Wilensky 2008; Mambrey, Schreiber, and Schmiemann 2022). These studies suggest that students have difficulties considering the complexity of food web interactions in their descriptions, often describing individuals engaging in linear interactions, or less often in mutual interactions, which result in direct effects in the food web. The studies' findings are summarised in Table 1 and expanded in a, b and c below.

Most students tend to refer to individuals rather than populations when describing food web interactions

Students from primary level to undergraduate education frequently describe actions of individual organisms and the consequences for them, as opposed to the effects on the population level (Cuzzolino et al. 2019; Grotzer and Bell Basca 2003; Mambrey, Schreiber, and Schmiemann 2022). However, studies have shown that adopting an agent-based perspective can facilitate the comprehension of group behaviours, such as populations in a food web, among young students (Grotzer, Derbiszewska, and Solis 2017; Levy and Wilensky 2008). Students start by examining the behaviour of individuals and then, through cumulative anticipation, predict the behaviour of small groups, subsequently inferring the behaviour of entire populations.

Most students tend to describe linear interactions in a food web

An intervention study by Grotzer and Bell Basca (2003) revealed that participants from the 3rd grade described interactions between predators and prey primarily in a linear way, and on occasion in a mutual manner (see also Hogan 2000). The authors define mutual interactions as 'those where the subject noted that two components impact each other' (Grotzer and Bell Basca 2003, 21). Following the intervention, in which causal patterns in ecosystems were discussed, five out of ten students were able to describe cyclic interactions; that is, fluctuating population densities caused by predator–prey interactions. A subsequent intervention study by Eilam (2012), this time with 9th graders, found that students tended to describe linear (and irreversible) interactions within a food chain before and after working with a living ecosystem model. However,

Table 1. Three main findings from previous studies about the understanding of food web interactions, mainly at the early secondary level, with short description and aligning studies.

Main finding	Description	Relevant studies	
a. Most students refer to individuals while describing interactions.	Students have difficulties describing food relationships as interactions between (small) groups of individuals or populations. Instead, they describe actions and effects of and on single animals and plants.	Grotzer and Bell Basca (2003)	3rd grade, N = 60, US
		Levy and Wilensky (2008)	6th grade, N = 10, US
		Grotzer, Derbiszewska, and Solis (2017)	4th, 6th grade, N = 41, US
		Cuzzolino et al. (2019)	7th grade, N = 216, US
		Mambrey, Schreiber, and Schmiemann (2022)	9–12 years, N = 20, Germany
b. Most students describe linear interactions in a food web.	Students have difficulties describing mutual and cyclic effects in a food web. Instead, they display monocausal reasoning patterns; e.g. they describe one living being acting on another, "the mouse eats the snail" (Mambrey, Schreiber, and Schmiemann 2022, 86).	Hogan (2000)	6th grade, N = 52, US
		Grotzer and Bell Basca (2003)	3rd grade, N = 60, US
		Evagorou et al. (2009)	11–12 years, N = 13, UK
		Eilam (2012)	9th grade, N = 50, Israel
		Hokayem, Ma, and Jin (2015)	1st–4th grade, N = 44, US
		Mambrey, Schreiber, and Schmiemann (2022)	9–12 years, N = 20, Germany
c. Most students describe direct effects in a food web.	Students have difficulties describing indirect effects of interactions. Instead, they describe direct consequences of interactions mostly within the same food chain without considering further (long-term) effects in neighbouring chains of the food web.	Hogan (2000)	6th grade, N = 52, US
		Demetriou, Korfiatis, and Constantinou (2009)	4th grade, N = 46, Cyprus
		Eilam (2012)	9th grade, N = 50, Israel
		Grotzer and Solis (2015)	2nd, 4th, 6th grade, N = 10, US
		Allen (2017)	3–5 years, N = 75, UK
		Mambrey, Schreiber, and Schmiemann (2022)	9–12 years, N = 20, Germany

a small number of students exhibited an improvement in their explanations of food web interactions following the intervention.

An interview study by Hokayem, Ma, and Jin (2015) provides more in-depth insight into the descriptions of interactions made by elementary school students; specifically, when examining the students' use of feedback loop reasoning, they found that the majority described either only the increase of both predator and prey populations because of their reproduction or only the decrease of both populations because of food deficiency. Mambrey, Schreiber, and Schmiemann (2022) conducted a study with participants from elementary and secondary schools and obtained analogous results: the students exhibited a tendency to employ monocausal reasoning without delineating additional consequences for other organisms.

Most students tend to describe only direct effects in a food web

In a study with undergraduate students, White termed this phenomenon the 'dissipation effect', defined as 'a tendency to judge that effects of a perturbation at a particular locus in an ecosystem weaken or dissipate as they spread out from that locus' (1997, 229). Hogan discovered analogous outcomes when studying 6th-grade students, who exhibited a propensity to 'focus on local rather than extended effects within an ecological system' (2000, 27) and predominantly described direct rather than indirect interactions between organisms. Hogan's results are consistent with the earlier findings of Griffith and Grant (1985), who identified five central 'misconceptions' in students' understanding of ecosystems, one of which relates to the perception of food webs as unattached chains rather than interconnected networks. Similar observations were made with students from grades 4 to 6 by Mambrey, Schreiber, and Schmiemann (2022), who attributed their findings to the absence of explicit illustration of indirect interactions in the food web.

Research questions

Although previous studies have explored students' descriptions of food web interactions, the question of how different components develop and correlate, especially when students start to conceptualise individuals as members of groups, remains unanswered. To address this gap, the present study aims to investigate students' descriptions of food web interactions. To do this, it will use text-based learning materials specifically designed to foster a change of perspective from individuals to populations. The study is thus guided by the following research questions:

RQ1: How do different components of students' descriptions of food web interactions develop while the students are acquiring a scientifically more adequate understanding?

(a) How do students' descriptions of interactions develop at the level of individuals and populations?
(b) How do students' descriptions of different kinds of interactions develop?
(c) How do students' descriptions of direct and indirect effects in food webs develop?

RQ2: To what extent are these components interlinked during the development of a scientifically more adequate understanding?

We expect that most early secondary students will initially describe linear interactions between individuals and focus on direct effects (e.g. describing one organism feeding on another without considering changes in population densities). We hypothesise that recognising individuals as members of groups could play a pivotal role in advanced descriptions of food web interactions, enabling students to describe indirect effects, which is fundamental for understanding more complex interactions such as predator-prey fluctuations. We further hypothesise that emphasising the role of populations in curricula and teaching practices may foster scientifically more adequate descriptions of interactions and dynamics in food webs in biology classes. This, in turn, could lay the foundation for exploring the consequences of human intervention in ecosystems in early secondary education, and may set the stage for understanding material and energy flows in later grades.

