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Development of the biotic impacts of climate change core concepts (BIC^4) framework

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ABSTRACT
The ability of living organisms to respond and adapt to a changing climate is an urgent concern. However, current educational efforts aimed at increasing US undergraduate student climate literacy primarily focus on the causes of, and abiotic responses to, climate change, mostly neglecting the biotic impacts. Here, we present a new framework, the Biotic Impacts of Climate Change Core Concepts (BIC^4), which provides context for addressing student understanding of how climate change will impact the living environment. The BIC^4 consists of 7 Core Concepts arranged into 3 overarching themes: Species Outcomes, Systems Outcomes, and Scale of Outcomes. This framework was developed through literature review, expert and novice surveys and interviews, and expert review. We show how the BIC^4 is well suited to support educational efforts developed with other frameworks (most notably the 4DEE), and we discuss future use of the BIC^4 as an education research tool.

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Climate change; education research; education; 4DEE; framework

1. Introduction

Climate change education fosters a climate-literate public and STEM workforce (UNFCCC. 2012), enables students to link climate change issues to their everyday lives (Scannell and Gifford 2013), serves as motivation for action (Halady and Rao 2010; Sinatra et al. 2012), and builds adaptive capacity into communities facing significant impacts from climate change (Feinstein and Mach 2020). As such, climate change education remains a key component in formal calls for undergraduate biology education reform. However, research on systemic approaches to formal climate change education in biology is lacking (Mochizuki and Bryan 2015; Rousell and Cutter-Mackenzie-Knowles 2020) and it is unclear what topics should be included in climate change curricula in US undergraduate biology classrooms (Brownlee, Powell, and Hallo 2013; Hess and Collins 2018; Molthan-Hill et al. 2019). Student conceptions of the impacts of climate change on biotic systems are rarely the prime focus in climate change education research, and this information contributes to the development of evidence-based climate curricula. In this article, we present and describe the development of a framework to help educators incorporate biotic consequences into undergraduate-level climate change curricula. The framework also highlights educational research focus areas for further studies in climate change education.

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1.1. Importance of the biotic impacts of climate change

The documented impacts of climate change are extensive and of a devastating scale. Changes in global temperatures directly impact abiotic components of ecosystems, including the distribution and quality of water (Whitehead et al. 2009; Parkinson et al. 2014; Dutton et al. 2015), extreme weather events (Stott 2016), and soils and nutrient cycling (Nearing, Pruski, and O'neal 2004; Estiarte and Peñuelas 2015). However, the ultimate consequences of climate change are the catastrophic, irreversible impacts on the biota (Hoegh-Guldberg and Bruno 2010; Nolan et al. 2018). Biotic impacts from climate change have negative impacts on both natural ecosystems (Walther et al. 2002; Grimm et al. 2013) and urban environments (Patz et al. 2005; McMichael 2013). While education alone cannot solve these problems without action, climate change education holds promise in fostering mitigation behaviors (Busch, Henderson, and Stevenson 2019) promoted through instructional interventions (Monroe et al. 2019). Unfortunately, education research on climate change primarily focuses on the causes and abiotic consequences of climate change, often omitting discussions of the ways global climate change impacts living organisms. While individual instructors may provide a robust discussion of these biotic outcomes in their own classrooms, the lack of published research or guidelines for instructors means that there is a large knowledge barrier for inclusion of this topic across broader biology curricula. Providing a framework to categorize and describe the ways in which climate change impacts living things should serve biology and ecology instructors well in their curriculum planning and ensure that they provide comprehensive coverage of this topic in their course.

1.2. Research on climate change education

In both primary and secondary school settings and the general public, education research on climate change focuses primarily on mechanistic causes and abiotic consequences of climate change (Wachholz, Artz, and Chene 2014; Monroe et al. 2019; UNESCO. 2019; UNESCO. 2021). Research on student knowledge has found enduring misconceptions about the cause of climate change (Shepardson et al. 2009; Lombardi and Sinatra 2012), such as confounding climate change with the depletion of the ozone layer (Papadimitriou 2004; Huxster, Uribe-Zarain, and Kempton 2015; Varela, Sesto, and García-Rodeja 2020).

Few studies examine student understanding of the impacts of climate change, and of those that do, most are focused on students' understanding of abiotic impacts such as higher temperatures and rising sea levels (Cordero, Todd, and Abellera 2008; Kilinc, Stanisstreet, and Boyes 2008; Shepardson et al. 2012; Rousell and Cutter-Mackenzie-Knowles 2020; Jarrett and Takacs 2020). Previous studies examining students' understanding of biotic impacts often focused on non-specific (e.g. 'Because of climate change, certain plants and animals may become extinct'; Dijkstra and Goedhart 2012) or broad-scale outcomes (e.g. 'Global climate change will impact our environment in the next 10 years'; Christensen and Knezek 2015; see also Boyes and Stanisstreet 1992; Shepardson et al. 2012; Carter and Wiles 2014; Danielson and Tanner 2015; Hermans and Korhonen 2017; Evans and Elisan-Visperas 2018). Shepardson et al. (2009) describe some of the most thorough work on student understanding of biotic impacts of climate change. They found K-12 students expect negative impacts from climate change on 'wild' plants and animals due to higher temperatures, less water drinking, and loss of habitat (Shepardson et al. 2009). Holt et al. (2021) interviewed undergraduate biology students and found post-secondary students mostly recognize the range of biotic outcomes from climate change, yet many of their ideas represented an incomplete understanding. Shepardson et al. and Holt et al.'s findings indicate students may be aware of potential biotic impacts of climate change and conceive of those in ways inclusive of community-level ecological processes. However, putting these research findings into practice involves clarifying and defining critical concepts of biotic impacts.

Most of the research on climate change education investigating what students know about the biotic impacts of climate change use K-12 student populations. Holt et al. (2021) is the only published research focused strictly on undergraduate populations on the biotic consequences of climate change. Generally, the climate change education literature shares this bias against studies in higher education institutions (Molthan-Hill et al. 2019). Additionally, most research on undergraduate climate change education is focused on geoscience or atmospheric science classroom instruction (e.g. Cordero, Todd, and Abellera 2008; McCuin, Hayhoe, and Hayhoe 2014; Aksit et al. 2018), thus there is a need to 'mainstream' climate change in biology courses to promote cross-curricular perspectives (Molthan-Hill et al. 2019).

1.3. Previous frameworks in undergraduate biology education

Numerous efforts over the past two decades sought to define the core ideas of biology in US undergraduate education (Brownell et al. 2014). The effort garnering the greatest attention, and against which most undergraduate biology curricula and programming is still compared, is *Vision and Change* (AAAS 2011). The *Vision and Change* framework proposed five core biological concepts and six core competencies as critical to biology undergraduate education. The authors of *Vision and Change* described their core concepts (i.e. evolution; structure and function; information flow, exchange, and storage; pathways and transformations of energy and matter; systems) as intentionally broad to act as a 'starting point' (AAAS 2011, 11). These concepts and competencies have served as the foundation for guidelines in programmatic assessment (Aguirre et al. 2013; Brownell et al. 2014), as metrics to evaluate student achievement and progression in biology programs (Cary, Wienhold, and Branchaw 2019; Smith et al. 2019a), and for evaluation of reform efficacy (Auerbach and Schussler 2017). In the subsequent decade, numerous biology-related professional organizations translated *Vision and Change*'s core concepts into narrower subdiscipline-specific frameworks (e.g. Society for Microbiology (Merkel et al. 2012), American Society of Plant Biologists (ASPB and BSA 2012), American Society for Biochemistry and Molecular Biology (Tansey et al. 2013), Genetics Society of America (Genetics Society of America Education Committee 2015 (Core Concepts and Competencies in Genetics)).

In the subdiscipline of ecology, numerous authors proposed multiple frameworks to help define the key basic ecology topics, even before *Vision and Change* (described in McBride et al. 2013). However, recent efforts leveraged elements of *Vision and Change* and the *Next Generation Science Standards* (a science framework for K-12 settings; NGSS Lead States 2013), leading to the development of the Four-Dimensional Ecology Education framework—or 4DEE (Klemow et al. 2019)—which is endorsed by the Ecological Society of America. The 4DEE expanded *Vision and Change*'s concepts and competencies to account for the interactive and interdisciplinary nature of ecology. The 4DEE has four broad dimensions that help to describe and categorize all content in ecology education; Core Ecological Concepts (I), Ecology Practices (II), Human-Environment Interactions (III), and Cross-Cutting Themes (IV).