Materials and methods

To assess students' descriptions of food web interactions, semi-structured individual interviews were conducted with 6th graders, who were asked to describe food web interactions on three separate occasions. Between these occasions, the students worked with two text-based learning materials about food web interactions in a floodplain forest (focusing on indirect effects and cyclic interactions). These materials were designed to support the development of students' descriptions during the interview process.

The interviews were transcribed and subjected to qualitative content analysis (Saldana 2021) using a deductive coding scheme adapted from Grotzer and Bell Basca (2003) and Hogan (2000). The coding scheme covers the distinction between individual organisms and populations as well as the conceptions of population dynamics and non-dissipation within three main categories: (a) use of grammatical number (UGN), (b) type of relation (ToR) and (c) type of connection (ToC). The three categories represent unique components of describing interactions in ecosystems. Quantitative frequency analyses were used to compare code distribution before and after reading text 1 and text 2, respectively.

Sampling and recruitment

The present study involved a sample of 6th graders ($N = 28$, 60.7% female, $M_{age} = 11.96$ years, $SD_{age} = 0.33$) from three urban secondary schools in Leipzig (Federal State of Saxony, Germany) with mixed socio-economic backgrounds. Of the 28 participants, 5 stated that their first language was not German but was instead Arabic, English, Kurdish, Russian or Turkish.

12 weeks prior to the start of the study, biology teachers belonging to a school cooperation network established by the authors disseminated information regarding the study to their students and the students' parents. This was facilitated by the authors, who provided the teachers with a set of informational materials. The teachers obtained consent from both the students and their parents to participate in the study. We emphasised that data would be collected through individual interviews conducted during the students' regular biology lessons. The students were informed that participation was voluntary, that there would be no negative consequences for non-participation and that no compensation would be provided.

The teachers provided the authors with a list of potential participants. To ensure a homogeneous sample, a purposive sampling approach was employed, following a structured selection process (Palinkas et al. 2015). The inclusion criteria for potential participants were as follows: students in the 6th grade at the participating schools, not having received instruction on food relationships in their biology classes and having expressed their willingness to participate. In the second step, the final sample of 28 students was selected by means of a random but purposeful sampling method, with a view to ensuring a balanced distribution of gender and schools.

In addition to the interview data, we also noted age, gender and first language. In the interests of data protection, all information and interview transcripts were pseudonymised, and the study was submitted to regional school authorities and approved accordingly. All interviews were conducted by the study's first author at the time of the students' regular biology lessons, although they were conducted in another room. Each interview lasted an average of 35:21 minutes (SD_{time} = 05:29 minutes). The interviews were conducted in German; the questions and responses quoted below are our translations.

Interview procedure

The interviews were part of a compulsory learning unit in the 6th-grade curriculum (SMK 2019) focusing on forest ecosystems. The interview itself was designed to explore the development of students' descriptions of interactions within the context of a forest food web and was divided into three phases, as summarised in Figure 2.

Following a brief personal introduction by the interviewer (phase 1), the interview started with an introductory task designed to recall prior knowledge regarding food webs and the interpretation of food web arrows (phase 2). Despite the absence of prior instruction about food relationships in a forest, it was anticipated that the students, having received instruction in 5th-grade biology lessons on aquatic habitats, would possess the capacity to comprehend food webs. However, where difficulties were encountered by the students, the principles of constructing and interpreting food webs were reiterated.

Subsequently, the interview section relevant for data analysis commenced (phase 3), comprising a total of five steps. First, participants were presented with two questions regarding interactions in a food web [t_1], adapted from previous research (Grotzer and Bell Basca 2003; Hokayem 2012; Hokayem, Ma, and Jin 2015). Utilising Figure 3, which shows a food web in a European broadleaf forest, the students were asked to (i) describe changes in population densities caused by a disturbance in the food web ('What happens to the other animals and plants in the forest if all the mice disappear?') and (ii) describe changes in predator and prey populations over a longer period of time ('Imagine there are only 200 foxes and 200 mice left in the forest. How many foxes and mice would be in the forest after half a year, one year, and two years respectively?').

Secondly, after answering the questions, students engaged with a text-based learning material [reading activity R1] to promote reflection processes and thus facilitate the development of students' descriptions during the interview. Text 1 and text 2 are learning materials specially designed for the study as interview stimuli, dealing with food web interactions in a floodplain forest. The texts were created by a biology teacher who also works as a freelance children's and young adult writer – for this reason, the teacher was considered a qualified author for the learning materials. In general, both texts aim to support students' descriptions of food web interactions. Empirical studies on students' preconceptions about food webs informed the content design (Grotzer and Bell Basca 2003; Hogan 2000; Mambrey, Schreiber, and Schmiemann 2022), addressing common preconceptions such as the focus on linear interactions, direct effects and individual organisms rather than interacting populations.

Text 1 commences with instances of linear food web interactions between individual organisms with direct effects, contrasting them with examples of indirect effects (neighbouring connections) between populations. In comparison, text 2 focuses on mutual and cyclic relations between populations. An agent-based perspective was employed in both texts (see Levy and Wilensky 2008), where small groups of animals and plants occur as representatives of their respective populations. To prevent learners from confusing phenomena across different

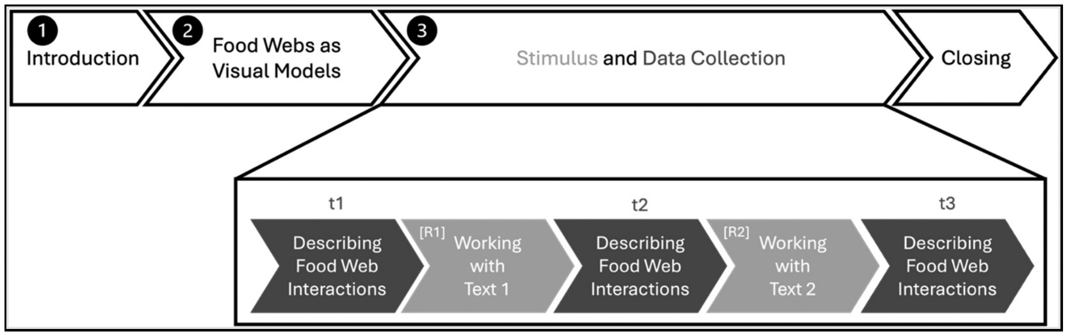

Figure 2. Interview procedure.