2. Project goals

The 4DEE framework and *Vision and Change* are excellent tools for broadly guiding curricula in ecology and biology, respectively. However, climate change is treated as a single subtopic among many, rather than the unifying and crosscutting concept it is (McCright et al. 2013). To equip students to understand the looming threat of climate change to the biota, we argue specific instructional support regarding the biotic impacts of climate change is needed throughout multiple areas of the biology and ecology curricula. While prior educational efforts have been successful in galvanizing support for climate change mitigation (Cordero, Centeno, and Todd

2020) and increasing acceptance of climate change (Goldberg et al. 2019), more work is needed to formalize education related to the biotic impacts of climate change.

Here, we present the Biotic Impacts of Climate Change Core Concepts, or BIC^4, a framework we have developed through review of the scientific literature, surveys of and interviews with students and faculty, along with expert review. The BIC^4 serves as a biology-focused framework of climate change education. Following development, we realized the BIC^4 strongly aligns with existing frameworks, such as the 4DEE, but we propose the biotic impacts of climate change exist as multiple core concepts spanning biology and ecology curricula rather than nested as a single idea within each subject. In our novel framework, we identify three overarching themes, under which seven Core Concepts are described. These BIC^4 concepts document the biotic effects of climate change and allow for important consideration of the unique threat climate change poses to ecological systems. As part of this presentation, we retrospectively situate the BIC^4 within the 4DEE to underscore the relevance for ecology educators. By highlighting key concepts of the biotic impacts of climate change, the BIC^4 serves both as a tool for curriculum development and as a guide for ecology education researchers.

3. Methodological approach and concept development

The goal of developing a novel framework to describe the biotic impacts of climate change arose as the first phase in development of a concept inventory to measure the same topic, which is not described here. To address this goal, we followed best practices in education research concept development (Libarkin 2008) using an iterative process. This process comprised four steps: (1) identification of specific topics of the biotic impacts of climate change, (2) consolidation of specific topics into general topics, (3) refinement of general topics into overarching themes, and (4) expansion of each theme into core concepts (Figure 1). This process is described in greater detail below.

The starting place for the BIC^4 development was to articulate specific topics related to the biotic impacts of climate change. We developed an initial list of 17 specific topics from three data sources (Figure 1). All human-subject data upon which these topics were based were

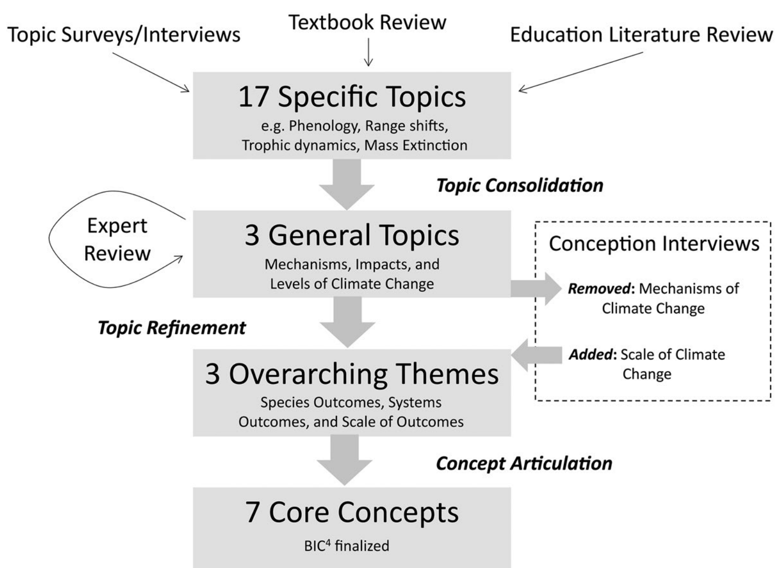

Figure 1. Schematic diagram illustrating the four steps of development of the BIC^4. External sources of data and input are noted with arrows, and internal team analysis are noted in bolded italics.

collected with IRB approval UNCO IRB #1288162). First, 55 participants (15 faculty across the college curricula including life sciences, social sciences, and physical sciences, and 40 biology undergraduates) from across the US were surveyed and interviewed to explore topics they taught or learned about related to climate change. Second, we surveyed four textbooks commonly used in US university-level ecology courses (Supplement A) to outline the curricular focus of climate change in biology coursework. Third, we reviewed 56 climate change education journal articles (Supplement A) to compile relevant concepts or misconceptions documented in the research realm. The resulting list of 17 topics highlighted that biotic impacts of climate change may be ecosystem-specific (e.g. coral bleaching) and interactive (i.e. more than one outcome is possible depending on a range of complex factors, e.g. trophic dynamics).

The second step of the BIC^4 development involved consolidation and organization of these 17 topics into a narrower list of three general topics (Figure 1). Our team thematically evaluated the 17 topics and parsed them into Impacts, a category in which we recognized impacts to species' distributions, their reproduction, or their growth and survival. We further noted that these topics differed in their Level of impact, a category reflecting where the impact affected different levels of the biological hierarchy, e.g. organism vs. community, and can be either direct or indirect. For the third general topic, we also described the Mechanisms that lead to these impacts (i.e. change in temperature, change in moisture, or change in air, water, or soil chemistry).

As a rigorous evaluation of this step, we disseminated these three general topics to 13 climate science experts for expert validation. These experts included researchers at universities and federal agencies specializing in ecology, biology, biometrics, and meteorology. We identified the experts through recommendations from colleagues, their publication record related to biotic climate change research, and through our own professional contacts. On a Likert scale of importance (i.e. extremely important, very important, moderately important, slightly important, not at all important), experts reported the extent to which they thought each general topic was important to the science of climate change and how important it was for college students to learn these topics. The experts also provided input on any concepts they thought were missing from our list.

We noted overwhelming agreement that our general topics were considered important by climate experts. Over 90% of expert ratings of our general topics deemed them 'very important' or 'extremely important' to climate science, and 87% of expert ratings labeled these topics as 'very important' or 'extremely important' for students to learn in college. The experts identified several topics they thought were missing from our list; yet, we determined that all of the additional topics suggested by experts were already ideas within our existing general topics (e.g. the idea that climate change 'changes interactions' was already captured in our Impacts and Levels categories). However, the expert feedback clarified where more detail and clarification were needed in our general topics. The expert feedback also highlighted the relative importance of system versus individual-level processes, which encouraged us to expand this area of coverage in the next step.

The third step of the BIC^4 development refined the general topics into overarching themes. Using the original three general topics as a guide, we developed an interview protocol. We then conducted conceptions interviews with 13 undergraduate students, recruited from biology courses across the US (see Holt et al. 2021), to determine how they understood our general topics in hypothetical climate warming scenarios. The interview data provided insight to help us modify the general topics. Notably, we removed the mechanistic causes of climate change and narrowed the focus of our framework to the biotic impacts of climate change. While mechanisms describe the causes of climate change, individual mechanisms (i.e. change in temperature vs. change in physical environment) are interactive and may be irrelevant for a focus on the subsequent biotic response. In many cases interview participants were unclear about which mechanism caused a biotic consequence, yet it did not seem to affect their conception of the biotic response. We therefore removed Mechanisms in refining the overarching themes (Figure 1) to sharpen our focus on the biotic impacts of climate change.

As part of this third step, we recategorized and expanded the remaining general topics (i.e. Impacts and Levels) into three overarching themes: Species Outcomes, Systems Outcomes, and Scale of Outcomes. The Impacts topic was renamed the Species Outcome theme and narrowly described impacts at the species or population-level. Biology system impacts at higher levels (e.g. communities, ecosystems) were folded into the Systems Outcomes theme. Further, directness of impact described in the Levels topic was included as part of the Systems Outcomes.