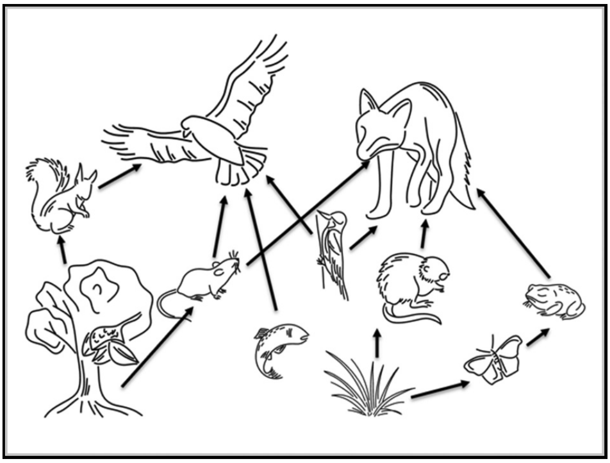

Figure 3. Food web with selected connections of a hypothetical community in a broadleaf forest.

levels (levels-confusion, Wilensky and Resnick 1999), the distinction between individuals and small groups was explicitly made and introduced progressively within the texts (Jördens et al. 2016). The terms 'population', 'interaction' and 'connection' were not introduced explicitly.

Following the completion of reading activity 1, which focused on indirect effects in food webs, a subsequent iteration of interview questions, which were similar in structure and content to those asked in the first round of interviews, was posed [t_2]. It should be noted that these questions were not identical to those previously presented; rather, they were equivalent, thereby ensuring the maintenance of equivalency with the questions posed in t_1 (refer to Additional file 1 for a comprehensive overview of all interview questions). Subsequently, the participants engaged with text 2 [R2], which addressed mutual and cyclic relations between populations. The texts' sequence and content were intended to aid investigation into whether the quality of the students' descriptions develops in parallel or independently. Finally, in steps four and five of phase 3, the interview questions were presented to the students for a third time [t_3]. Given the similarity between the ecosystems featured in the interview and those in the stimuli, it was hypothesised that most participants would be familiar with both the European broadleaf forest and the floodplain forest due to local proximity.

Audio recordings were made of each interview. These recordings were subsequently transcribed and subjected to an in-depth data analysis.

Measurement and data analysis

Students' descriptions of food web interactions

To assess students' descriptions of food web interactions, directed content analysis (Saldana 2021) was applied to examine students' (a) distinction between individual organisms and populations, as well as their conceptions of (b) population dynamics and (c) non-dissipation. Therefore, the three main categories were differentiated within the coding scheme. The first of these, UGN, was developed to examine students' understanding of predator-and-prey relationships and their changes over time, with subcategories representing students' use of grammatical number as a proxy measurement (Table 2). If a predator was mentioned, we also differentiated whether it was a carnivore, omnivore or herbivore.

Subcategories were also used for the second and third categories, ToR and ToC, which were adapted from two previous studies (Table 3).

In the first study, we drew on, Grotzer and Bell Basca (2003) defined three different levels for increasingly elaborate descriptions of interactions in a food web, differentiating *linear*, *mutually causal (two-way)* and *cyclic* interactions. The levels are based on students' explanations ($N = 30$, 3rd grade) on population changes caused by a disturbance; thus, descriptions of unidirectional predator–prey relationships were coded as linear, mutually causal interactions were coded if students described how two populations impact each other, and they were coded as cyclic when students mentioned iterative patterns like decomposition (Grotzer and Bell Basca 2003).

In the second study drawn on, Hogan (2000) developed a category system similar to that just described. If students described the effect of a disturbance in one direction of the food chain, the description was coded as *one-way linear*. For Grotzer and Bell Basca (2003), *two-way linear* is not congruent with mutually causal; however, for Hogan, it means 'that students traced a perturbation in two opposite trophic level directions, for instance from the rabbit to the owl and the berries' (2000, 24). Descriptions of feedback loops which mention the original population again were coded as *cyclic*. Hogan's study also considered whether students described interactions within or beyond the initial food

Table 2. Final coding scheme representing the UGN of food web understanding.

Subcategory	Subcategory descriptions	Example
(a) Use of grammatical number (UGN)		
a.1 Singular Unspecific	Student describes an interaction while using singular for a population/individual. It is unclear if the population/individual interacts as prey or predator in the described interaction.	—
a.2 Singular Prey	Student describes an interaction while using singular for the prey population/individual. The population/individual is coded as prey if the description includes how it is eaten by a predator or acted upon as prey.	'[. . .] the muskrat would have less food, that [muskrat] is also a food from the fox' (LWLDL5UE6)
a.3 Singular Predator a.3.1 Carnivore a.3.2 Omnivore a.3.3 Herbivore	Student describes an interaction while using singular for the predator population/individual. The population/individual is coded as a predator if the description includes how it feeds on or preys upon other population(s)/individual(s).	'[. . .] because the fox then has to look for other food as a substitute [. . .]' (GGLBZ8IT8)
a.4 Plural Unspecific	Student describes an interaction while using plural for a population. It is unclear if the population interacts as prey or predator in the described interaction.	—
a.5 Plural Prey	Student describes an interaction while using plural for the prey population. The population is coded as prey if it is described how it is eaten by a predator or acted upon as prey.	'[. . .] the fox would be able to eat more frogs [. . .]' (LWLEU0ET5)
a.6 Plural Predator a.6.1 Carnivore a.6.2 Omnivore a.6.3 Herbivore	Student describes an interaction while using plural for the predator population. The population is coded as a predator if the description includes how it feeds on or preys upon other population(s)/individual(s).	'[. . .] because the butterflies would have more to eat' (GGLIL7TU6)

Table 3. Final coding scheme representing the ToR and ToC of food web understanding, adapted from Hogan (2000) and Grotzer and Bell Basca (2003).

Subcategory		Subcategory descriptions	Example
(b) Type of relation (ToR)			
b.1	Linear	Student describes an interaction as a one-sided action and by providing no information about further medium- or long-term effects for individuals/populations.	'[. . .] so, the beavers are eaten more often' (GGLBZ8IT8)
b.2	Mutual	Student describes an interaction between two individuals/populations by giving information about further medium- or long-term effects for individuals/populations. Changes in at least one population (size) or for at least one individual are mentioned; e.g. an increase or decrease in the number of individuals or long-term effects like starvation.	'Then the falcon would also get less [food] and then at some point the falcon would starve to death' (LWLEU0ET5) '[. . .] here would then perhaps be more grass' (LWLEU0ET5)
b.3	Cyclic	Student describes an interaction between two populations by giving information about further long-term effects for individuals/ populations. Fluctuation or repetitive changes in at least one population (size) are mentioned; e.g. a fluctuation in the number of individuals or dynamic equilibrium processes.	'[. . .] for example, the grass that nutrias eat, which would then produce more. But then there would also be more butterflies and then there would be less grass again. And then there will be fewer butterflies again' (LWLÖS6IK5)
(c) Type of connection (ToC)			
c.1	Embedded	Student describes an interaction between two populations/individuals that both occur in the same food chain (see Figure 3) as the initial population mentioned in the interview question.	*Initial population: Mouse* '[. . .] so that, yes [. . .] the fox can no longer eat the mouse' (GGLBZ8IT8)
c.2	Neighbouring	Student describes an interaction between two populations/individuals of which at least one population/individual does not occur in the same food chain (see Figure 3) as the initial population mentioned in the interview question.	*Initial population: Mouse* 'The fox would also have one [food source] fewer, which means that more frogs [. . .] are eaten' (GGLIL7TU6)

chain where the population and disturbance from the interview question occur. The author uses the terms *embedded* and *neighbouring*, which could be reframed as a distinction between descriptions of direct and indirect effects in a food web.