Importantly, our interviews also highlighted students' inability to discriminate that the biotic impacts described in our general topics (i.e. Impacts and Levels) could be similarly reproduced by biota in response to non-climate change disturbances, such as wildfires, cyclical droughts, species invasion, etc. For example, native rodent population density could decline due to predation pressure of an invasive predator, not just because of climate change (e.g. Greenville, Wardle, and Dickman 2017). So while biotic impacts from climate change may be similar to those caused by other disturbances (as seen in both the Species Outcomes and System Outcomes themes), the temporal and spatial scales of climate change impacts are unique. For example, a wildfire acts as a perturbation with distinct geographic boundaries, immediate impacts, a distinct temporal end, and relatively fast recovery rate. Climate change, being a global event occurring for an undetermined period of time, at differential rates of change, generally results in slower impacts with limited opportunity for recovery. Since the BIC^4 framework seeks to focus on differentiating biotic impacts due to climate change versus other causal factors, we added the Scale of Outcomes theme as a lens unique to climate change through which the other two themes must be interpreted. The temporal and spatial elements of climate change help differentiate biotic impacts caused by climate change from those impacts which are not caused by climate change.

The fourth step of the BIC^4 development was to articulate Core Concepts, using data from all previous steps of development, under each overarching theme into the final BIC^4 framework (Figure 1, Table 1). The Core Concepts further define their overarching themes, while providing more tangible concepts for practitioners. The final set of seven Core Concepts of the BIC^4 reflect all the original topics noted in the development process (Figure 1), but focus in an organized and non-redundant manner on the biotic impacts from climate change.

4. Results: Description of the BIC^4

The BIC^4 contains seven Core Concepts, organized into three overarching themes (Table 1), that clarify the range of impacts living organisms will experience due to climate change. The three

Table 1. The overarching themes and Core Concepts of the BIC^4.

Theme 1: Species outcomes (organism, population, species, guild) —single species or multiple closely-related or functionally similar species	*Core Concept 1*: Species' distributions may be affected in time or space—phenology or range shift *Core Concept 2*: Species' reproduction and life history traits may be affected *Core Concept 3*: Species' growth or survival may be affected
Theme 2: Systems outcomes (community or ecosystem) —multiple different species are affected collectively	*Core Concept 4*: Species' relationships can be affected by climate change: (a) Many different types of relationships may be affected, including competition, exploitation (trophic dynamics), mutualisms; (b) Nature of the change affecting the relationship may be direct or indirect *Core Concept 5*: Biological processes can be affected (e.g. nutrient cycling, change in diversity, succession)
Theme 3: Scale of outcomes—Climate change is a unique type of disturbance	*Core Concept 6*: Climate change has unique spatial effects: (a) Climate change, as a disturbance, occurs on a global scale; (b) The effects of climate change are often similar across a landscape *Core Concept 7*: Climate change has unique temporal effects: (a) Climate change is a continuous disturbance, and not a discrete event; (b) The observed effects of climate change occur over a long period of time

overarching themes are: Species Outcomes, Systems Outcomes, and Scale of Outcome. Here, we describe the framework using the themes as an organizing structure. We also connect the Themes and Core Concepts to evidence of each in the scientific literature to highlight their application in real systems.

4.1. Theme 1: Species outcomes

The first theme is Species Outcomes. Species Outcomes describe the unique impacts of climate change on lower levels of biological organization from individual organisms up through populations, whole species, and guilds (i.e. interviewees often discussed changes in a functional group such as 'grasses' without specifying a species). Within this theme, we identified three Core Concepts of climate-related effects: (1) Species Distribution, (2) Reproduction and Life History, and (3) Growth and Survival (Table 1).