In the present study, these category systems were adapted, and a scheme was developed with two independent main categories. The category ToR differentiates three kinds of relations which can be described by students, and the category ToC distinguishes descriptions of food web interactions in the same or another food chain as the population initially mentioned in the interview question. For ToR and ToC, the subcategories are ordered by complexity; in comparison, there is no clear complexity gradient for UNG.

Units of analysis comprise all answers from the commencement of interview question 1 to the conclusion of interview question 2 for each participant. Interactions between species that were specified in the food web or were otherwise scientifically accurate were incorporated into the data analysis; those that were scientifically inaccurate were excluded. The same interview section could be coded up to three times if the codes belonged to different main categories of the coding scheme.

The initial coding scheme for ToR and ToC was derived from previous research (see Saldana 2021; Schreier 2012), and preliminary codes were assigned to 25% of the transcripts by the first author. The first author then discussed and revised both codes and coding schemes with all authors. The final coding scheme was then applied to all transcripts by the first author, and 25% of the transcripts were independently coded by a second trained rater to assess inter-rater reliability.

For ToR, weighted kappa with linear weights was calculated to assess the agreement between these two coders; this showed substantial agreement, $\kappa_{w,ToR} = 0.80$ (95% CI, 0.69 to 0.91), p = .001. For the ToC, the consensus was almost perfect: $\kappa_{ToC} = 0.81$ (95% CI, 0.70 to 0.92), p = .001. For UGN, no secondary coding was carried out, as it solely involves the grammatical distinction between singular and plural forms. The categorisation of predator and prey is unambiguously determined by the provided food web (Figure 3) combined with the identification of whether a particular organism is described as consuming another or being consumed itself.

Data analysis

All statistical analyses were conducted in RStudio (Version 2023.12.0 + 369). The dataset (Additional file 2), as well as the R-Script (Additional file 3), can be accessed in the additional information. For UGN, we compared the relative use of singular or plural in students' descriptions at t_1, t_2 and t_3, whereby we examined singular and plural for predators separated from singular and plural for prey. Friedman Tests were applied instead of a repeated measurement ANOVA because of the non-normally distributed data. For ToR and ToC, the highest subcategory achieved by each student was determined for each measurement point (t_1, t_2 or t_3). To examine statistically significant differences in the frequency of maximum subcategories achieved at different time measurement points, a 3 × 3 Fisher's Exact Test for ToR and a 2 × 3 test for ToC were performed. The decision to utilise Fisher's Exact Test as opposed to the more conventional Chi-Square Test was because the number of observations per cell in the contingency table was less than five. Bonferroni-corrected post-hoc comparisons were conducted for both Friedman's and Fisher's Exact Tests when statistically significant differences were identified at a global level. All the statistical analyses were performed at a significance level of $\alpha = .05$. Spearman's non-parametric correlation coefficient was calculated to evaluate the relationships between subcategories of ToR and ToC, ToR and UNG, and ToC and UNG. This analysis was performed to identify which subcategories occur together in student responses.

Results

This study examines the development of early secondary-level students' descriptions of food web interactions during semi-structured individual interviews with a focus on students' reasoning on individual and population levels. The interviews included working with two text-based learning materials, which emphasise a change of perspective from individuals to populations. Qualitative content analysis and frequency analyses were employed to assess how students described the interactions between populations in food webs and their connection along food chains, as well as students' use of grammatical number. Each main category was assessed three times: before engaging with two text stimuli covering different components of food web interactions (t_1), after text stimulus 1 (t_2) and after text stimulus 2 (t_3). In total, we coded 1,631 passages in 28 interview transcripts. Additionally, for ToC and ToR, the maximum subcategory achieved by every student is reported for each time point. The subsequent tables comprise both the absolute and relative frequencies of the codes attributed to the three overarching categories at each of the three measurement points (Table 4, 5 and 6).

The results show an increase in the complexity of students' descriptions across all three main categories and time measurement points on a descriptive level. The following sections examine whether the changes in students' descriptions are of statistical significance (RQ1a – c). In addition, the correlation between the subcategories is examined (RQ2).

Research question 1a

Students changed their perspective and developed more elaborate descriptions while using the plural form more often for predators but not for prey. Statistically significant changes occurred mainly for the use of singular for (carnivore) predators.

For the use of grammatical number, changes are most evident in the use of singular and plural for predators. In the beginning, participants primarily used the singular form while describing the actions of predators ($t_{1,sing.pred} = 83.1\%$), with references to

Table 4. Relative and absolute frequency of codes for type of grammatical number (UNG) at t_1, t_2 and t_3.

	t_1 (before stimuli)		t_2 (after text stimulus 1)		t_3 (after text stimulus 2)	
	Rel. Freq.	Abs. Freq.	Rel. Freq.	Abs. Freq.	Rel. Freq.	Abs. Freq.
Singular Predator	83.1	(74)	45.7	(69)	54.1	(98)
Carnivores	91.9	(68)	92.8	(64)	61.1	(58)
Omnivores	8.1	(6)	7.3	(5)	35.8	(34)
Herbivores	0.0	(0)	0.0	(0)	3.2	(0)
Plural Predator	16.9	(15)	54.3	(82)	45.9	(83)
Carnivores	46.7	(7)	53.7	(44)	59.0	(49)
Omnivores	53.3	(8)	36.6	(30)	32.5	(27)
Herbivores	0.0	(0)	9.8	(8)	8.4	(7)
Sum	100.0	(89)	100.0	(151)	100.0	(181)
Singular Prey	32.4	(24)	21.0	(35)	27.8	(47)
Plural Prey	67.6	(50)	79.0	(132)	72.2	(122)
Sum	100.0	(74)	100.0	(167)	100.0	(169)
Singular Unspecific	5.3	(1)	10.3	(3)	2.9	(1)
Plural Unspecific	94.7	(18)	89.7	(26)	97.1	(33)
Sum	100.0	(19)	100.0	(29)	100.0	(34)

Table 5. Relative and absolute frequency of codes for type of relation (ToR) and type of connection (ToC) at t_1, t_2 and t_3.

		t_1 (before stimuli)		t_2 (after text stimulus 1)		t_3 (after text stimulus 2)	
		Rel. Freq.	Abs. Freq.	Rel. Freq.	Abs. Freq.	Rel. Freq.	Abs. Freq.
ToR	Linear	60.9	(67)	41.4	(58)	41.3	(62)
	Mutual	37.3	(41)	54.3	(76)	41.3	(62)
	Cyclic	1.8	(2)	4.3	(6)	17.3	(26)
	Sum	100.0	(110)	100.0	(140)	100.0	(150)
ToC	Embedded	63.4	(52)	37.5	(42)	45.2	(56)
	Neighbouring	36.6	(30)	62.5	(70)	54.8	(68)
	Sum	100.0	(82)	100.0	(112)	100.0	(124)

Table 6. Relative and absolute frequency of students ($N = 28$) and their maximum subcategory achieved for ToR and ToC at t_1, t_2 and t_3.

		t_1 (before stimuli)		t_2 (after text stimulus 1)		t_3 (after text stimulus 2)	
		Rel. Freq.	Abs. Freq.	Rel. Freq.	Abs. Freq.	Rel. Freq.	Abs. Freq.
ToR	Linear max	14.3	(4)	7.1	(2)	17.9	(5)
	Mutual max	78.6	(22)	82.1	(23)	25.0	(7)
	Cyclic max	7.1	(2)	10.7	(3)	57.1	(16)
	Sum	100.0	(28)	100.0	(28)	100.0	(28)
ToC	Embedded max	50.0	(14)	25.0	(7)	32.1	(9)
	Neighbouring max	50.0	(14)	75.0	(21)	67.9	(19)
	Sum	100.0	(28)	100.0	(28)	100.0	(28)

predators in the plural form being rare ($t_{1,plu.pred} = 16.9\%$). After stimulus 1, students more frequently referred to predators in the plural form ($t_{2,plu.pred} = 54.3\%$) and less frequently in the singular form ($t_{2,sing.pred} = 45.7\%$). The use of singular and plural for describing the actions of prey remained consistent across all three measurement points, with students using the plural rather than singular form relatively more often when describing interactions with prey populations. Additionally, students mainly used singular for carnivore predators ($t_{1,sing.pred,carni} = 91.9\%$, $t_{2,sing.pred,carni} = 92.8\%$), which does not change until t_3. It is noteworthy that a small number of students did not talk about predators or prey at all at certain measurement points. When students addressed predators using the plural form, they evenly talked about carnivores and omnivores.

In addition to the overall code distribution, we examined the relative distribution of singular and plural forms in the individual students' descriptions, separately for predators and prey. For predators, students initially mainly used singular for describing their interactions ($M_{1,sing.pred} = 0.86$, $SD_{1,sing.pred} = 0.30$). Thereby, students used singular and plural for describing interactions of and with prey ($M_{1,sing.prey} = 0.22$, $SD_{1,sing.prey} = 0.35$; $M_{1,plu.prey} = 0.53$, $SD_{1,plu.prey} = 0.45$) and they nearly never used plural while talking about predators ($M_{1,plu.pred} = 0.14$, $SD_{1,plu.pred} = 0.30$) (Figure 4(a,b)).

After stimulus 1, a Friedman Test indicated statistically significant differences for the relative distribution of singular and plural for predators within student's individual descriptions. On average, the descriptions of interactions concerning single predators decreased from t_1 to t_2 and also t_3, $\chi 2_{(2,\ N = 28)} = 16.53$, $p = .001$. Conversely, students more often talked about predator interactions using plural after stimulus 1, $\chi 2_{(2,\ N = 28)} = 13.98$, $p = .001$ and $\varpi_{Kendall} = 0.250$, which indicates a small effect. For the use of singular and plural for prey, no considerable changes occurred between t_1, t_2 and t_3. After stimulus 2, hardly any differences appeared for the type of grammatical number.

Research question 1b

Students developed more elaborate descriptions of relations. Statistically significant changes occurred towards descriptions of cyclic interactions.

For the type of relation, the relative frequency of linear interactions described decreased after stimulus 1 from $t_{1,linear} = 60.9\%$ to $t_{2,linear} = 41.4\%$ ($t_{3,linear} = 41.3\%$). The relative frequency of descriptions of mutual interactions fluctuated between 37.3% ($t_{1,mutual}$) and 54.3% ($t_{2,mutual}$). The number of cyclic interactions described changed notably after reading text stimulus 2, increasing from $t_{2,cyclic} = 4.3\%$ to $t_{3,cyclic} = 17.3\%$.