First, species' distributions can change through time, such as phenology alterations, or in space, such as range shifts (Core Concept 1). These distributional changes can vary widely in their proximate cause, from patch-level changes due to competition (e.g. Fitt and Lancaster 2017) or foraging behavior (e.g. Hückstädt et al. 2020) to large-scale changes, such as salinity, temperature, and dissolved oxygen (e.g. Lauchlan and Nagelkerken 2020) in aquatic environments. Additionally, species' reproduction and life history traits may also be affected by climate change (Core Concept 2). This can be observed, for example, in the form of decreased reproductive output due to climate-induced food scarcity (e.g. Stubbs et al. 2020), reductions in fertility and attractiveness to mates due to increased temperature (e.g. Walsh et al. 2019; Martinet et al. 2021), or even sex ratio differences due to temperature changes during development (e.g. Wapstra et al. 2009). Lastly, climate change affects individuals', populations', species', or guilds' growth or survival (Core Concept 3). Within this concept, coral bleaching and declining polar bear populations are well documented examples (e.g. Pilfold et al. 2017; Hughes et al. 2018), and climate change is directly implicated in species extinction (Watson 2016; Román-Palacios and Wiens 2020).

4.2. Theme 2: Systems outcomes

The second theme is Systems Outcomes. While Species Outcomes describe the unique impacts of climate change on lower levels of biological organization, Systems Outcomes describe climate change consequences on higher levels of the biological organization, including communities and ecosystems. Within this latter overarching theme, we identified two Core Concepts: Species Relationships and Biological Processes (Table 1).

Climate change, like most disturbances, does not affect species in isolation. At higher levels of the biological hierarchy, climate change affects multiple interacting species across small and large geographic areas. Notably, some of these impacts manifest as emergent effects, only seen when considering the impacts at the level of communities or ecosystems (Core Concept 4). Nearly any type of species relationship may be affected by climate change (Core Concept 4a). For example, competition between native and invasive species is affected by a warming climate in many ways (e.g. Lin, Wu, and Ho 2018; Lauchlan et al. 2019). Further, warming temperatures are associated with increased incidence of parasites as well as the diseases they carry (e.g. Short, Caminade, and Thomas 2017) which by association affects their hosts. Most dramatically, mutualisms can be affected by changes in climate, and may be particularly foreboding for obligate mutualists where climate change could change the nature of their relationship (e.g. Baker et al. 2018). Further, the way that climate change impacts species' relationships can be direct or indirect (Core Concept 4 b). Even if an individual population or species is not directly impacted by climate change in the ways described in the Species Outcomes overarching theme above, climate effects on its symbionts may indirectly affect both partners via species interactions. For example, Miller-Struttmann et al. (2015) describe how climate change reduced floral resources which drives anatomical adaptations (i.e. shifts in tongue length) that subsequently affect overall pollination patterns, further breaking down the mutualistic relationship between these flowers and their pollinators.

Biological processes seen at the community scale and above are also affected by climate change (Core Concept 5). As described above, the abiotic elements of ecosystems are often among the more commonly cited impacts from climate change (e.g. how climate change affects the rainfall pattern in an ecosystem). However, we argue that the ways the biotas in an ecosystem are affected by climate change are equally worth inclusion in climate change curricula. Shifts in community composition are attributed to rising temperatures and changes in precipitation associated with climate change (e.g. Feeley et al. 2020). Changes in nutrient fluxes and cycling are another example of how ecological processes are affected by climate change (Bernal et al. 2012). The shifts in the nutrients themselves, e.g. carbon, has direct effects on the ecosystem, as photosynthetic organisms will generally be able to assimilate more carbon, resulting in global net productivity increases (e.g. Gang et al. 2017); which organisms benefit most from this shift, however, varies, with organisms specialized for quick growth, often invasives, benefitting more (e.g. Bradley, Wilcove, and Oppenheimer 2010). The effect on competitive ability can further lead to changes in succession or diversity of patches (e.g. Wang et al. 2015).

4.3. Theme 3: Scale of outcome

The final theme is Scale of Outcome. While the above outcomes, regardless of the biological unit, reflect responses to climate change, similar biotic responses may result from other types of disturbance. Our interviews highlighted that the biotic outcomes from climate change may closely resemble those resulting from other types of disturbances like fire, flooding, and pest outbreak. This similarity necessitated a third theme that differentiates biotic outcomes caused by climate change from other types of disturbance by describing the unique scale of biotic outcomes from climate change. We identified two ways that the scale of climate change impacts living things, which comprise our final two Core Concepts: climate change has unique spatial effects, and climate change has unique temporal effects (Table 1).