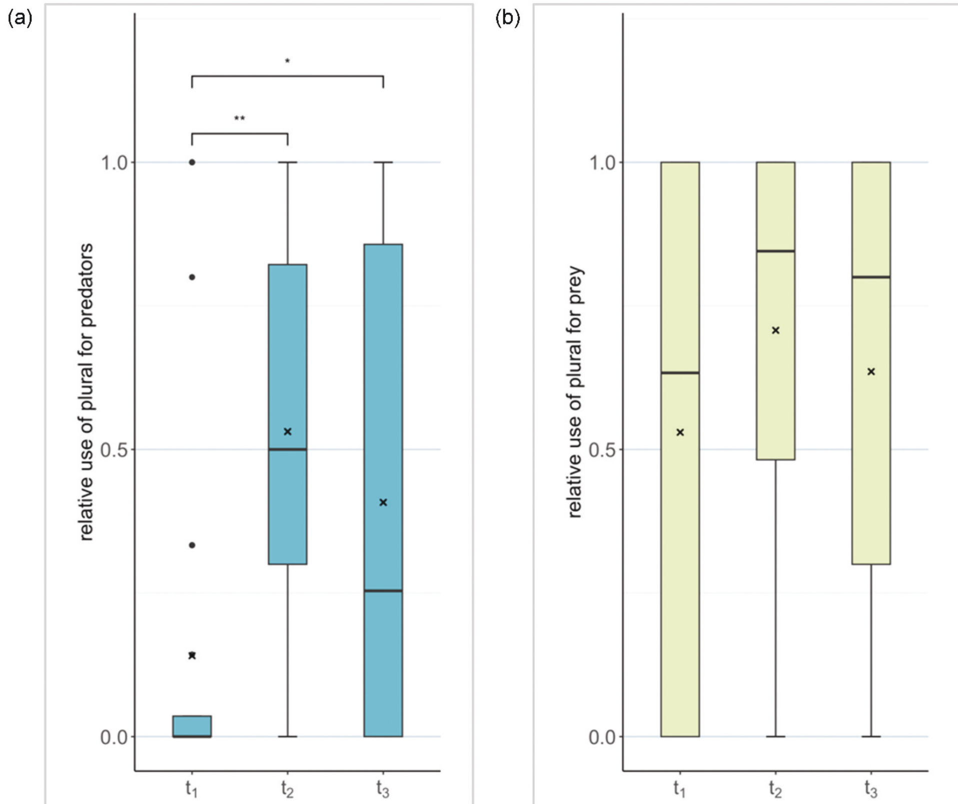

Figure 4. Use of grammatical number. Relative use of the plural form while describing interactions of a) predators (left) or b) prey (right) before stimuli (t_1), after stimulus 1 (t_2) and after stimulus 2 (t_3); $*p < .05$, $**p < .01$. $Mdn_{1,pred.plu} = 0.0$, $M_{1,pred.plu} = 0.14$; $Mdn_{2,pred.plu} = 0.50$, $M_{2,pred.plu} = 0.53$; $Mdn_{3,pred.plu} = 0.25$, $M_{3,pred.plu} = 0.41$ $\chi2_{pred.plu\ (2,\ N = 28)} = 13.98$, $p = .001$; $\varpi_{Kendall,\ pred.plu} = 0.250$ $Mdn_{1,prey.plu} = 0.63$, $M_{1,prey.plu} = 0.53$; $Mdn_{2,prey.plu} = 0.85$, $M_{2,prey.plu} = 0.71$; $Mdn_{3,prey.plu} = 0.80$, $M_{3,prey.plu} = 0.64$ $\chi2_{prey.plu\ (2,\ N = 28)} = 0.06$, $p = .969$.

Regarding the maximum category achieved, 22 out of 28 participants were already able to name at least one mutual relation in the beginning of the interviews (Figure 5) and only two students described cyclic relations. After stimulus 1, barely any difference occurred. After stimulus 2, the global Fisher's Exact Test showed a statistically significant change for descriptions of mutual and cyclic relations, $\chi2_{(4,\ N = 28)} = 27.97$, p = .001. The number of students describing at least one cyclic interaction increased from 3 to 16, while the number of students describing mutual relations at t_2 decreased from 23 to 7, $\chi2_{(2,\ N = 28)} = 18.71$, p = .001; $\varpi_{Cohen} = 0.58$ indicates a large effect.

Research question 1c

The relative frequency of more elaborate descriptions of connections and indirect effects increased. However, differences were not statistically significant.

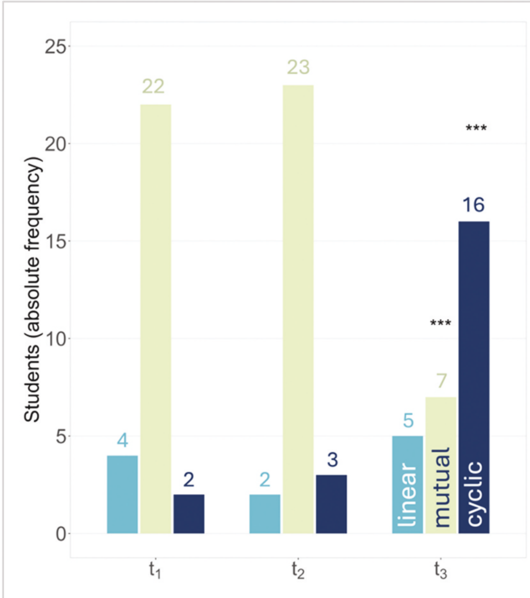

Figure 5. Type of relation. Absolute frequency of students ($N = 28$) describing different ToR before stimuli (t_1), after stimulus 1 (t_2) and after stimulus 2 (t_3). Light Blue: linear, Green: mutual, Dark Blue: cyclic. ***$p = .001$. $\chi 2_{(4,\ N = 28)} = 27.97$, $p = .001$, $\varpi_{Cohen} = 0.577$.

The relative frequency of descriptions of embedded interactions decreased from $t_{1,embedded} = 63.4\%$ to $t_{2,embedded} = 37.5\%$ and $t_{3,embedded} = 45.2\%$, respectively, while the relative frequency of descriptions of neighbouring interactions increased from $t_{1,neighbouring} = 36.6\%$ to $t_{2,neighbouring} = 62.5\%$ ($t_{3,neighbouring} = 54.8\%$).

Regarding the maximum number of subcategories achieved for a given type of connection, half of the sample was able to describe at least one neighbouring connection at the beginning of the interview (Figure 6). The students named indirect effects of changes in the initial population while describing an interaction in a food chain beside the initial one. The other half of the sample described only embedded connections in the beginning, just naming interactions within the same food chain mentioned in the interview question. Half of the group could already anticipate indirect effects of interactions. After text stimulus 1 and as intended, the number of participants describing at least one neighbouring connection increased from 7 to 21. After text stimulus 2, a difference is barely observable. However, a global Fisher's Exact Test indicates no statistically significant differences in the maximum categories achieved by the students during the interview, $\chi 2_{(2,\ N = 28)} = 4.04,\ p = .165$.

Research question 2

Descriptions of direct effects often appeared together with descriptions of linear interactions. Students more often used the plural than the singular form for describing interactions of predators when they talked about indirect effects.

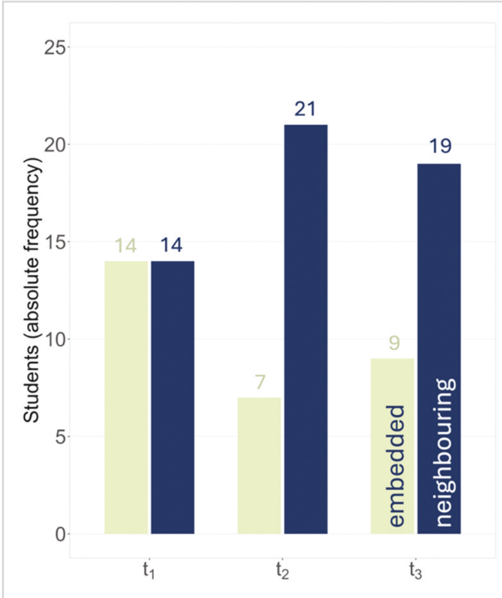

Figure 6. Type of connection. Absolute frequency of students (*N* = 28) describing different ToC before stimuli (t_1), after stimulus 1 (t_2) and after stimulus 2 (t_3). Green: embedded, Dark Blue: neighbouring.

Weak Spearman correlations appeared between ToR and the use of singular and plural for predators, whereby the use of singular tended to decrease with higher levels of ToR and, conversely, the use of plural increased (Table 7). Similar results were found for ToC and the use of singular and plural for predators. Further, a statistically significant positive relationship between ToC and the use of plural for predators was found with a moderate correlation (Cohen 1988), $\rho_{S\ (27)} = .357$, $p = .001$.

Another moderate correlation between ToC and ToR saw more elaborate levels of ToR (mutual and cyclic relations) related to the more elaborate level of ToC (neighbouring connection), $\rho_{S\ (27)} = .385$, p = .001. Reciprocal descriptions of linear interactions often appeared together with descriptions of embedded connections and therefore direct effects. The correlation analysis suggests that while descriptions of cyclic interactions are often associated with descriptions of indirect effects, it is also possible to describe at least mutual interactions without considering indirect effects.

Discussion

This study investigated whether an age-appropriate population concept, introduced through two consecutive text stimuli, can serve as a stepping stone to more sophisticated descriptions of (in-)direct effects and population dynamics in food webs. We conducted semi-structured interviews with 6th graders and used qualitative content analysis to examine the interview transcripts. The deductive coding scheme covered three main categories; that is, number (UGN), relation (ToR) and connection (ToC). Quantitative analyses compared code distributions before and after the stimuli, and correlations

Table 7. Spearman correlation between ToR, ToC and UNG; rho and *p* value shown for every paired spearman Test.

	Type of relation		Type of connection	
	ρ	p	ρ	p
Type of Connection	*.385*	*.001*		
Singular Predator	*– .222*	*.042*	*- .266*	*.014*
Plural Predator	*.243*	*.026*	*.357*	*.001*
Singular Prey	*.099*	*.371*	*- .001*	*.996*
Plural Prey	*.067*	*.543*	*.290*	*.007*

between the three categories were examined to gain deeper insight into the evolution of students' descriptions. Our results indicate that pluralising groups of individuals, mainly predators, helped students to describe indirect effects in food webs and fluctuating predator–prey relations. We also suggest that students understood mutual interactions without necessarily considering indirect effects and vice versa.

Putting our results in perspective

Previous studies have repeatedly demonstrated that students struggle to describe food web interactions at population level (Grotzer and Bell Basca 2003; Grotzer, Derbiszewska, and Solis 2017; Levy and Wilensky 2008; Mambrey, Schreiber, and Schmiemann 2022). Instead, students tend to apply a so-called agent-based reasoning, which has been extensively documented (e.g. Cuzzolino et al. 2019; Mambrey, Schreiber, and Schmiemann 2022). Earlier studies remain inconclusive as to what extent this agent-based perspective acts as a barrier to understanding food web interactions in depth (see Cuzzolino et al. 2019) or as a developmental stepping stone towards more sophisticated ecological reasoning (see Levy and Wilensky 2008).

Our findings align with the body of research on students' reasoning at primary individual level. Building on existing research, we confirmed that when our learning materials framed organisms as part of groups or populations, students were able to shift their perspective towards the population level (RQ1a). Moreover, we found that in the case of students who remained at the individual level, this phenomenon primarily occurred for the apex predator in the food chain. When students try to understand food web interactions as interactions between different populations, imagining apex predators as members of groups, instead of single agents, seems to be a major challenge.

This observation may be explained by students' everyday experiences, where herbivores and omnivores are more frequently observed as groups than apex predators such as foxes. In addition, we assume that students may anthropomorphise individual organisms, attributing intentionality to their actions (see Hammann and Asshoff 2019). The act of predation is thus perceived as an intentional behaviour actively carried out by animals with a specific purpose, thereby facilitating students' ability to envision individual organisms engaging in such actions. Consequently, apex predators, which are generally regarded as active hunters, are more likely to be persistently conceptualised as individuals. In contrast, other living beings, particularly plants, which are predominantly perceived as passive food sources, are more frequently described in the plural, reflecting their role as a collective resource within the food web.

Expanding on earlier research, we found that an agentive perspective does not inherently limit students' conceptual development but may instead facilitate the gradual construction of a more scientific understanding of indirect effects (RQ2). The conceptualisation of apex predators as groups rather than isolated individuals appears to be a crucial step in enabling students to describe propagating effects in food webs and fluctuating predator–prey relationships. In line with Levy and Wilensky (2008), we found that the comprehension of population-level dynamics gradually emerged as students aggregate individual behaviours into group-level patterns. A pivotal factor in this conceptual transition appears to be the deliberate linguistic structuring of learning materials. Our texts explicitly framed organisms as part of populations, consistently using plural forms to reinforce the idea that food webs represent groups rather than individual organisms. This finding suggests that linguistic cues play a crucial role in shaping students' ecological reasoning.

The study's findings indicate that, within the context of biology education, it may be fruitful to emphasise that predators do not merely exist as solitary individuals, but frequently function within group dynamics. By drawing attention to this aspect, biology classes may support students in shifting from an agent-based to a small-group perspective (mid-level understanding) and then to a population-level understanding. This can be facilitated through the utilisation of the grammatical use of plural forms and examples such as pack-hunting species (e.g. wolves), helping students to bridge the gap between individual-level observations and population-scale ecological processes.

In addition, explicit opportunities to reflect on the model-like nature of food webs are also required. The active discussion of the distinction between individual organisms and populations, as well as between real food relationships and their model representations, may facilitate the development of a more profound understanding of emergent ecological processes among students. However, it is important to note that our correlation analysis only allows for an examination of the co-occurrence of different subcategories. Future research should explore the joint development of pluralising predator descriptions and students' ability to conceptualise interactions and effects in adjacent food chains.

Regarding research questions 1b and 1c, previous studies on students' understanding of food web interactions indicate that they predominantly focus on linear (Evagorou et al. 2009; Grotzer and Bell Basca 2003; Hogan 2000; Mambrey, Schreiber, and Schmiemann 2022) and sometimes mutual (Eilam 2012; Hokayem, Ma, and Jin 2015) interactions and direct consequences (Eilam 2012; Hogan 2000; Mambrey, Schreiber, and Schmiemann 2022; White 1997). Explicit prompting of students to consider complex interactions as well as contexts familiar to the students has been shown to facilitate the recognition of more elaborate relationships (Allen 2017; Grotzer and Solis 2015; Hokayem, Ma, and Jin 2015). The present study's findings align with this prior research (RQ1b, c), whereby we assume that our participants were able to recognise causal patterns from the outset, thus enabling them to describe indirect effects and population dynamics. Importantly, our findings suggest that the text-based material used in this study played a supportive role in fostering this ability.