Climate change differs from other disturbances in spatial extent (Core Concept 6); its effects are global (Core Concept 6a) and occur in similar patterns across a landscape (Core Concept 6 b). Other disturbances may be devastating, but occur over a localized range; forests damaged by fires may have patches less than a kilometer away that are undisturbed, and these patches serve as an important source for recovery from disturbance. Climate change allows few such *in situ* refugia, and the impact of warmer temperatures or altered precipitation are often felt across a whole landscape limiting *ex situ* refugia (Ashcroft 2010).

Biotic outcomes from climate change also have unique temporal elements (Core Concept 7) when compared to, for example, impacts created by a fire disturbance. Climate change is a continuous and ongoing process (Core Concept 7a), and the observed effects of climate change occur over a long period of time (Core Concept 7 b). Because of these protracted temporal patterns, systems disturbed by climate change, especially those with low resilience, will be shifted ever slowly towards a new steady state. This outcome is in contrast to other disturbances like fire; while recovery following a fire is slow—depending on the size and intensity of the fire—the fire itself acts within a short time frame. This difference in scale is important for the resilience of organisms. For example, many plants with below-ground structures can recover from a single fire, while the repeated stress of climate warming may prove unsurmountable (e.g. Malhi et al. 2008). While immediate responses to climate change involve plastic responses to environmental stressors that an organism encounters (Merilä and Hendry 2014), long-term, sustainable responses to climate change necessitate evolutionary adaptation to new environmental conditions via natural selection (e.g. Nadeau and Urban 2019). The latter process is notoriously slow, and even more so for species with long life spans, low genetic diversity, or low dispersal ability.

Our inclusion of temporal and spatial scales in our framework is in agreement with Bellard et al. (2012) who suggest that the impacts of climate change on biodiversity are 3-dimensional, with time and space represented as two of the axes on which climate change can affect living things. While their work identifies how climate change impacts different ecological scales of the environment, Bellard et al. (2012) do not use scale to categorize the impacts of climate change thematically as we do here.

5. Discussion: The BIC^4 as a supplemental framework

As described above, we developed the BIC^4 as the first phase of a concept inventory development process using review of the literature, surveys, interviews, and expert review. The BIC^4 is a framework intended to describe the key concepts related to the biotic impacts of climate change. It was late in the development process that we recognized the potential overlap between the BIC^4 and existing frameworks such as the 4DEE and *Vision and Change*. Unlike these existing frameworks, the BIC^4 is not organized around a single course subject, like ecology or introductory biology; it is instead a cross-curricular framework organized around aspects of biotic impacts and the way in which biological and ecological operants respond to the unique conditions presented due to climate change. We view the BIC^4 framework as well suited for use in conjunction with these existing disciplinary frameworks that include scientific practices.

We acknowledge that understanding many of the specific concepts in the BIC^4 requires a breadth of biological and ecological content knowledge. As an example, BIC^4 Core Concept 1 discusses how populations may experience range shifts due to climate change. At a minimum, to demonstrate mastery of this Core Concept, an individual must understand dispersal ability, life history, evolutionary limitations, and physiological tolerances (Donelson et al. 2019). Thus, the BIC^4's utility is fully realized when used together with other frameworks like *Vision and Change* and 4DEE that cover a broader scope of basic biological or ecological subject knowledge.

While 4DEE mentions climate change in more than one element of their framework, key areas where climate change can be integrated into ecology curricula are not clearly articulated. In our opinion, climate change is vital to two components of the 4DEE, namely, Core Ecological Concepts (I) and Cross-Cutting Themes (IV). While ecology practices (dimension II) are important for educating students on the skills and approaches used in studies of climate change and its effects on natural ecological systems, these practices are enduring and transcend content (Laverty et al. 2016), and thus are not our area of focus. Dimension III, understanding how humans interact with the environment, is also critical for understanding both how humans and our societies contribute to and will be affected by climate change. However, we propose elaboration of dimension III is best served through collaboration between climate scientists, biologists, and social scientists. Therefore, we limit our focus in this article to the impacts climate change has on natural systems and expand only upon the conceptual and thematic dimensions (i.e. I and IV) of the 4DEE.