In addition, we suggest that our interview questions, combining a familiar food web representation with explicit questions about cyclic interactions and indirect effects, resulted in more scientifically adequate descriptions of food web interactions. This conclusion extends prior research by demonstrating that structured guidance presumably not only enhances students' recognition of complex ecological interactions in the moment but may also equip them with the skills to generate increasingly sophisticated explanations independently at later stages. These insights underscore the potential of carefully designed instructional prompts to scaffold students' conceptual development.

In considering the relationship between students' understanding of population dynamics and non-dissipation, Hogan (2000) hypothesised that students initially develop the capacity to articulate indirect effects prior to progressing to more sophisticated explanations of mutual and cyclic interactions, thereby indicating a correlation between these components in their conceptual evolution. In contrast, our correlation analysis indicates that these two components do not develop in a strictly linear progression; rather, they may emerge independently, depending on context and cognitive demand. This finding underscores a significant decoupling of ecological concepts in students' reasoning, suggesting that mutual interactions can be comprehended without necessitating an explicit awareness of indirect effects. However, in more complex responses, mutual and cyclic interactions are frequently described together with both direct and indirect effects (e.g. 'because mice and [. . .] then there would be a lot more nuts [. . .] but the fox would have less to eat because all the mice would be gone', transcript 10_GGLHE2UR5). This finding suggests that while mutual interactions can be conceptualised in isolation, cyclic processes, such as predator-prey dynamics, may require students to anticipate indirect effects. This finding indicates a cognitive threshold for understanding cyclic interactions, as these require students to integrate multiple interactions over time rather than considering single causal links. Consequently, cyclic interactions, at least between more than two populations, may represent a more advanced stage in students' conceptual development, requiring a shift from a linear to a more dynamic systems perspective.

Limitations and further research

Our study adds to the existing research on early secondary students' understanding of food web interactions, but it is important to consider its limitations. We focused on a relatively large sample for qualitative content analysis and applied a deductive category system to achieve depth in measurement. Our data suggest certain stepping stones, such as how students use pluralisation when discussing the apex predator in a food chain, which could be key to more sophisticated descriptions overall. Further exploration of these stepping stones could help to clarify crucial steps for understanding food web interactions.

Additionally, we acknowledge that the development of students' descriptions presumably depends on the specific intervention used. Although our text stimuli were intended to simulate an everyday classroom setting as far as possible, it can be questioned whether our results represented a natural learning progression for our chosen content – particularly because we strongly emphasised the shift in perspective from individuals to populations with the texts.

Previous intervention studies have shown that working with living ecosystems (Eilam 2012; Hogan 2000), discussing causal patterns in ecosystems (Grotzer and Bell Basca 2003) or constructing food webs based on real data (Demetriou, Korfiatis, and Constantinou 2009) in biology class are efficient to foster scientifically more adequate descriptions of food web interactions. However, these teaching interventions require significantly more time and resources compared to reading our text-based learning materials. Therefore, further research is needed to examine whether our resource-efficient text stimuli are equally efficient as other interventions in this context and for our target group.

Furthermore, our data were analysed within the specific context of food webs in a designated ecosystem. While this focus provided valuable insights, it is important to acknowledge the significance of broader conceptions, such as feedback loops and ecosystem dynamics. According to Verhoeff et al. (2018) and Gilissen, Knippels, and van Joolingen (2020), the use of such broader conceptions – referred to as system concepts – for explaining and predicting biological phenomena is described as systems thinking. Interpreting our findings through that lens may offer deeper insights into how students' context-specific understanding is intertwined with their ability to apply system concepts in biology. However, it would far exceed the scope of this paper.

Implications for biology education at early secondary level

The findings of this study offer valuable insights for the early secondary biology curriculum, particularly with regard to the instruction on food web interactions. Given the diverse objectives of biology education at this level, it is crucial to identify and emphasise key conceptual aspects to ensure that students develop a coherent and scientifically more adequate understanding.

In terms of lesson planning, we first suggest that a less developed understanding of population dynamics or indirect effects does not necessarily hinder students' ability to grasp other aspects of food web interactions. In addition, students can build an age-appropriate population concept through scaffolded instructional approaches, which supports them to understand other aspects of food web interactions in a scientifically more adequate way. We suggest recognising students' position in their conceptual development and systematically guiding them from an individual-level perspective to a group- or population-level understanding. This approach would enable students to progressively integrate more complex ecological concepts, such as indirect effects and cyclic interactions. By scaffolding their shift from agent-based reasoning to a broader perspective, biology classes can better support students in constructing a coherent understanding of food web interactions.

Secondly, we explicitly suggest that framing individuals as part of populations supports students' conceptual progression from simple food web interactions to more elaborate explanations of population dynamics and indirect effects. In particular, conceptualising carnivorous predators as part of a group rather than as isolated individuals facilitates the recognition of broader ecological patterns, such as population fluctuations and cascading effects within food webs. This finding underscores the importance of teaching students that food web representations depict populations rather than singular organisms. A practical method for reinforcing this concept is to employ plural grammatical forms when discussing food relationships, as language structures have been shown to influence cognitive processing in science learning.

Third, we suggest that the understanding of indirect effects, on the one hand, and mutual or cyclic interactions on the other can be developed independently, thereby challenging the prevailing assumption that different aspects of food web interactions must be imparted in a strictly sequential manner. Instead, a modular approach enables these components to be introduced in discrete lessons. For instance, a lesson on indirect effects could lay the foundation for subsequent discussions on environmental pollution, while a separate lesson on population density changes and dynamic equilibrium could introduce students to broader ecological issues such as climate tipping points. This flexible approach is consistent with previous research, which suggests that students do not necessarily integrate all ecological concepts concurrently. However, there is no universally accepted sequence for the development of these concepts.

In summary, the findings of this study demonstrate how placing a strong emphasis on a simplified population concept fosters a scientifically more adequate understanding of food web interactions. By conceptualising organisms as part of populations rather than as isolated individuals, students can better grasp population dynamics, indirect effects and cyclic interactions. Notably, the results suggest that this conceptual shift can be fostered through the use of structured learning materials and linguistic cues, such as the consistent use of plural forms. Given that students demonstrated the ability to articulate complex ecological processes when supported accordingly, this approach opens up opportunities to introduce complex ecological issues – such as environmental pollution and biodiversity loss – in an age-appropriate yet meaningful way, even at the early secondary level.

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Ethics approval

As per German regulations, ethics committee approval was not required as the study did not involve patients, was non-invasive, and participation was entirely voluntary. Permission to conduct the study was acquired from the regional educational authority. We also obtained permission to conduct this study from the principals and the students' parents, as is a common procedure for under-age students in Germany. The research team was guided by the 'Guidelines for Good Scientific Practice' (Deutsche Forschungsgemeinschaft, 2022).

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