To facilitate integration of the BIC^4 Core Concepts with curricula designed using the 4DEE framework, we mapped areas of overlap between the two frameworks (Table 2). As illustration, the 4DEE concept of 'landscapes' relates to the BIC^4 Core Concepts 5 and 7; landscapes help to define the scale at which climate change occurs and are the level at which system-wide processes such as nutrient cycling occur. In this way, using the BIC^4 allows for integration of climate change concepts across existing ecology curriculum. Similarly, the 4DEE (and *Vision and Change*) cross-cutting theme of Structure and Function overlaps with the BIC^4 Core Concepts

Table 2. Overlap of the BIC⁴ and the 4DEE frameworks.

			Biotic Impacts of Climate Change (BIC⁴) Framework						
			Theme 1: Species Outcomes			Theme 2: Systems Outcomes		Theme 3: Scale of Outcomes	
			Core Concept 1	Core Concept 2	Core Concept 3	Core Concept 4	Core Concept 5	Core Concept 6	Core Concept 7
Four-Dimensional Ecology Education (4DEE) Framework	Dimension I: Core Ecology Concepts	Organisms	X	X	X				
		Population Dispersion	X	X	X	X			
		Communities				X	X		
		Ecosystems				X	X		
		Landscapes					X	X	
		Biomes					X	X	
		Biosphere					X	X	X
	Dimension IV: Cross-Cutting Themes	Structure & Function	X	X	X	X			
		Pathways & Traormations				X	X		
		Systems				X	X		
		Space & Time						X	X

"X"s represents overlap of concepts and themes from both frameworks.

1, 2, 3, and 4. In addition to basic understanding of how climate change may affect anatomy, morphology, and physiology of lower levels of the biological hierarchy (BIC^4 Theme 1), Core Concept 4 of the BIC^4 highlights the importance of understanding how individual-level effects can have emergent responses when climate effects are considered in the context of species interactions. In this way, the BIC^4 can supplement the 4DEE by identifying areas where modules could be added into existing course materials in an effort to facilitate learners' ability to transfer general ecological knowledge to a more specific set of climate change circumstances.

Though these other frameworks were developed as tools for curriculum guidance, both the 4DEE and *Vision and Change* have seen utility in STEM education research as well (e.g. Smith et al. 2019a; Smith et al. 2019b; Brownell et al. 2014). We believe the BIC^4 framework has similar potential, as it is the first tool we are aware of that categorizes the multitude of ways that climate change impacts living things. In defining these biotic impacts, the BIC^4 highlights specific areas of climate change education that can be addressed with the various tools and methods available to STEM education researchers. As an example, Holt et al. 2021 used the BIC^4 Theme 1: Species Outcomes as a coding frame to better describe student conceptions about the biotic response to climate change. Our hope is that the BIC^4 framework will be adapted by those who seek to explore more about this topic in the future.

6. Conclusion and future directions

We present a new educational framework, the Biotic Impacts of Climate Change Core Concepts (or BIC^4), which we developed through a rigorous concept development process. We believe the BIC^4 holds the greatest promise as a framework to inform curricula in biology and ecology, so that instructors and students alike can center on the core concepts describing how climate change impacts the living environment. While we recognize that climate change education is context-dependent, we hope the BIC^4 represent overarching ideas to guide instruction. As a pedagogical tool, it can be used in conjunction with existing frameworks such as 4DEE and *Vision and Change,* which situates the climate-specific BIC^4 in a larger curriculum and include disciplinary practices. In addition to this main utility, we hope that future work will define the ways in which this framework can be used by biology education researchers for identifying the unique areas in which climate change can be discussed in biology classrooms. Additionally, future work could expand the framework to describe how climate change affects humans and urban environments, including aspects of Dimension III of the 4DEE. We foresee the BIC^4 as a useful tool as is, but also the beginning of much new work to come on understanding, describing, and teaching how climate change impacts living aspects of the environment.

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The authors report there are no competing interests to declare.

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Data availability statement

Data sharing is not applicable to this article as no new data are reported directly as results in this study.

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